Study to Identify BATEA for the Management and Control of Effluent Quality from Mines

MEND Report 3.50.1

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Prepared by:
Kristin Pouw, PEng
Kathryn Campbell, EIT
Lisa Babel, PEng

Summary

Hatch was commissioned by the Mine Environment Neutral Drainage (MEND) Program to complete a study to identify best available technologies economically achievable (BATEA) to manage and control effluent from metal, diamond, and coal mines in Canada. The objective of the study was to provide reference information for potential forthcoming changes within the *Metal Mining Effluent Regulations* (*MMER*) to the types of regulated mining facilities, the list of Schedule 4 parameters, and the authorized limits of Schedule 4 concentrations in effluent discharged to the environment. These potential changes are outlined in the Environment Canada 2012 discussion paper, "*10-Year Review of Metal Mining Effluent Regulations*". For metal mining effluent, Environment Canada has proposed the addition of aluminum, iron, selenium, and total ammonia to the list of Schedule 4 substances, and has proposed the reduction of authorized limits for arsenic, copper, cyanide, lead, nickel, and zinc. For diamond mining effluent, which is currently not regulated under *MMER*, Environment Canada has proposed limits for chloride, phosphorus, ammonia, and total suspended solids (TSS) concentrations in effluent discharged to the environment, as well as limits for pH. For coal mining effluent, which is currently not regulated under *MMER*, Environment Canada has proposed limits for arsenic, aluminum, iron, manganese, selenium, ammonia, and TSS concentrations in effluent discharged to the environment, as well as limits for pH. Other proposed changes include the addition of a new requirement that effluent be non-acutely lethal to *Daphnia magna* and changes to Environmental Effects Monitoring requirements.

The study describes the effluent management and treatment technologies and techniques currently employed at metal (base metal, precious metal, uranium, iron ore), diamond and coal mine operations in Canada. The study provides an overview of each (sub)sector's water management and effluent treatment practices and establishes a model effluent treatment process and treated effluent quality to carry forward for use in BATEA selection.

The study identifies effluent treatment technologies that could be considered best available technologies (BAT) for the Canadian mining sector. The technologies were compiled from treatment technologies currently available on the market, both active and passive, that are applicable to the control of effluent quality for current and proposed *MMER* parameters. The potential BAT technologies were then screened against a set of criteria: "Can this technique achieve current *MMER* discharge limits?", "Has this technique been demonstrated at full scale on mining effluent?", and "Has this technique been demonstrated under representative climate conditions?". Technologies that satisfied all three criteria were considered BAT, and carried forward for consideration as BATEA. A technical characterisation is presented for each BAT, which describes contaminant removal mechanisms, removal efficiencies and/or achievable concentrations, major equipment, synergies with other technologies, operational challenges, current application at Canadian operations, and capital and operating costs.

For each (sub)sector, BAT technologies were further screened to identify BAT that could be applied to augment the model effluent treatment system. BAT were screened out from consideration if the technology was already included in the model effluent treatment system flowsheet, or if the technology could not improve effluent quality beyond that typically achieved by the model effluent treatment system. For BAT that passed this screening, order of magnitude equipment, installed, and operating cost estimates were prepared, based on capital and operating cost data from vendors and operations, in-house information, and literature.

BATEA for the augmentation of the model effluent treatment system for each (sub) sector were selected based on a comparative assessment of the costs and benefits of the applicable BAT technologies. BATEA selection was bounded by the strict criteria for BATdescribed above and in the context of a model non-greenfield operation with existing effluent management and treatment systems. BATEA for greenfield operations may be different than that selected for existing model operations. Removal efficiencies and/or achievable effluent concentrations are based on reported operations data, literature values, and/or vendor data and may not be possible for every application. Ultimately, BATEA for any given mining operation is site-specific, as a result of the multitude of geographic and operational factors that influence effluent quality, impact the technical feasibility of treatment technologies, and dictate financial constraints on capital and operating expenditures that can be borne by operations while still maintaining economic viability.

Review of the **base metal subsector** included a total of 43 operations. The model effluent treatment system for the subsector consists of hydroxide precipitation for metals removal and pond-based settling for bulk TSS removal. Coagulant and flocculant are dosed to facilitate metal precipitate and TSS sedimentation. The pond-based system also enables passive natural degradation of ammonia. The pH of settling pond decant is adjusted with carbon dioxide to meet *MMER* pH limits and/or un-ionized ammonia/toxicity requirements prior to discharge to the environment. The design and nominal flow rates selected to estimate capital and operating costs for system augmentation for the model treatment system were 2,000 m^3/h and 870 m^3/h, respectively. BATEA was defined as sulfide precipitation with proprietary polymeric organosulfide chemicals for dissolved metals polishing and the model effluent management and treatment system for total ammonia, bulk metals, and TSS removal.

Review of the **precious metal subsector** included a total of 40 precious metal operations. The model effluent treatment system for the subsector consists of SO_2/air cyanide destruction on tailings and low density sludge lime hydroxide precipitation for bulk metal removal from effluent from tailings, mine, and waste rock areas. The design and nominal flow rates selected to estimate capital and operating costs for system augmentation for the model treatment system were 600 m^3/h and 180 m^3/h, respectively. BATEA was defined as sulfide precipitation with proprietary polymeric organosulfide chemicals for dissolved metals polishing, active aerobic biological oxidation for total ammonia removal, and the model effluent management and treatment system for cyanide, bulk metals, and TSS removal.

Review of the **iron ore subsector** included all 6 operating iron ore operations. The model effluent treatment system for the subsector consists of pond-based settling for bulk TSS removal with flocculant dosing to aid settling. The design and nominal flow rates selected to estimate capital and operating costs for system augmentation for the model treatment system were 7,000 m^3/h and 3,900 m^3/h, respectively. BATEA was defined as the model effluent management and treatment system for TSS, metals, and total ammonia removal.

Review of the **uranium subsector** included a total of 12 operations. The model effluent treatment system for the subsector consists of 2 stages: a high pH stage for precipitation of metals that precipitate in basic conditions and a low pH stage for metals and other parameters that precipitate or co-precipitate in acidic conditions. Between and after these pH stages, clarification and filtration are employed to separate precipitates from treated water. The design and nominal flow rates selected to estimate capital and operating costs for system augmentation for the model treatment system were 500 m^3/h and 350 m^3/h, respectively. BATEA was defined as active aerobic biological oxidation for total ammonia removal and the model effluent management and treatment system for metals and TSS removal.

Review of the **diamond sector** included a total of 4 operations. The model effluent treatment system for the sector consists of settling pond(s), clarification, and media filtration for TSS removal. Coagulant is dosed into the clarifier. Prior to discharge to the environment, pH is adjusted using sulfuric acid to meet un-ionized ammonia/toxicity limits. The settling and polishing ponds enable passive natural degradation of ammonia and phosphorus. The design and nominal flow rates selected for the model treatment system were 3,000 m^3/h and 2,000 m^3/h, respectively. These flow rates were used to estimate capital and operating costs for system augmentation. BATEA was defined as the model effluent management and treatment system for chloride, bulk metals, ammonia, and TSS removal.

Review of the **coal sector** included a total of 16 operations. In the model effluent treatment system for the sector, bulk TSS is removed via pond-based settling and polishing which may be aided by the addition of flocculant. The settling and polishing pond(s) enable passive natural degradation of ammonia. The design and nominal flow rates selected for the model treatment system were 3,000 m^3/h and1,000 m^3/h, respectively. BATEA was defined as the model effluent management and treatment system for metals, total ammonia, and TSS removal.

For all (sub)sectors, testwork is recommended to confirm proprietary reagent demand, efficacy, and precipitate settleability, as well as to verify that treated effluent complies with toxicity requirements. It is also advised that treated effluent be discharged rather than recirculated for any purpose such that cycling up of residual chemical concentration is limited. Due to the relatively recent adoption of these reagents and the proprietary nature of their formulations, little is known about the long term stability of residuals and the potential for acid generation and metals remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred. Hatch cautions that this technique should only be considered BATEA for operations that are capable of and dedicated to careful control of operating regimes to prevent effluent toxicity, as well as, careful control of residuals storage conditions to prevent long term instability and the potential generation of acid through sulfide oxidation and metals remobilization.

Sommaire

Les responsables du Programme de neutralisation des eaux de drainage dans l’environnement minier(NEDEM) ont chargé l’entreprise Hatch de compléter une étude visant à établir les Meilleures techniques existantes d’applicable rentable (MTEAR) pour gérer et contrôler les effluents provenant des mines de métaux, de diamants et de charbon au Canada. L’objectif de l’étude était de fournir des données de référence pour les changements futurs potentiels, qui seront apportés au *Règlement sur les effluents des mines de métaux* (*REMM*) et qui visent les types d’installations minières réglementées, la liste de paramètres de l’annexe 4 ainsi que les concentrations maximales permises selon l’annexe 4 pour les effluents rejetés dans l’environnement. Ces changements potentiels sont décrits dans le document de travail publié en 2012 par Environnement Canada et intitulé « *Examen décennal du Règlement sur les effluents des mines de métaux* ». Pour les effluents des mines de métaux, Environnement Canada a proposé l’ajout de l’aluminium, du fer, du sélénium et de l’ammoniac total à la liste des substances de l’annexe 4 et a proposé la réduction des limites permises pour l’arsenic, le cuivre, le cyanure, le plomb, le nickel et le zinc. Pour les effluents des mines de diamants, qui à l’heure actuelle ne sont pas réglementés en vertu du *REMM*, Environnement Canada a proposé des limites pour le chlorure, le phosphore, l’ammoniac et le total des solides en suspension (TSS) dans les effluents rejetés dans l’environnement, ainsi que des limites pour le pH. En ce qui concerne les effluents des mines de charbon, qui à l’heure actuelle ne sont pas réglementées en vertu du *REMM*, Environnement Canada a proposé des limites pour les concentrations d'arsenic, d'aluminium, de fer, de manganèse, de sélénium, d'ammoniac et le TSS dans les effluents rejetés dans l'environnement, ainsi que des limites pour le pH. D'autres changements proposés comprennent l'ajout d'une nouvelle exigence de non létalité aiguë pour *Daphnia magna* ainsi que des modifications apportées aux exigences pour l'étude du suivi des effets sur l'environnement.

L'étude décrit les technologies ainsi que les techniques de gestion et de traitement des effluents utilisées à l'heure actuelle dans les opérations des mines de métaux (métaux communs, métaux précieux, uranium, minerai de fer) de diamants et de charbon au Canada. Le document présente un aperçu des pratiques de traitement des effluents et de gestion de l'eau de chaque sous-secteur et établit un procédé modèle pour le traitement des effluents ainsi que la qualité des effluents traités pour aller de l'avant avec l'utilisation de la sélection des MTEAR.

L'étude identifie les technologies de traitement des effluents qui pourraient être considérées comme les meilleures techniques disponibles (MTD) du secteur minier canadien. La liste des technologies a été dressée à partir des technologies de traitement disponibles à l'heure actuelle sur le marché, tant actives que passives, qui s'appliquent au contrôle de la qualité des effluents pour les paramètres actuels et proposés du *REMM*. Les technologies MTD potentielles ont été sélectionnées en fonction des critères suivants : « Cette technologie peut-elle respecter les limites de rejet actuelles prévues par le *REMM*? »; « L'efficacité de cette technologie a-t-elle été validée à grande échelle pour les effluents des mines? »; « Cette technologie a-t-elle fait l'objet d'une démonstration dans des conditions climatiques représentatives? ». Les technologies qui respectaient les trois critères susmentionnés ont été considérées comme les MTD et ont été mises de l'avant pour être considérées comme MTEAR. Une caractérisation technique est présentée pour chaque MTD, qui décrit les procédés d'élimination des contaminants, le rendement d'élimination et/ou les concentrations atteignables, l'équipement majeur, les synergies avec d'autres technologies, les défis opérationnels, leur application actuelle à des entreprises canadiennes ainsi que les coûts de capitaux et de l'exploitation.

Pour chaque secteur/sous-secteur, les technologies MTD ont fait l'objet d'un examen plus poussé dans le but d'identifier les MTD qui pourraient être appliquées pour perfectionner le système de traitement des effluents modèle. Des MTD n'ont pas été sélectionnées à des fins de considération, si ces technologies faisaient déjà partie de la grille d'évaluation de suivi du système de traitement des effluents modèle ou encore si la technologie ne pouvait améliorer la qualité des effluents au-delà de ce qui est habituellement réalisé par le système de traitement des effluents modèle. Pour les MTD qui satisfaisaient aux critères de sélection, des estimations de l'ordre de grandeur des coûts ont été préparées pour les éléments suivants : l'équipement, l'installation et l'exploitation en se fondant sur des données portant sur les coûts de capitaux et d'exploitation provenant des vendeurs et des entreprises, des informations à l'interne et de la documentation.

Les MTEAR destinées à l'amélioration du système de traitement des effluents modèle pour chaque secteur/sous-secteur ont été sélectionnées en se fondant sur une évaluation comparative des coûts-avantages des technologies MTD applicables. La sélection de MTDAR était fondée sur les critères rigoureux mentionnés plus haut pour les MTD dans le contexte d'une entreprise modèle non nouvelle avec les systèmes existants de gestion et de traitement des effluents. Pour les nouvelles entreprises, les MTDAR peuvent différer de celles sélectionnées pour les entreprises modèles existantes. L'efficacité de l'élimination et/ou les concentrations atteignables dans les effluents sont fondés sur les données déclarées par les entreprises, les valeurs documentées et/ou des données provenant de vendeurs et peuvent ne pas être réalisables pour chaque application. Finalement, les MTDAR pour toute exploitation minière donnée sont propres à un site et découlent d'une multitude de facteurs géographiques et opérationnels ayant une incidence sur la qualité des effluents, la faisabilité technique des technologies de traitement et imposent des contraintes financières sur le capitaux et les frais d'exploitation qui peuvent être assumés par les entreprises tout en maintenant la rentabilité du secteur.

L'examen du **sous-secteur des métaux communs** visait un total de 43 entreprises. Le système de traitement des effluents modèle pour le sous-secteur utilise des technologies de précipitation sous forme d'hydroxydes pour l'élimination des métaux et des bassins de décantation pour l'élimination en vrac du TSS. Les agents de coagulation et les floculants sont dosés pour faciliter la précipitation des métaux et la sédimentation du TSS. Le système de bassins de décantation permet aussi la dégradation naturelle passive de l'ammoniac. Le pH des bassins de décantation est ajusté avec du dioxyde de carbone pour respecter les limites du pH en vertu du *REMM* ainsi que les exigences en matière de toxicité et les concentrations d'ammoniac non-ionisé avant le rejet dans l'environnement. Le débit de conception et le débit nominal sélectionnés pour estimer les coûts de capitaux et de l'exploitation associés à l'amélioration du système pour le système de traitement modèle étaient de 2 000 m^3/h et de 870 m^3/h, respectivement. Les MTEAR suivantes ont été définies : la précipitation de sulfures en utilisant des polymères organosulfurés de propriété exclusive pour le polissage de métaux dissous et le système de gestion et de traitement des effluents modèle pour l'élimination de l'ammoniac total, des métaux en vrac et du TSS.

L'examen du **sous-secteur des métaux précieux** était destiné à un total de 40 entreprises de métaux précieux. Le système de traitement des effluents modèle pour le sous-secteur comprend les technologies suivantes : la suppression du cyanure par SO2/atmosphérique des résidus miniers et le traitement par boues à chaux de faible densité pour la précipitation sous forme d'hydroxydes destinée à l'élimination en vrac des métaux des effluents provenant des résidus miniers, des mines et des zones de stériles. Le débit de conception et le débit nominal sélectionnés pour estimer les coûts de capitaux et de l'exploitation associés à l'amélioration du système pour le système de traitement modèle étaient de 600 m^3/h et de 180 m^3/h, respectivement. Les MTEAR suivantes ont été définies : la précipitation de sulfures en utilisant des polymères organosulfurés de propriété exclusive pour le polissage de métaux dissous, l'oxydation biologique aérobie active pour l'élimination de l'ammoniac total, ainsi que le système de gestion et de traitement des effluents modèle pour l'élimination du cyanure, des métaux en vrac et du TSS.

L'examen du **sous-secteur du minerai de fer** visait l'ensemble des six entreprises qui exploitent le minerai de fer. Le système de traitement des effluents modèle pour ce sous-secteur comprend les procédés suivants : bassins de décantation pour l'élimination en vrac du TSS par l'ajout de doses de floculants pour favoriser la sédimentation. Le débit de conception et le débit nominal sélectionnés pour estimer les coûts de capitaux et de l'exploitation associés à l'amélioration du système pour le système de traitement modèle étaient de 7 000 m^3/h et de 3 900 m^3/h, respectivement. Les MTEAR suivantes ont été définies : système de gestion et de traitement des effluents modèle pour l'élimination du TSS, des métaux et de l'ammoniac total.

L'examen du **sous-secteur de l'uranium** visait un total de 12 entreprises. Dans ce sous-secteur, le système de traitement des effluents modèle procède en deux étapes : une étape à pH élevé, pour la précipitation des métaux dans des conditions basiques et une étape à pH faible, pour la précipitation ou la co-précipitation métaux et d'autres paramètres en milieu acide. Entre la réalisation de ces étapes liées au pH et après, la clarification et la filtration sont utilisées pour séparer les précipités des eaux traitées.

Le débit de conception et le débit nominal sélectionnés pour estimer les coûts de capitaux et de l'exploitation associés à l'amélioration du système pour le système de traitement modèle étaient de 500 m^3/h et de 350 m^3/h, respectivement. Les MTEAR suivantes ont été définies : l'oxydation biologique aérobie active pour l'élimination de l'ammoniac total et le système de gestion et de traitement des effluents modèle pour l'élimination des métaux et du TSS.

L'examen du **secteur du diamant** visait un total de 4 entreprises. Pour ce secteur, le système de traitement des effluents modèle utilise les technologies suivantes : des bassins de décantation, ainsi que la clarification et la filtration par médias pour l'élimination du TSS. L'agent de coagulation est dosé dans le clarificateur. Avant le rejet des effluents dans l'environnement, le pH est ajusté en utilisant de l'acide sulfurique pour respecter les limites des concentrations d'ammoniac non-ionisé et /ou de toxicité. Les bassins de décantation et pollisage permettent la dégradation naturelle et passive de l'ammoniac et du phosphore. Le débit de conception et le débit nominal sélectionnés pour le système de traitement modèle étaient de 3 000 m^3/h et 2 000 m^3/h, respectivement. Ces débits ont été utilisés pour calculer les coûts de capitaux et de l'exploitation associés à l'amélioration du système. Les MTEAR suivantes ont été définies : système de gestion et de traitement des effluents modèle pour l'élimination du chlorure, des métaux en vrac, de l'ammoniac et du TSS.

L'examen du **secteur du charbon** visait un total de 16 entreprises. Selon le système de traitement des effluents modèle pour ce secteur, le TSS en vrac est éliminé au moyen de bassins de décantation et pollisage, ce qui peut être facilité par l'ajout d'un floculant. Les bassins de décantation et pollisage permettent la dégradation naturelle passive de l'ammoniac. Le débit de conception et le débit nominal sélectionnés pour le système de traitement modèle étaient de 3 000 m^3/h et de1 000 m^3/h, respectivement. Les MTEAR suivantes ont été définies : système de gestion et de traitement des effluents modèle pour l'élimination des métaux, de l'ammoniac total et du TSS.

Pour tous les secteurs/sous-sectors, des essais sont recommandés pour confirmer la demande en réactif de propriété exclusive, l'efficacité et la décantabilité des précipités, ainsi que pour vérifier la conformité des effluents aux exigences en matière de toxicité. Il est également conseillé de rejeter les effluents traités plutôt que de les recycler à des fins diverses, de façon à limiter l'augmentation de la concentration résiduelle des substances chimiques. En raison de l'adoption relativement récente de ces réactifs et du caractère exclusif de leur préparation, on connaît peu de choses sur la stabilité à long terme des substances résiduelles et sur le potentiel de production d'acide et de remobilisation des métaux. Si la stabilité des substances résiduelles n'est pas assurée au moyen de techniques d'élimination avisées, des coûts importants associés à la technologie de stabilisation des substances résiduelles ou d'un nouveau traitement du lixiviat résiduel pourraient devoir être engagés. L'entreprise Hatch met en garde que cette technologie devrait être uniquement considérée comme une MTEAR pour des entreprises qui possèdent les ressources nécessaires et se consacrent au contrôle soigné des régimes d'exploitation pour prévenir la toxicité des effluents, ainsi qu'au contrôle minutieux des conditions de stockage des substances résiduelles en vue de prévenir l'instabilité à long terme et le potentiel de production d'acide par le biais de l'oxydation des sulfures et de la remobilisation des métaux.

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Appendices

1. Executive Summary

1.1 Summary of Report

Hatch was commissioned by the Mine Environment Neutral Drainage (MEND) Program to complete a study to identify best available technologies economically achievable (BATEA) to manage and control effluent from metal, diamond, and coal mines in Canada (henceforth “BATEA Study”). The study was commissioned to provide reference information for potential forthcoming changes within the *Metal Mining Effluent Regulations* (*MMER*) to the types of regulated mining facilities, the list of Schedule 4 parameters, and the authorized limits of Schedule 4 concentrations in effluent discharged to the environment. These potential changes are outlined in the Environment Canada 2012 discussion paper, “*10-Year Review of Metal Mining Effluent Regulations*”.

In particular, for metal mining effluent, Environment Canada has proposed the addition of aluminum, iron, selenium, and total ammonia to the list of Schedule 4 substances, and has proposed the reduction of authorized limits for arsenic, copper, cyanide, lead, nickel, and zinc. For diamond mining effluent, which is currently not regulated via *MMER*, Environment Canada has proposed the inclusion of limits for chloride, phosphorus, ammonia, and TSS concentrations in effluent discharged to the environment, as well as limits for pH. For coal mining effluent, which is currently not regulated via *MMER*, Environment Canada has proposed the inclusion of limits for arsenic, aluminum, iron, manganese, selenium, ammonia, and TSS concentrations in effluent discharged to the environment, as well as limits for pH. Existing authorized limits for existing Schedule 4 substances are summarized in Appendix A. Other proposed changes include the addition of a new requirement that effluent be non-acutely lethal to *Daphnia magna* as indicator organisms and changes to Environmental Effects Monitoring requirements.

Environment Canada has established a multi-stakeholder *MMER* Working Group consultation process. Through this process, a need for this study was identified to help inform mining sector stakeholders on BATEA for the management and control of effluent from operations. MEND has taken on the administration of this contract as part of its mandate to support Canadian national and regional information needs related to controlling and limiting environmental liabilities and promoting sustainable development in the mining sector.

The study was performed in two phases with a distinct scope of work for each phase. The first phase of work produced a Draft Study Report, Revision A, culminated in the production of an Interim Study Report, Revision 0. The Revision and Revision 0 reports were based on the original terms of reference established by MEND for the study. The second phase of work culminated in the production of this Final Study Report, Revision 1 and was based on a scope established by MEND and Hatch to augment the Interim Study Report, Revision 0.

The study budget for the scope of work for the first phase was established by MEND at CAD$75,000 for a study period originally intended to be from late July 2013 to December 2013. The study timeline for the completion of the Draft Study Report, Revision A was later extended to mid-January 2014. As a result of the magnitude of this study, this timeline placed limitations on the effort that could be exerted on the tasks comprising this study. The Interim Study Report, Revision 0 completed in February 2014, represents the information gathered and the data evaluations conducted during the period of July 2013 to February 2014. During this period, data gaps and further investigations were identified, which Hatch felt would benefit the process and address critical limitations inherent in the study.

Following the completion of the Interim Study Report, Revision 0, it was decided by MEND that an extension of the study, to fill in the data gaps identified and to carry out further data analysis was warranted. An additional scope of work for this study extension was established by MEND and Hatch based on commentary received on the Draft Study Report, Revision A. This additional scope was completed during April to June 2014 and culminated in this Final Study Report, Revision 1. △1

The methodology followed to carry out this study was consistent with the structure originally outlined in MEND's Statement of Work, within the Terms of Reference for this study. The tasks and sub-tasks constituting this methodology can be found in detail in ***Section 5***. Modifications to the report other than minor changes to address spelling, grammar, and consistency errors are indicated through the use of revision triangles (shown in the right margin of the page adjacent to the paragraph with the modification, as illustrated for this paragraph). The number within the revision triangle indicates the version of the document for which the modifications were made. △1

Section 6 describes the existing effluent management and treatment technologies and techniques at metal (base metal, precious metal, uranium, iron ore), diamond and coal mine operations in Canada. The main purpose of this section is to provide an overview of each (sub)sector's current water management and effluent treatment practices, and to establish a model site wide water management model, model effluent treatment process, and treated effluent quality to carry forward for use in BATEA selection.

Information provided in this section was collected from independent research, documents provided by MEND and questionnaires distributed to mine operations in Canada. Independent research sources included in-house information and data, publicly available information concerning mining operations and effluent treatment processes, certificates of authorization, provincial summaries of reported effluent quality by mining operations, specific project or operations technical reports, environmental performance reports, conference proceedings/reports, and information available through mine operation websites. Documents provided by MEND include effluent quality data reported by metal mines to Environment Canada as part of *MMER* reporting from 2008 – 2010 (Schedule 4), Environmental Effects Monitoring data from 2009 – 2011 and data for selenium from 2012 (Schedule 5), a list of metal mines potentially impacted by proposed *MMER* discharge limits, and a summary of effluent treatment technologies employed in Ontario by mine operations sourced from the Ontario Ministry of the Environment Industrial Sewage Works Certificates of Authorizations). For Revision 1, supporting information provided by MEND included Environmental Effects Monitoring data for selenium from 2012 (Schedule 5), monthly diamond sector effluent quality data provided to Environment Canada by diamond operations, and volumetric discharge data from 2005 – 2012 for metal mines (Schedule 4). △1

For Revision 1, The Coal Association of Canada also provided a database of effluent quality data for coal operations in Canada, which was used to update the coal sector effluent summary and revise augmentative technologies. △1

Questionnaires were sent to a total of 164 mine operations in Canada. These were comprised of operating mines subject to *MMER* and a few development projects that requested participation in the study. The operations questionnaire was designed to collect information concerning mining operations, ore processing, mine waste and water management practices, and effluent treatment systems and performance.The questionnaire had an overall completion rate of 45% on an operations basis (i.e., 45% of individual operations identified as relevant to the study submitted completed questionnaires). This corresponds to about 75 of the 164 operations identified as relevant. By (sub)sector, the questionnaire completion rate varied between 32% and 75%. A more detailed summary of questionnaire completion status by (sub)sector is provided in Table 5-2.

The operations questionnaire was designed to collect information concerning mining operations, ore processing, mine waste and water management practices, and effluent treatment systems and performance. The operations questionnaire was reviewed by the Mining Association of Canada and select industry contacts. The operations questionnaire is attached to this report as Appendix B.

As part of the additional scope of work, a mini follow-up survey was also sent to a select group of mining operations where further information was needed specifically regarding their effluent treatment system, its influent quality and its performance.

The water management and effluent quality control information collected via the operations questionnaires and independent research, and provided in support documents from MEND was then organized by mining (sub)sector and compiled into summaries which are presented in ***Section 6***. For each (sub)sector, the following summaries are provided:

- Subsector Overview:
    - List and summary of subsector operations and operational status.
    - Summary of the number of reviewed mines.
    - Primary and secondary commodities produced by the subsector.
- Untreated Effluent Quality Summary:
    - Typical contaminants.
    - Factors influencing untreated effluent quality.
    - Summary of untreated effluent quality received from Revision 0 questionnaire respondents and Revision 1 mini-survey respondents.
- Water Management Techniques Summary:
    - Mine facility water management techniques.
    - Explosives use.
    - Waste rock disposal methods and water management techniques.
    - Tailings disposal methods and water management techniques.

- Summary of Effluent Treatment Technologies Employed by Operations for Final Effluent Quality Control:
    - Relative use of observed effluent treatment technologies.
    - Discussion of common or typically employed treatment technologies.
- Treated Effluent Quality Summary
- Model Effluent Treatment System:
    - Process flow diagram of a typical effluent treatment system employed by the subsector operations for control of effluent quality on which to base subsequent cost estimates and BATEA selection.
    - Model water management plan.
    - Model effluent treatment system flow rate.
    - Model effluent treatment system effluent quality analysis and summary.

Section 7 describes the effluent treatment technologies that could be considered best available technologies (BAT) for the Canadian mining sector. This list was compiled from treatment technologies currently available on the market, both active and passive, that are applicable to the control of effluent quality for those contaminants dictated in MEND's Terms of Reference: total aluminum, ammonia and its related species, total arsenic, chloride, total copper, cyanide, total iron, total lead, total manganese, total nickel, phosphorus, total selenium, total zinc, TSS and pH. The list was generated from in-house knowledge, as well as, information from numerous industry reports currently available as public documents.

A vendor questionnaire was also distributed to Hatch's vendor contacts to solicit input concerning available technologies and existing case studies of their use, as well as capital and operating cost information.

The technologies identified were then screened against the following criteria questions:

1. Can this technique achieve current *MMER* discharge limits?
2. Has this technique been demonstrated at full scale on mining effluent?
3. Has this technique been demonstrated under representative climate conditions?

Those technologies that satisfied all three criteria were considered best available technologies (BAT), and carried forward in the study for consideration as best available technologies economically achievable (BATEA). BAT selection did not consider technical or economic aspects of the effluent treatment technique installation or operation.

A technical description of each of the best available technologies was then generated and is presented in ***Section 8.*** Each technology was technically and economically characterized, in terms of contaminant removal mechanisms, removal efficiencies and/or achievable concentrations, major equipment, synergies with other technologies, operational challenges, current application for effluent treatment at Canadian operations, capital and operating cost considerations, and typical range of costs.

For each (sub)sector, this list of BAT technologies was further screened to establish which of the BAT were applicable for the augmentation of the (sub)sector model effluent treatment system. BATs were deemed non-applicable if the technology was already employed in the model effluent treatment system, or if the typical effluent quality rendered the technology unnecessary (e.g., if the concentration of a given contaminant is lower than the achievable concentration for that contaminant by a given technology).

Order of magnitude capital equipment, capital installed and operating cost estimates were then prepared for each BAT technology for each sector. These costs are presented in ***Section 9***. Where relevant, costs include not only the BAT in question but also any auxiliary technology critical to the operation of the BAT technology within the model effluent flow sheet (e.g., to apply reverse osmosis to a model effluent treatment system that has no system for the bulk removal of contaminants, it was assumed a bulk removal system would also be installed for optimal reverse osmosis operation).

To generate these cost estimates, a variety of cost data sources were utilized to identify capital equipment costs, including:

- Capital and operating cost data collected via the vendor and operations questionnaire.
- Validated capital and operating cost data collected from operations via review of Revision A and Revision 0 of this report. △1
- In-house capital and operating cost information.
- Capital and operating cost data specifically collected from vendors in response to commentary received during review of Revision A and Revision 0 of this report. △1
- Relative contribution of reagents, labour, power, utilities, transportation, sludge management and maintenance to operating costs, reported in the operations questionnaire data.
- Cost data reported in literature.

It is important to note that the capital and operating costs presented in ***Section 9*** have been developed on an order-of-magnitude basis (±50%) for the sole purpose of this study. These costs are intended to be generally representative of the incremental capital and operating costs that the model operation would incur to install and operate the studied technologies, to support the BATEA selection in this study. Accordingly, the level of engineering performed to develop these costs was that which was sufficient to produce approximate order-of-magnitude cost estimates while remaining feasible within the time and budget constraints of the study. These costs do not include site-specific factors such as process factors (e.g., effluent parameters of concern and concentrations, pH, temperature, volume/flow rate) and site factors (e.g., site location, shipping costs, electricity costs, existing effluent management and treatment facilities, existing residuals storage/disposal facilities, site layout, available outdoor footprint, available footprint in process buildings, available utilities, available skilled labour, discharge criteria, etc.) which may significantly impact the overall cost for implementation of the technology at a specific site. Therefore, these cost estimates should be used as indicative or comparative costs only as actual installed costs will vary by site.

Section 10 contains the BATEA Selection Tables. By (sub)sector, these tables compare, for each potentially augmentative BAT, the achievable concentrations, operating cost, capital cost, process reliability/robustness, and pertinent risks or opportunities against the model effluent management and treatment systems. ***Section 10*** then selects the BATEA technology for each (sub)sector to augment the model treatment flow sheet presented in ***Section 6***. The BATEA evaluation was based on a series of comparisons weighing the cost/benefit of the various BAT technologies. Best professional judgment was then used to make the selection.

- Effluent concentrations achievable by the BAT technology were compared against the performance of the (sub)sector model flow sheets to determine the magnitude of reductions in concentration, if any.
- Capital cost and operating cost of the BAT technology was compared against the reported model flow sheet capital and operating cost and the resultant percentage increase in cost noted as either a minor, moderate, or major increase.
- Capital cost of the BAT technology was also compared against the reported range of previous capital investments for upgrades and retrofits to existing (sub)sector effluent treatment systems and the cost noted as either within the range or exceeding the range.

Section 11 contains the conclusions reached and recommendations going forward. It is important to note that BATEA selection is not universal for each (sub)sector due to site-specific considerations. The BATEA selection is bounded by strict criteria for BAT (e.g., technology/technique has been demonstrated at full scale on mining effluent and under representative climate conditions) and in the context of a model non-greenfield operation with an existing effluent management and treatment system for given nominal and design treatment capacities.

Selected BATEA would be upgrades or retrofits to existing equipment for which capital has already been expended and therefore, associated with sustaining costs rather than initial capital costs. This affects the consideration of what is economically achievable. BATEA selected for greenfield operations may be different than that selected for existing model operations. Selection of BATEA for greenfield operations was not the focus of this study; however, some suggestions for greenfield operations are made. Technologies screened out as BAT and not selected as BATEA in this report could, in fact, prove to be BATEA for some site-specific applications.

1.2 Summary of BATEA by (Sub)Sector

1.2.1 Metals Sector: Base Metal

The review of the Canadian base metal subsector included a total of 43 mine, mill and smelter sites (“operations”), out of a total of 57 operations identified as relevant to this study (see Section 6.1 for details). Of the operations reviewed, 33 submitted questionnaires as part of the data collection portion of the study. Information for an additional 12 operations was collected from independent research efforts and from in-house information.

The model effluent treatment system is illustrated in Figure 6-16. In this model, effluent is treated via hydroxide precipitation and bulk TSS removal via pond-based settling. The lime addition/holding/settling pond(s) also allows time for passive natural degradation of ammonia.

The effluent is dosed with coagulant and flocculant before precipitates and TSS are then allowed to settle in the settling pond. Settling pond decant is pH adjusted with carbon dioxide to meet *MMER* pH limits and/or un-ionized ammonia/toxicity requirements prior to discharge to the environment.

An analysis of the complete data set of final discharge effluent quality for the base metal subsector was undertaken to identify the effluent qualities produced by effluent treatment systems that are similar or equivalent to the model effluent treatment system. This analysis is presented in Section 6.1.5.4 and utilizes Schedule 4 and Schedule 5 final discharge effluent quality reported to Environment Canada in 2008 – 2010, and 2009 – 2012, respectively.

Based on this analysis, Table 6-20 summarizes the effluent quality (maximum, minimum, average and 95th percentile concentrations) estimated to be achieved by the model effluent treatment system based on this analysis. Where parameters are not targeted by the model effluent treatment system, the 95th percentile of the total cohort was utilized to represent the concentration of that parameter from the model effluent treatment system.

The range, average and median values for flow rates from several information sources reporting treatment system flow rate and discharge volumes at base metal operations are presented in Table 6-8. 2,000 m^3/h was chosen as the design capacity for the base metal subsector model effluent treatment system and was used for capital cost estimating for system augmentation. For operating cost estimating for system augmentation, the nominal flow rate for the base metal subsector model effluent treatment system of 870 m^3/h was utilized.

For the base metal subsector, BATEA has been defined as:

- Sulfide precipitation with proprietary polymeric organosulfide chemicals for dissolved metals polishing (including copper, iron, nickel, and zinc).
- Model flow sheet for total ammonia, bulk metals (including aluminum, arsenic, copper, iron, lead, nickel, radium-226, selenium, zinc), and solids (TSS) removal.

When compared to the model flow sheet, sulfide precipitation with proprietary polymeric organosulfide chemicals resulted in the following:

- Order of magnitude reduction in many of the metals of concern (iron, nickel, and zinc).
- Upgrade capital cost investment of roughly 5 to 42% of the model flow sheet capital cost and an operating cost increase of almost 100% up to 1,640%, representing a minor to moderate capital cost investment but a major operating cost expenditure from the model operation.
- The capital cost for this BATEA is within the reported range of previous capital investments for upgrades and retrofits to existing base metal effluent management and treatment systems (less than CAD$5,000,000). It is of interest to note that two Canadian base metal operations have already undertaken upgrades to include this technique within their effluent management and treatment systems; however, both of these operations have equipment-based effluent treatment systems rather than pond-based systems.

- No generation of spent regenerant (ion exchange) or concentrate (reverse osmosis, nanofiltration) stream. Other technologies evaluated produce these residual streams, which require specific management, therefore increasing the overall capital and operating cost of these options.

It should be noted that testwork is recommended to confirm proprietary reagent demand, efficacy, and precipitate settleability. Also, as the chemicals may be acutely lethal to rainbow trout and *Daphnia magna* at certain residual chemical concentrations in effluent, testing is advised to verify that treated effluent complies with toxicity requirements. It is also advised that treated effluent be discharged rather than recirculated for any purpose such that cycling up of residual chemical concentration is limited.

Due to the relatively recent adoption of these reagents and the proprietary nature of their formulations, little is known about the long term stability of residuals and the potential for acid generation and metals remobilization. If residuals are not kept stable, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.

Hatch cautions that this technique should only be considered BATEA for operations that are capable of and dedicated to careful control of operating regimes to prevent effluent toxicity as well as careful control of residuals storage conditions to prevent long term instability and the potential generation of acid through sulfide oxidation and metals remobilization.

1.2.2 Metals Sector: Precious Metal

A total of 56 mine and mill operations were identified as relevant to this study. The review of the Canadian precious metal subsector for this study included a total of 40 precious metal mine operations, 31 of which began or completed questionnaires during the data collection portion of this study. Additional effort undertaken during the second phase of work for this study resulted in the receipt of additional effluent treatment system information and paired influent/effluent data from operations that had previously begun (but not completed) or completed the questionnaire. Information for an additional 9 operations was collected from independent research efforts and from in-house information.

The typical model effluent treatment system for precious metal operations carried forward in this study is INCO SO_2/air cyanide destruction applied to tailings prior to final deposition, followed by low density sludge lime hydroxide precipitation for treatment of tailings run-off, tailings supernatant and mine and waste rock untreated effluent prior to discharge. This treatment process is illustrated in Figure 6-31.

It is acknowledged that due to the high variability in treatment processes among operations, this process is not representative of the majority of the effluent treatment systems reviewed. However, this process is expected to achieve an effluent quality similar to systems employing other cyanide destruction processes and so provides a system representative of the achievable effluent concentrations.

An analysis of the complete data set of final discharge effluent quality for the precious metal subsector was undertaken to identify the effluent qualities produced by effluent treatment systems that are similar or equivalent to the model effluent treatment system. This analysis is presented in Section 6.2.5.4 and utilizes Schedule 4 and Schedule 5 final discharge effluent quality reported to Environment Canada in 2008 – 2010, and 2009 – 2012, respectively.

Based on this analysis, Table 6-40 summarizes the effluent quality (maximum, minimum, average and 95th percentile concentrations) estimated to be achieved by the model effluent treatment system based on this analysis. Where parameters are not targeted by the model effluent treatment system, the 95th percentile was utilized to represent the concentration of that parameter from the model effluent treatment system.

The range, average and median values for flow rates from several information sources reporting treatment system flow rate and discharge volumes at precious metal operations are presented in Table 6-46. 600 m^3/h was chosen as the design capacity for the precious metal subsector model effluent treatment system and was used for capital cost estimating for system augmentation. For operating cost estimating for system augmentation, the nominal flow rate for the precious metal subsector model effluent treatment system of 180 m^3/h was utilized.

For the precious metal subsector, BATEA has been defined as:

- Sulfide precipitation with proprietary polymeric organosulfide chemicals for dissolved metals polishing (including arsenic, copper, iron, nickel, and zinc).
- Active aerobic biological oxidation for total ammonia removal.
- Model flow sheet for cyanide, bulk metals (including aluminum, arsenic, copper, iron, lead, nickel, radium-226, selenium, zinc), and solids (TSS) removal.

When compared to the model flow sheet, sulfide precipitation with proprietary polymeric organosulfide chemicals resulted in the following:

- Order of magnitude reduction in many of the metals of concern (arsenic, copper, iron, and nickel).
- Upgrade capital cost investment of less than 1% of the model flow sheet capital cost and an operating cost increase of roughly 6 to 58%, representing a relatively minor capital cost investment but a moderate to major operating cost expenditure from the model operation.
- The capital cost for this BATEA is within the reported range of previous capital investments for upgrades and retrofits to existing precious metal effluent management and treatment systems (less than CAD$5,000,000).
- No generation of spent regenerant (ion exchange) or concentrate (reverse osmosis, nanofiltration) stream. Other technologies evaluated produce these residual streams, which require specific management, therefore increasing the overall capital and operating cost of these options.

It should be noted that testwork is recommended to confirm proprietary reagent demand, efficacy, and precipitate settleability. Also, as the chemicals may be acutely lethal to rainbow trout and *Daphnia magna* at certain residual chemical concentrations in effluent, testing is advised to verify that treated effluent complies with toxicity requirements. It is also advised that treated effluent be discharged rather than recirculated for any purpose such that cycling up of residual chemical concentration is limited.

Due to the relatively recent adoption of these reagents and the proprietary nature of their formulations, little is known about the long term stability of residuals and the potential for acid generation and metals remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.

Hatch cautions that this technique should only be considered BATEA for operations that are capable of and dedicated to careful control of operating regimes to prevent effluent toxicity as well as careful control of residuals storage conditions to prevent long term instability and the potential generation of acid through sulfide oxidation and metals remobilization.

Many precious metal operations use cyanide in ore processing. Cyanide which reports to tailings is oxidized to cyanate via cyanide destruction processes or passive natural degradation, and cyanate hydrolyzes to ammonia. Thus, the origins of ammonia in precious metal effluent are both explosives used in mining operations and cyanide used in ore processing. Well established and executed explosives best management plans can minimize some of the amount of ammonia that reports to effluent. Moreover, conditions that are conducive to natural degradation of ammonia in pond(s) could be promoted to achieve further ammonia removal within the subsector model effluent management and treatment system (e.g., elevating pH, aerating, maximizing surface area to depth ratio). Active aerobic biological oxidation (via MBBR) was selected as BATEA to achieve additional removal of total ammonia from the model flow sheet.

When compared to the model flow sheet, active aerobic biological oxidation (via MBBR) resulted in the following:

- Active aerobic biological oxidation (via MBBR) has been shown to reduce total ammonia concentrations to <2 mg-N/L. Given that the concentration of total ammonia achieved by the model effluent treatment system in the precious metal subsector is 12 mg-N/L (Table 6-40), this represents an 83% reduction in total ammonia concentrations. For operations that are achieving effluent concentrations closer to the average total ammonia concentration of the sector, the addition of this BATEA technology would not be warranted.
- Upgrade capital cost investment of 33 to 530% of the model flow sheet capital cost and an operating cost increase of roughly 19 to 178%. This represents a major capital cost investment and a moderate to major operating cost expenditure for the model operation. However, it is recognized that operating costs could increase substantially if heat exchange was required to be implemented for year-round operating purposes.

- The capital cost for this BATEA exceeds the reported range of previous capital investments for upgrades and retrofits to precious metal effluent management and treatment systems (<CAD$5,000,000). However, the precious metal subsector seems to be developing more interest in the technology, with one operation in Quebec converting its RBC active aerobic biological oxidation process to MBBR, one operation in Saskatchewan implementing MBBR by the end of 2013, and one operation in Ontario piloting MBBR during winter 2013/2014.

1.2.3 Metals Subsector: Iron Ore

The review of the Canadian iron ore subsector included all 6 operating iron ore operations, one of which submitted a completed questionnaire and four of which completed the mini-survey distributed during the Revision 1 phase of work. Information for these operations and the operation that did not submit any information was also collected from independent research efforts and from in-house information.

The model effluent treatment system is illustrated in Figure 6-34. In this model, effluent is treated for solids removal via pond-based settling. The use of flocculant to aid in the settling of solids is employed. This system closely resembles reviewed effluent treatment systems, but is not identical to any one treatment system.

An analysis of the complete data set of final discharge effluent quality for the iron ore subsector was undertaken to identify the effluent qualities produced by effluent treatment systems that are similar or equivalent to the model effluent treatment system. This analysis is presented in Section 6.4.5.4 and utilizes Schedule 4 and Schedule 5 final discharge effluent quality reported to Environment Canada in 2008 – 2010, and 2009 – 2012, respectively and additional effluent data gathered through independent research on iron ore operations in Newfoundland and Labrador.

Based on this analysis, Table 6-57 summarizes the effluent quality (maximum, minimum, average and 95th percentile concentrations) estimated to be achieved by the model effluent treatment system based on this analysis. Where parameters are not targeted by the model effluent treatment system, the 95th percentile was utilized to represent the concentration of that parameter from the model effluent treatment system.

The range, average and median values for flow rates from several information sources reporting treatment system flow rate and discharge volumes at iron ore operations are presented in Table 6-46. 7,000 m^3/h was chosen as the design capacity for the iron ore subsector model effluent treatment system and was used for capital cost estimating for system augmentation. For operating cost estimating for system augmentation, the nominal flow rate for the iron ore subsector model effluent treatment system of 3,900 m^3/h was utilized.

For the iron ore subsector, BATEA has been defined as:

- Model flow sheet for solids (TSS), metals (aluminum, arsenic, copper, iron, lead, nickel, radium-226, selenium, and zinc) and total ammonia removal.

1.2.4 *Metals Subsector: Uranium*

The review of the Canadian uranium subsector included a total of 12 operations, 7 of which submitted complete operations questionnaires as part of the data collection portion of the study. Information for the other 5 operations was collected from independent research efforts and from in-house information. As the information provided via the original questionnaire was complete and detailed, no additional information was collected from these sites, except where necessary to clarify original submissions.

The model effluent treatment system is illustrated in Figure 6-48. In this model, effluent is treated by 2 stages of treatment, to target parameters that are removed at significantly different pHs; one high pH stage for precipitation of metals which precipitate in basic conditions (i.e., nickel) and one low pH stage for metals and other parameters that precipitate or co-precipitate in acidic conditions (i.e., molybdenum, selenium, radium co-precipitation with barium sulfate). Between the chemical reaction stages, there is a clarification step to separate precipitates from the treated water followed by filtration for additional suspended solids removal. Ponds are employed for pre-treatment equalization and for post-treatment monitoring and/or settling. This system closely resembles two of the existing effluent treatment systems reviewed, however is not identical to any one operation’s effluent treatment system.

An analysis of the complete data set of final discharge effluent quality for the uranium subsector was undertaken to identify the effluent qualities produced by effluent treatment systems that are similar or equivalent to the model effluent treatment system. This analysis is presented in Section 6.4.5.4 and utilizes Schedule 4 and Schedule 5 final discharge effluent quality reported to Environment Canada in 2008 – 2010, and 2009 – 2012, respectively.

Based on this analysis, Table 6-77 summarizes the effluent quality (maximum, minimum, average and 95th percentile concentrations) estimated to be achieved by the model effluent treatment system based on this analysis. Where parameters are not targeted by the model effluent treatment system, the 95th percentile was utilized to represent the concentration of that parameter from the model effluent treatment system.

The range, average and median values for flow rates from several information sources reporting treatment system flow rate and discharge volumes at uranium operations are presented in Table 6-65. 500 m^3/h was chosen as the design capacity for the uranium subsector model effluent treatment system and was used for capital cost estimating for system augmentation. For operating cost estimating for system augmentation, the nominal flow rate for the uranium subsector model effluent treatment system of 350 m^3/h was utilized.

For the uranium subsector, BATEA has been defined as:

- Active aerobic biological oxidation for total ammonia removal.
- Model flow sheet for metals (including aluminum, arsenic, copper, iron, lead, nickel, radium-226, selenium, zinc) and solids (TSS) removal.

When compared to the model flow sheet, active aerobic biological oxidation (via MBBR) resulted in the following:

- Active aerobic biological oxidation (via MBBR) has been shown to reduce total ammonia concentrations to <2 mg-N/L. Given that the concentration of total ammonia achieved by the model effluent treatment system in the uranium subsector is 23 mg-N/L, this represents a 91% reduction in total ammonia concentrations. For operations that are achieving effluent concentrations closer to the average total ammonia concentration of the sector, the addition of this BATEA technology would not be warranted.
- Upgrade capital cost investment of 55 to 274% of the model flow sheet capital cost and an operating cost increase of roughly 15 to 30%. This represents a major capital cost investment and a minor to moderate operating cost expenditure for the model operation. However, it is recognized that operating costs could increase substantially if heat exchange was required to be implemented for year-round operating purposes.
- The capital cost for this BATEA exceeds the reported range of previous capital investments for upgrades and retrofits to uranium effluent management and treatment systems (CAD$1,000,000 to CAD$2,000,000).

In Revision 0 of this report, sulfide precipitation with proprietary polymeric organosulfide polymers was recommended as BATEA for dissolved metals polishing. However, this recommendation was eliminated based on the Revision 1 analysis of concentrations achieved by the model effluent treatment system for the uranium subsector which showed that augmentation of the model effluent treatment system with sulfide precipitation with proprietary polymeric organosulfide polymers would only permit an order of magnitude reduction in treated effluent concentration for nickel and marginal reductions in treated effluent concentrations for arsenic, copper, iron, and zinc.

1.2.5 *Diamond Sector*

The review of the Canadian diamond sector included all 4 producing Canadian operations, as listed in Table 6-78, 3 of which submitted questionnaires as part of the data collection portion of the study, and 1 of which was researched independently. Jericho Diamond Mine in Nunavut was not evaluated in this study as it is assumed to be an abandoned operation and is in the care of the federal Contaminated Sites Program. As the information provided via the original questionnaire was complete and detailed, no additional information was collected from these sites, except where necessary to clarify original submissions.

The model effluent treatment system is illustrated in Figure 6-59. In this model, effluent is equalized prior to treatment and bulk TSS is removed via pond-based settling. The equalization/settling pond(s) also allow time for passive natural degradation of ammonia and phosphorus. The effluent is coagulated (e.g., with ferric sulfate or aluminum sulfate). If required, to adjust effluent pH, hydroxide reagent (e.g., lime, sodium hydroxide) may be added on a contingency basis. Coagulated TSS and precipitates are then allowed to settle, aided by flocculant, in a clarifier. Clarifier overflow is then polished by media filtration before being pH adjusted with sulfuric acid to meet un-ionized ammonia/toxicity limits prior to discharge to the environment. Clarifier underflow is co-disposed with tailings.This system closely resembles several existing effluent treatment systems, but is not identical to any one treatment system. This system is consistent with the BAT and BACT findings of previous studies.

An analysis of the complete data set of final discharge effluent quality for the diamond sector was undertaken to identify the effluent qualities produced by effluent treatment systems that are similar or equivalent to the model effluent treatment system. This analysis is presented in Section 6.5.5.4 and utilizes final discharge effluent quality for diamond operations provided to Environment Canada.

Based on this analysis, Table 6-90 summarizes the effluent quality (maximum, minimum, average and 95th percentile concentrations) estimated to be achieved by the model effluent treatment system based on this analysis. Where parameters are not targeted by the model effluent treatment system, the 95th percentile was utilized to represent the concentration of that parameter from the model effluent treatment system. The range, average and median values for the typical effluent flow rates from diamond operations are presented in Table 6-85. 3,000 m^3/h was chosen as the design capacity for the diamond sector model effluent treatment system and was used for capital cost estimating for system augmentation. For operating cost estimating for system augmentation, the nominal flow rate for the diamond sector model effluent treatment system of 2,000 m^3/h was utilized.

For the diamond sector, BATEA has been defined as:

- Model flow sheet for chloride, bulk metals (including phosphorus), ammonia, and solids (TSS) removal.

1.2.6 Coal Sector

The review of the Canadian coal sector included a total of 16 operations, 13 of which submitted complete operations questionnaires as part of the data collection portion of the study. An additional 3 operations partially completed questionnaires. Stantec's 2011 report "Study on Canadian Coal Mining Effluents" prepared for Environment Canada was used to fill in any missing information not provided in the questionnaires.

The model effluent treatment system is illustrated in Figure 6-71. In this model, bulk TSS is removed via pond-based settling and polishing which may be assisted by the addition of flocculant. The settling and polishing pond(s) also allow time for passive natural degradation of ammonia. This system closely resembles several existing effluent treatment systems, but is not identical to any one existing system.

Table 6-96 summarizes the final discharge effluent quality for coal operations, based on the analysis of a data set provided by the Coal Association of Canada (CAC). The Coal Association of Canada data set was used to generate the summary as it is more complete than the concentration data set than that reported by coal operations through the operations questionnaire. Sites were not identified in the CAC data set, therefore analysis to identify what final discharge effluent qualities are those achieved by operations utilizing effluent treatment systems similar or equivalent to the model effluent treatment system could not be undertaken. The 95th percentile values for the entire coal final discharge effluent quality data set were utilized to represent the concentration of each parameter from the model effluent treatment system.

The range, average and median values for the typical effluent flow rates from coal operations are presented in Table 6-97. 3,000 m^3/h was chosen as the design capacity for the coal sector model effluent treatment system and was used for capital cost estimating for system augmentation. For operating cost estimating for system augmentation, the nominal flow rate for the coal sector model effluent treatment system of 1,000 m^3/h was utilized.

For the coal sector, BATEA has been defined as:

- Model flow sheet for metals (including arsenic, aluminum, iron, and manganese), selenium, total ammonia, and solids (TSS) removal.

1.3 Project Limitations

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1.3.1 Study Timeline and Budget Limitations

The study budget for Revision 0 work was established by MEND at CAD$75,000 for a study period originally intended to be from late July 2013 to December 2013. The study timeline for the completion of the draft was later extended to mid-January 2014. As a result of the magnitude of this study, this timeline placed limitations on the effort that could be exerted on the tasks comprising this study. To meet the study budget and timeline goals for Revision 0 work, effort was saved by the approaches summarized below; these approaches were largely retained for Revision 1 work, as the focus of the Revision 1 work was to expand on or validate specific areas of the study rather than the overall approach. Commentary with respect to these approaches within Revision 1 work has been included below.

- Limiting discussion of technologies to the treatment of current and proposed *MMER* “deleterious substance” parameters, although it is acknowledged that a larger set of parameters are present in Canadian mining effluent and are treated via the technologies and techniques discussed. This approach was retained for Revision 1 of this report.
- Focusing (though not limiting) questionnaire follow-up effort to those operations that have higher contaminant levels in effluent and to those employing treatment technologies that are relatively rare. For Revision 1, effort was focused on expanding data received from operations that submitted questionnaires in Revision 0 and operations that had participated in Revision 0 but not provided complete information.
- Utilizing published capital and operating cost information to the maximum extent possible and adjusting the published cost information for currency and time value of money, e.g., applying a 95% CAD/USD currency conversion rate and the appropriate year ratio from the Chemical Engineering Plant Cost Index (CEPCI). CEPCI considers cost escalation for process plants as a composite of four indexes: equipment, construction, labour, buildings, and engineering and supervision. The application of CEPCI is normally limited to a 5 year adjustment and adjustments outside of the 5 year window are less accurate. Some of applications of CEPCI within the study fall outside of the 5 year window. However, the costs presented in the study are order of magnitude and intended for comparative purposes only. Utilization of CEPCI to adjust costs was retained for Revision 1 of this report.

- Utilizing in-house budgetary quotations to the maximum extent possible and similarly adjusting the quotations for currency and time value of money. This approach was retained for Revision 1 of this report.
- Utilizing representative reagent, consumable, power cost, and total operating cost information provided by operations questionnaire respondents. This approach was retained for Revision 1 of this report. Additional information provided by operations via commentary on the Draft MEND BATEA Study (Revision A) was validated where possible and utilized to update cost estimates for Revision 1.
- Utilizing single vendor-supplied cost estimates where multiple cost estimates from a variety of vendors were not available. This approach was retained for Revision 1 of this report.

These effort-saving measures primarily impact the cost estimates generated in Section 9 (and subsequently incorporated into BATEA selection in Section 10) and the extent of data collection that could be achieved to support (sub)sector summaries and mine operations and effluent treatment practices relationships analysis (Section 6).

Cost estimates are, as a result, based on cost information that reflect variable site and operational conditions, may include implicit cost estimating factors, incorporate more or less equipment than necessary for the model effluent treatment systems, and may not precisely reflect current equipment costs. These factors ultimately affect the accuracy of the equipment and installed capital cost and operating cost estimates produced for this study. Operating costs estimates, in particular, are highly variable from site to site, and were difficult to establish with significant accuracy due to the limited amount of information available as a design basis (e.g., untreated effluent quality comprising all relevant chemical species, including those not subject to *MMER*, suspended solids particle size distribution, speciation of targeted contaminants, targeted effluent quality, etc.) and the time constraints placed on the study.

With respect to the amount of information available to support (sub)sector summaries and mine operations and the analysis of relationships between water management practices and effluent quality, substantial effort was expended to collect as much information about mine and mill operations in Canada as possible within the time constraints of the study; however time constraints ultimately limited the extent of this information collection. Collection of additional information in Revision 1 was limited to that required to support activities included in the scope of Revision 1 and an effort to collect additional general information was not undertaken. As a result, not all operations identified as relevant to this study could be reviewed and represented in the subsector summaries (especially those that did not submit Revision 0 questionnaires, Revision 1 mini-surveys or have publicly accessible information). Additionally, operations that were reviewed may not have been reviewed for all aspects of mine operations summarized in Section 6 if this information was not available through questionnaires and other resources (e.g., water management practices, explosive use, etc.).

1.3.2 *Data Limitations*

Data limitations experienced in undertaking this study were the applicability, the quality and amount of information and data available for this study.

Quality and Availability

In some cases, the information provided via the Revision 0 operations questionnaires and that which could be collected via independent research lacked detail and clarity, making the complete and accurate incorporation of the information into the study difficult. In these cases, an effort was made to clarify information through additional research or follow-up with mine operations. Additionally, where the scope of Revision 1 allowed, follow-up attempts to clarify Revision 0 questionnaire submissions were made during Revision 1 effort. However, when clarification attempts were not successful, this often left information and data subject to interpretation by the study team during data analysis, summarization and report writing. The quality of information collected via the Revision 1 mini-survey was on average better than that collected by the Revision 0 questionnaire.

Quality limitations in information available via independent research were frequently the result of the public accessibility of operation-specific information. A valuable resource in this study was discharge permits for operations in jurisdictions where they are publicly released online by provincial regulatory bodies. However, some provincial regulatory bodies do not make this information readily available to the public.

As a result, more reliable and detailed information could be collected for analysis for operations in provinces where this information was readily available. In provinces where this information is not publicly available, information concerning water management and effluent treatment practices had to be drawn from more diffuse sources, and was typically less detailed and less reliable. Another example of a valuable information resource that varied geographically was provincial and territorial mine effluent performance summaries, some of which included detail on effluent treatment systems. These were published by some provinces, but not all.

Independent research was also limited by the confidential nature of some of the information requested, e.g., effluent treatment system capital and operating costs, untreated effluent quality, and water management practices. This information is typically only available from mine operations themselves; for those mine operations that did not complete the questionnaire, or elected to not provide cost information, this information was simply not available.

In Revision 0 of this study, weekly/grab sample values for *MMER* Schedule 4 substances were not available to Hatch. For Revision 1 of this study, Hatch received *MMER* Schedule 4 grab data from Environment Canada to compare to the monthly mean values to assess whether the monthly mean concentrations adequately represent grab mining effluent data. There were concerns following Revision A that the use of monthly and quarterly concentration values may “dilute” or “mask” the true variability of untreated and treated effluent quality. An assessment of the differences between the concentration statistics (minimum, average, 95th percentile and maximum) revealed that the differences between the statistics generated through the use of monthly mean data and grab data were minimal. The most significant differences noted were between maximum values; however, the 95th percentiles, which are used throughout the report in analysis of the data and to represent the model effluent treatment systems, were reasonably well aligned. Thus, the monthly mean data used in Revision 0 has been assessed to be adequate to represent the variation in effluent quality and was used for Revision 1.

The Revision 0 operations questionnaire requested quarterly data to reduce complexity and data entry demands of the participating operations, therefore untreated effluent concentrations provided were on a quarterly basis.

Applicability

The main limitation concerning the applicability of data provided by questionnaire respondents was in the use of reported treated and untreated effluent quality to establish achievable concentrations, and removal efficiencies. Not all questionnaire respondents provided both untreated and treated effluent quality, making determination of site-specific removal efficiencies difficult.

Quality information in some cases also reflects dilution by incident precipitation onto ponds, and total suspended solids settling and natural degradation (e.g., total ammonia) within ponds, which may affect treated effluent concentrations and removal efficiency assessments. In systems where only one technology was employed in the effluent treatment system, the untreated and treated effluent values as provided were used to establish removal efficiencies or achievable concentrations for that technology.

1.3.3 BATEA Selection Limitations

It is important to note that BATEA selection is not universal for each (sub)sector due to site-specific considerations. The BATEA selection is bounded by strict criteria for BAT (e.g., technology/technique has been demonstrated at full scale on mining effluent and under representative climate conditions) and in the context of a model non-greenfield operation with an existing effluent management and treatment system for given nominal and design treatment capacities. **As a result, the BATEA selected in this study may not be universally applicable across all Canadian operations, due to technical and economic constraints that vary from site to site.**

Selected BATEA are upgrades or retrofits to existing equipment for which capital has already been expended and therefore, are associated with sustaining costs rather than initial capital costs. This affects the consideration of what is economically achievable. BATEA selected for greenfield operations may be different than that selected for existing model operations. Selection of BATEA for greenfield operations was not the focus of this study, however, some suggestions for greenfield operations are made. Technologies screened out as BAT and not selected as BATEA in this report could, in fact, prove to be BATEA for some site-specific applications.

Further, the removal efficiency and/or achievable effluent concentrations associated with the technology is based on reported operations data, literature values, and/or vendor data. It is important to note that achievable concentrations are typical and may not be possible for every application.

Ultimately, the best available technology that is economically achievable (BATEA) for any given mining operation is site-specific, as a result of the multitude of geographic and operational factors that influence effluent quality, impact the technical feasibility of treatment technologies, and dictate the financial constraints on the capital and operating expenditures that can be borne by operations while still maintaining economic viability.

2. Disclaimer

This report was prepared by the Hatch Water & Tailings Management Group (“Hatch”), for the sole and exclusive benefit of the Mine Environment Neutral Drainage Program (“MEND”) for the purpose of assisting MEND to identify best available technologies economically achievable (BATEA) to manage and control effluent from mines across Canada (the “Study”), in order to inform Environment Canada’s multi-stakeholder consultation process on proposed changes and additions to the *Metal Mining Effluent Regulations*, and any reliance upon, or use by, any third party is solely at that party’s own risk. Any use of this report by MEND is subject to the terms and conditions of the study contract dated September 18, 2013.

This report is meant to be read as a whole, and sections should not be read or relied upon out of context. The report includes information provided by MEND, operations, and vendors. Unless specifically stated otherwise, Hatch has not verified such information and disclaims any responsibility or liability in connection with such information.

This report contains the expression of the professional opinion of Hatch, based upon information available at the time of preparation. The quality of the information, conclusions and estimates contained herein is consistent with the intended level of accuracy as set out in this report, as well as the circumstances and constraints under which this report was prepared.

However, this report is a concept study and, accordingly, all estimates and projections contained herein are based on limited and incomplete data. Therefore, while the work, results, estimates and projections herein may be considered to be generally indicative of the nature and quality of the Study, they are not definitive. No representations or predictions are intended as to the results of future work, nor can there be any promises that the estimates and projections in this report will be sustained in future work.

3. Glossary

Term	Meaning
Active Operation	An operation that is not closed; is in development, producing, or suspended by planning to resume operations.
Al	Aluminum
ALD	Anoxic Limestone Drain
ANFO	Ammonium Nitrate/Fuel Oil (explosive)
ANSAGR	Anaerobic Submerged Attached Growth Reactor
(aq)	aqueous
As	Arsenic
BAT	Best Available Technology(ies)
BATEA	Best Available Technology(ies) Economically Achievable
BCR	Biochemical Reactor
BioteQ	BioteQ Environmental Technologies
BMP	Best Management Plan
BOD	Biological Oxygen Demand
BOD_5	Five Day Biological Oxygen Demand
CAC	Coal Association of Canada
CAPEX	Capital Expenditures
cBOD	Carbonaceous Biological Oxygen Demand
CEPCI	Chemical Engineering Plant Cost Index
Cl^-	Chloride
CN	Cyanide
CNSC	Canadian Nuclear Safety Commission
COD	Chemical Oxygen Demand
Cu	Copper
DAF	Dissolved Air Flotation
Degremont	Degremont Technologies
EC	Environment Canada
ECS	Enhanced Coagulation and Settling
ED/EDR	Electrodialysis/Electrodialysis Reversal
Envirogen	Envirogen Technologies
FBR	Fluidized Bed Reactor
Fe	Iron
(g)	Gaseous
GAC	Granular Activated Carbon
GE	GE Water & Process Technologies
HDPE	High Density Polyethylene
HDS	High Density Sludge
IBC	Intermediate Bulk Container
IFAS	Integrated Fixed Film Activated Sludge
ISP	Insoluble Sulfide Precipitation
IX	Ion Exchange
LDS	Low Density Sludge
m^3	cubic meter
MACCS	Maximum Authorized Concentration in a Composite Sample
MACGS	Maximum Authorized Concentration in a Grab Sample
MAMMC	Maximum Authorized Monthly Mean Concentration (implies current *MMER* value)
MBBR	Moving Bed Biofilm Reactor

Term	Meaning
MBR	Membrane Bioreactor
MEND	Mine Environment Neutral Drainage Program
MF	Microfiltration
MMER	*Metal Mining Effluent Regulations*
Mn	Manganese
Model	Most common generic representation of water management and/or effluent treatment practices, but not necessarily best practices.
Nalco	Nalco Company
NAG	Non-Acid Generating[1]
N	Nitrogen
NF	Nanofiltration
NH_3	Un-ionized Ammonia
NH_3/NH_4^+	Total Ammonia
Ni	Nickel
NL	Newfoundland and Labrador
NML	Non-Metal Leaching
OLD	Open/Oxic Limestone Drain
O/P	Open Pit
OPEX	Operating Expenditures
ORP	Oxidation-reduction Potential
P	Phosphorus
PAG	Potentially Acid Generating
Pb	Lead
PK	Processed Kimberlite
PML	Potentially Metal Leaching
PRB	Permeable Reactive Barrier
QC	Quebec
Ra-226	Radium-226
RAPS	Reducing and Alkalinity Producing Systems
RBC	Rotating Biological Contactor
RO	Reverse Osmosis
(s)	Solid
SAD CN	Strong Acid Dissociable Cyanide (Strong Metal-Cyanide Complexes of Fe)
SAPS	Successive Alkalinity Producing Systems
SAGR	Submerged Attached Growth Reactor
Se	Selenium
Siemens	Siemens Water Technologies LLC
SO_2	Sulfur dioxide
SQ	Study Questionnaire (Operations)
TCLP	Toxicity Characteristic Leaching Procedure
TDS	Total Dissolved Solids
Treated Effluent	Denotes discharge from effluent treatment process and/or combined discharge at *MMER* compliance point. In the operations questionnaire, treated effluent was called “outflow from effluent treatment process”.
TSF	Tailings Storage Facility
TSS	Total Suspended Solids
UASB	Upflow Anaerobic Sludge Blanket
UF	Ultrafiltration

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[1] Note that for the purposes of this study, this meaning is different to the more common meaning of “Net Acid Generation”.

Term	Meaning
U/G	Underground
Untreated Effluent	Denotes various combined mine and mill operation effluent streams that feed an effluent treatment process (e.g., pond influent, effluent treatment plant influent, etc.). In the operations questionnaire, untreated effluent was called “inflow to effluent treatment process”.
USEPA	United States Environmental Protection Agency
Veolia	Veolia Water Solutions & Technologies Canada
VSS	Volatile Suspended Solids (assumed to be organic fraction of TSS)
WAD CN	Weak Acid Dissociable Cyanide
WR	Waste Rock
Zn	Zinc
ZVI	Zero Valent Iron

N.B.: United Kingdom/United States English numbering conventions are used in this document, whereby commas denote demarcations between orders of magnitude and decimals denote demarcations between whole numbers and fractions. For example:

- CAD$42,000,000.00 denotes 42 million Canadian dollars and zero cents.
- 1,080 mg/L denotes one thousand and eight milligrams per litre.

4. Introduction and Purpose

Hatch was commissioned by the Mine Environment Neutral Drainage (MEND) Program to complete a study to identify best available technologies economically achievable (BATEA) to manage and control effluent from metal, diamond, and coal mines in Canada (henceforth “BATEA Study”). The study was commissioned to provide reference information for potential forthcoming changes within the *Metal Mining Effluent Regulations* (*MMER*) to the types of regulated mining facilities, the list of Schedule 4 parameters, and the authorized limits of Schedule 4 concentrations in effluent discharged to the environment. These potential changes are outlined in the Environment Canada 2012 discussion paper, “*10-Year Review of Metal Mining Effluent Regulations*”.

In particular, for metal mining effluent, Environment Canada has proposed the addition of aluminum, iron, selenium, and total ammonia to the list of Schedule 4 substances, and has proposed the reduction of authorized limits for arsenic, copper, cyanide, lead, nickel, and zinc. For diamond mining effluent, which is currently not regulated via *MMER*, Environment Canada has proposed the inclusion of limits for chloride, phosphorus, ammonia, and TSS concentrations in effluent discharged to the environment, as well as limits for pH. For coal mining effluent, which is currently not regulated via *MMER*, Environment Canada has proposed the inclusion of limits for arsenic, aluminum, iron, manganese, selenium, ammonia, and TSS concentrations in effluent discharged to the environment, as well as limits for pH. Existing authorized limits for existing Schedule 4 substances are summarized in Appendix A. Other proposed changes include the addition of a new requirement that effluent be non-acutely lethal to *Daphnia magna* as indicator organisms and changes to Environmental Effects Monitoring requirements.

Environment Canada has established a multi-stakeholder *MMER* Working Group consultation process. Through this process, a need for this study was identified to help inform mining sector stakeholders on BATEA for the management and control of effluent from operations. MEND has taken on the administration of this contract as part of its mandate to support Canadian national and regional information needs related to controlling and limiting environmental liabilities and promoting sustainable development in the mining sector.

The purpose and intent of the study is to:

- Review active and passive effluent treatment systems and mine practices and their relationships to and influence on effluent quality for operating Canadian metal, coal, and diamond mines.

- Identify, pre-screen, and then assess effluent treatment systems and practices that could be considered Best Available Technologies (BAT). Assessment of BAT to be conducted in terms of treatment efficiency and achievable effluent concentrations, reliability, applicability to mining subsectors, demonstration at full scale under representative climate conditions, and risks and opportunities ("challenges" and "synergies").
- Identify effluent treatment processes and practices that could be considered Best Available Technologies Economically Achievable (BATEA).

The methodology utilized to complete the above tasks is given in Section 5.

5. Methodology

The MEND BATEA Study was carried out in two phases of work. The scope of the first phase (culminating in Revision 0 of the MEND BATEA Study Report) was outlined in the original Terms of Reference generated by MEND, while the scope of the second phase (culminating in Revision 1 of the MEND BATEA Study Report) was based on feedback and commentary on the Draft Study Report (Revision A) received from MEND and the mining industry. These two phases are outlined below:

Revision 0 Phase: Culminated in the production of the Interim MEND BATEA Study Report, Revision 0. The work in this phase was based on MEND's original Terms of Reference, and commentary from MEND and the mining industry that was received on the Draft MEND BATEA Study Report (Revision A).

Revision 1 Phase: Culminated in the production of the Final MEND BATEA Study Report, Revision 1 and was based on the commentary received from MEND and the mining industry regarding the Draft MEND BATEA Study Report (Revision A) that pertained to concepts considered to be outside of the original scope of work. The commentary on concepts and material outside of the original scope of work was assessed by MEND and Hatch. Potential activities that could be included in an additional scope of work were brainstormed for each of the outstanding comments; those activities that were assessed by MEND and Hatch to add significant value to the study report were included in the scope for Revision 1.

The scope of work for each phase of the MEND BATEA Study is summarized below, in Sections 5.1.1 and 5.1.2. The narrative of the methodology and approach followed to complete the original tasks of the MEND BATEA Study (per the original Terms of Reference) and the limitations of the study in Sections 5.2, 5.3, 5.4 and 5.5 have been revised for Revision 1 to expand or modify where necessary the original approach to reflect the additional work and changes to the basis of study that occurred as part of the Revision 1 work.

5.1 Revision 0 and Revision 1 Scope of Work

5.1.1 Revision 0 Scope of Work

The methodology followed to carry out Revision 0 of this report was consistent with the structure originally outlined in MEND's Statement of Work, within the Terms of Reference for this study. The tasks and sub-tasks constituting this methodology were as summarized in Table 5-1. The text in this table is taken directly from MEND's statement of work. A discussion of Hatch's methodology to carry out these tasks and subtasks follows. The methodology presented in this section encompasses Hatch's general approach to the MEND BATEA Study; detailed methodology specific to individual sections of this report have been encompassed in the introduction to those sections for ease of reference.

Table 5-1: Summary of Tasks from MEND Terms of Reference

Task	Sub-Tasks
Task 1: Project Initiation	The Contractor will be required to participate in a kick off meeting (via teleconference) with MEND to review the Statement of Work and confirm key deliverables and timelines. Following this meeting the Contractor will prepare and provide a detailed work plan and a draft outline of the report for approval by MEND.
Task 2: Review and Identify Mines and Effluent Control Technologies in Use in Canada	The Contractor shall prepare: • An up-to-date list of operating metal (e.g., base metal, iron ore, uranium, and gold), coal and diamond mines in Canada. • An up-to-date summary of the mining, processing and mine waste disposal methods used in Canada with a focus on factors that influence effluent treatment and quality. • An up-to-date list of the effluent treatment systems and mine operation practices[2] used by mines in Canada. The systems and practices used at each individual mine should be identified to the extent possible. This list should be developed by researching available information, using the contractor's in-house knowledge and surveying mines in Canada, with an emphasis on contacting mines with higher levels of the parameters specified in Task 3. Include in the list to the extent possible the contaminant removal efficiency of the treatment systems that are used. • An analysis of any relationships of mine effluent performance (using *MMER* effluent data and any other available data) with the effluent treatment systems in place, mine operation practices, the type of mine and any other relevant parameters.

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[2] For the scope of this contract, mine operation practices are actions which could be adopted by mines during the operation of the mine without significant reconstruction of the mine. These could include practices such as improved explosives handling practices, or switching to less soluble explosives.

Task	Sub-Tasks
Task 3: Identify management and control technologies which could be considered BAT	• Identify and describe mine effluent treatment systems (including both active and passive systems) and mine operation practices that could be considered Best Available Technologies (BAT)[3] for the following parameters: ◆ Total aluminum, ammonia and its related species, total arsenic, chloride, total copper, cyanide, total iron, total lead, total manganese, total nickel, phosphorus, total selenium, total zinc, TSS and pH. • Identify and assess the pros and cons of each treatment system and mine operation practice that could be considered BAT including: ◆ Estimates of the capital and operating costs (on a CAD$/m^3 of effluent basis). ◆ The possible treatment (or parameter reduction) efficiencies for the parameters listed in Task 3, for each subsector where applicable. ◆ The achievable effluent concentrations of the parameters listed above, for each subsector where applicable; the applicability to the various mining sub sectors, mine types found in Canada, greenfield and retrofit situations. ◆ Synergies or challenges that the treatment systems or mine operation practices may offer such as the potential to address multiple or parameters not listed in Task 3.

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[3] BAT should be informed by demonstration of the technique in any country and applicability to climate conditions similar to those in Canada. It is acknowledged that Canadian climate conditions vary widely and the use of this criteria to screen BAT was limited.

Task	Sub-Tasks
Task 4: Conclusions	• Based on the information gathered in Tasks 2 and 3, identify which effluent treatment and mine operation practice could be considered Best Available Technologies Economically Achievable (BATEA) in a Canadian context and the achievable effluent concentrations the technology can meet for the parameters listed in Task 3 (for each subsector where applicable). In addition, identify and explain in detail the factors that were taken into account in developing these conclusions. Principles to guide BATEA should be: ◆ Full scale demonstration of the technology under Canadian climate conditions, or as a minimum, under conditions that closely represent those in Canada. ◆ The reliability of the performance of the technology to meet the achievable effluent concentration for the parameters listed in Task 3. ◆ The technology should have a reasonable cost, based on the contractor's assessment.

5.1.2 *Revision 1 Scope of Work*

1

The methodology followed to carry out Revision 1 of this study was based on an assessment of the commentary received on the Draft MEND BATEA Study Report that pertained to concepts or material that was considered out of the original scope of the Terms of Reference. The comments on concepts or material outside of the original scope of work were reviewed and aggregated to generate "Potential Improvement Areas", which are aspects of the study that could be improved based on commentary received on the Draft MEND BATEA Study (Revision A). For each potential improvement area, potential actions that could be taken to address the concerns with that area were brainstormed and the rough level of effort required to carry out those actions was estimated. Each potential action was assessed on the basis of the following criteria:

1. Is the potential action likely to impact BATEA Selection?
2. Is the value added to the study relative to the level of effort expended to complete the action sufficient to justify the expenditure?
3. Is the information necessary to complete the potential action available or obtainable with a reasonable amount of effort and a reasonable timeline?

These criteria were imposed on the potential actions to narrow down the number of actions by identifying critical or priority actions and to generate a scope that would be feasible within a reasonable period of time and level of effort. Recommended actions were presented to MEND in a memo entitled, "Potential Areas of Improvement and Recommendations for MEND BATEA Study Report, Rev. 1". This memo and the recommended actions were reviewed with MEND to establish the scope of work for Revision 1.

5.2 Task 2: Review and Identify Mine and Effluent Control Techniques and Technologies in Use in Canada

5.2.1 Summary of Task as Defined in MEND's Terms of Reference

The aims of Task 2 were to prepare a list of operating metal, coal and diamond mines in Canada, and to identify to the extent possible:

- The mining, processing and mine waste disposal methods used at operations, with a focus on factors that influence effluent treatment and quality.
- The effluent treatment systems and mine operation practices employed at operations.

The statement of work mandated that this information be collected via independent research, in-house knowledge, and the distribution of a questionnaire to mine operations in Canada. A focus was to be placed on contacting those operations with higher levels of contaminants in their effluent streams, as identified by Environment Canada as operations 'at risk' of non-compliance with *MMER* discharge limits.

This information was then to be analyzed to identify relationships between mine effluent performance, effluent treatment systems, operations practices, the type of mine and any other relevant parameters.

5.2.2 Approach

An up-to-date list of metals (i.e., base metal, precious metal, iron ore, uranium), coal, and diamond mines in Canada was identified through the use of various resources, including:

- Summary Review of Performance of Metal Mines Subject to the Metal Mining Effluent Regulations in 2011 (Published by Environment Canada).
- 2011 Canadian and American Mines Handbook (Published by BIG Magazines LP.).
- 2012 Facts and Figures of the Canadian Mining Industry (Published by the Mining Association of Canada).
- 2011 Canadian Minerals Yearbook (Published by Natural Resources Canada).
- Provincial mining associations' members list.
- Federal, provincial, and territorial mining and mineral project summaries.
- Mine owner and operator websites.

A preliminary list including the operation name, (sub)sector classification by primary commodity, the operating company, the location, and the operational status of the mining operation was generated. Operations with the operational status of closed, in development or redevelopment, suspended, under care and maintenance subject, or potentially subject (in the case of development projects) to the *Metal Mining Effluent Regulations* were identified in addition to operating mines.

Once the preliminary list was generated, a preliminary contact list of individuals at either the corporate or operational level (or both) was established through the use of publicly available information (e.g., contact information available through Environment Canada's National Pollutant Release Inventory (NPRI) database) and in-house information.

An e-mail was distributed to this preliminary contact list to provide them with information about the MEND BATEA study and the associated operations questionnaire that would be distributed to operations. The contact list was then revised and refined with the assistance of the Mining Association of Canada, provincial mining associations, industrial representatives, individuals who had been contacted as part of the notification e-mail, and Environment Canada to identify key contacts to either participate or co-ordinate participation on behalf of their companies in the questionnaire.

The preliminary operations list was also shortened to remove those development projects that are not yet subject to *MMER* (with the exception of development projects that sought to participate in the study, who remain in the operations list) to generate a focused list of operations relevant to this study with respect to its role in the *10-Year Review of Metal Mining Effluent Regulations*.

The final list was divided into sectors/subsectors based on the primary commodity produced by the mine or mill (base metal, precious metal, iron ore, coal and diamond). A final list of mine and mill operations was generated for each of these sectors/subsectors; these lists are included in this report in Section 6.

Simultaneously, the Revision 0 questionnaire for distribution to operations was developed. The Revision 0 operations questionnaire was designed to collect information concerning mining operations, ore processing, mine waste and water management practices, and effluent treatment systems and performance. The Revision 0 operations questionnaire was reviewed by the Mining Association of Canada and select industry contacts. The operations questionnaire is attached to this report as Appendix B.

The final Revision 0 operations questionnaire was then distributed to the contact list. The operations questionnaire could be completed online via SurveyMonkey, or a PDF version attached to the distribution e-mail could be filled in and returned to Hatch via e-mail. The operations questionnaire was distributed in both English and French. The original study schedule allowed for 15 working days for operations to complete the questionnaire; this was later extended by an additional 10 working days in response to requests for an extension from operations. Five operations questionnaires which were received after the extended deadline were included in the data.

Follow-up communications in the form of e-mail and/or telephone call were undertaken for those operations that had not submitted questionnaires nor responded to any of Hatch’s previous communications. A focus was placed on those operations identified as at risk of non-compliance should the discharge limits tabled in the 10-Year Review of *Metal Mining Effluent Regulations* come into effect.

The questionnaire had an overall completion rate of 45% on an operations basis (i.e., 45% of individual operations identified as relevant to the study submitted completed questionnaires). This corresponds to about 75 of the 164 operations identified as relevant. By (sub)sector, the questionnaire completion rate varied between 32% and 75%. A more detailed summary of questionnaire completion status by sector/subsector is provided in
Table 5-2.

Table 5-2: Summary of Revision 0 Questionnaire Completion by (Sub)sector

(Sub)sector	Number of Companies	Number of Operations Identified	Number of Operations Questionnaires Submitted	Expressed Intent to Submit or Started	Will Not Submit	Missing/ No Response
Coal	12	30	13 (43%)	5	6	4
Diamond	4	4	3 (75%)	0	1	1
Base Metal	31	57	31 (54%)	10	5	11
Precious Metal	33	56	18 (32%)	8	7	22
Iron Ore	4	6	2 (33%)	2	1	1
Uranium	4	16	7 (44%)	0	6	0

A number of operations either submitted partially complete questionnaires or began questionnaires via SurveyMonkey but did not complete them – this information was also incorporated into the study.

Some feedback was received from those operations that did not submit completed questionnaires; many of these operations indicated that they were not provided sufficient time to complete the questionnaire. Several operations also indicated that participation in the questionnaire and BATEA study was not a priority given other operational demands or because they did not anticipate being impacted by the proposed changes to the *MMER*.

The quality of Revision 0 questionnaire submissions varied considerably. Many questionnaires were well-completed and provided significant detail concerning water management and effluent treatment processes; however, in some instances, questionnaires were submitted with important information missing or with unclear or vague responses to questionnaire questions. This made the interpretation and utilization of some information provided by respondents difficult and in some cases resulted in extra effort being expended to fill in missing information so that the submissions were useable.

Revision 0 questionnaire respondents submitted information concerning their operations in a variety of formats, including via discharge permits, process flow diagrams, block flow diagrams, site wide water balance diagrams, and written descriptions – this information was processed and transferred into database format so the data could be easily compared and analyzed. During this process, follow-up questions were sent when necessary to questionnaire respondents to clarify the information provided prior to inclusion in the database and study report.

As part of the Revision 1 scope of work, Hatch sought to collect additional information from operations about effluent treatment systems via a Revision 1 mini-survey, to support the revision of the concentrations achieved by the model effluent treatment system and to update iron ore flow rates. The Revision 1 mini-survey consisted of three questions and requested information on flow rates, final discharge point names used in reporting to Environment Canada as part of *MMER* requirements, treatment system process, mechanism of removal of targeted parameters, and influent and effluent data. Operations were asked only to provide information that they had not already provided Hatch via the Revision 0 operations questionnaire.

In addition to information collection via the Revision 0 operations questionnaire, Hatch also undertook independent research as part of the Revision 0 scope to collect supplemental information about mining operations, primarily concerning those operations that had not participated in the questionnaire. This expanded the amount of information available concerning Canadian mine operations upon which to base (sub)sector summaries. This independent research drew from in-house knowledge, publicly available information concerning mining operations and effluent treatment processes (e.g., certificates of authorization, discharge permit limits, etc.), provincial summaries of reported effluent quality by mining operations, specific project or operations technical reports, environmental performance reports, conference proceedings/reports, and information available through mine operation websites.

To support Revision 0 and Revision 1 study effort, Hatch was also provided support documents by MEND. For Revision 0, supporting information provided by MEND included effluent quality data reported by metal mines to Environment Canada as part of *MMER* reporting from 2008 – 2010 (Schedule 4), Environmental Effects Monitoring data from 2009 – 2011 (Schedule 5), a list of metal mines potentially impacted by proposed *MMER* discharge limits, and a summary of effluent treatment technologies employed in Ontario by mine operations sourced from the Ontario Ministry of the Environment Industrial Sewage Works Certificates of Authorizations. For Revision 1, supporting information provided by MEND included Environmental Effects Monitoring data for selenium from 2012 (Schedule 5), monthly diamond sector effluent quality data provided to Environment Canada by diamond operations, and volumetric discharge data from 2005 – 2012 for metal mines (Schedule 4).

For Revision 1, The Coal Association of Canada also provided a database of effluent quality data for coal operations in Canada, which was used to update the coal sector effluent summary and revise augmentative technologies.

The water management and effluent quality control information collected via the Revision 0 operations questionnaire, the Revision 1 mini-survey and independent research, and provided in support documents from MEND was organized by mining (sub)sector and compiled into summaries which are presented in Section 6[4].

Table 5-3 summarizes the information provided for each (sub)sector (e.g., base metal, precious metal, iron ore, uranium, coal and diamond) and the source of information for the summary.

Table 5-3: Information Sources for Sector Summaries 1

Information Included in Sector Summaries	Information Source(s)
List of operations relevant to the MEND BATEA Study.	• Independent research. • *MMER* reported data provided by MEND.
Commodities produced by the sector and the relative occurrence of the production of these commodities.	• Revision 0 Operations Questionnaire. • Independent Research.
Untreated effluent characteristics.	• Revision 0 Operations Questionnaire. • Revision 1 Mini-Survey (for base metal and precious metal subsectors).
Mine operations that affect untreated effluent characteristics (e.g., processing facilities present on site, specific ore processing steps that impact untreated effluent quality, etc.).	• Revision 0 Operations Questionnaire. • Independent Research.

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[4] Information collected in Revision 1 was used to update Section 6 as dictated by the scope established for the Revision 1 update. However, water management and technology summaries, model water management and effluent treatment systems from Revision 0 were considered frozen during Revision 1 work.

Information Included in Sector Summaries	Information Source(s)
Water management technologies employed for key site features (i.e., mines, waste rock stockpiles, tailings storage facilities, ore stockpiles) and explosives use practices.	• Revision 0 Operations Questionnaire.
Effluent treatment technologies employed by operations.	• Revision 0 Operations Questionnaire. • Independent Research. • Summary of Effluent Treatment Technologies Employed at Mines in Ontario provided by MEND.
Treated effluent quality, including typical contaminants, range of concentrations present in treated effluent, etc.	• Effluent quality data reported by metal mines to Environment Canada as part of *MMER* reporting from 2008 – 2010 (Schedule 4 data available for base metal, precious metal, uranium, and iron ore operations subject to *MMER*). • Environmental Effects Monitoring data from 2009 – 2011 provided by MEND (Schedule 5 data available for base metal, precious metal, uranium, and iron ore operations subject to *MMER*). • Environmental Effects Monitoring data on selenium from 2012 provided by MEND (Schedule 5 data available for base metal, precious metal, uranium, and iron ore operations subject to *MMER*).[5] • Diamond effluent quality data reported to Environment Canada by Canadian Diamond Operations. • Coal Association of Canada Effluent Quality from Coal Operations. • Independent Research. • Revision 0 Operations Questionnaire.

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[5] Selenium reporting through Schedule 5 became mandatory in 2012. It is believed by Environment Canada to be more accurate than selenium voluntarily reported to Schedule 5 and included in the 2009 – 2011 data set.

It should be noted that the data sets for 2008 – 2010 Schedule 4, 2009 – 2011 Schedule 5, and 2012 Schedule 5 vary in terms of operations and final discharge points (FDPs). This is due in part to changes in site operational status (e.g., new developments beginning operations and operations being suspended or closed), changes in water management and effluent treatment practices (e.g., discontinuation of discharges at certain FDPs and introduction of new FDPs), and changes in site wide water balance (e.g., variations in meteorological conditions, mining, or processing that impact whether or not an operation must discharge excess water). Where possible, the sources of data summarized in this report are noted.

Some information included in (sub)sector summaries (as summarized in the left column of Table 5-3) was not available for all operations reviewed, because the information was not included in questionnaire submissions, not publicly available, or not readily accessible. For example, water management technologies surrounding mine facilities or the untreated effluent quality was not available in all instances.

Based on the information included in the (sub)sector summaries in Revision 0, a generic effluent management and control technologies model was established for each mining (sub)sector. The generic water management and control technologies model consists of a model water management block flow diagram, a model effluent treatment system which comprises of a process flow diagram, design and nominal treatment system flow rates, and a summary of the effluent quality produced by operating treatment systems similar or identical to the model effluent treatment system based on quality reported to Environment Canada.

The methodology utilized to generate the process flow diagrams, design and nominal treatment system flow rates and the summary of the effluent quality produced by the model effluent treatment system vary slightly between subsectors. The methodology utilized for each subsector is described in their respective subsections of Section 6.

Model effluent treatment systems were generated for this study as a means to reflect common or baseline practices in use at mine and mill operations upon which improvements could be made in order to improve final effluent quality, while allowing the study to be feasible within time and information constraints. To comprehensively and precisely assess the cost impacts of changes to the allowable concentrations in Schedule 4 of *MMER* and the BATEA for every operation in Canada, the tasks performed for each of the six subsectors in this study would have to be performed for each of the over 150 mine and mill operations in Canada (combined count of the operations in the precious metal, base metal, iron ore, uranium, coal and diamond subsectors). This level of effort was not supported by the time, budget or information limitations associated with this study. Generating model water management and effluent treatment systems is the most practical method of translating the wide variety of information collected about operations water management and effluent treatment into a basis upon which to characterize and cost currently employed and augmentative technologies to select BATEA.

The water management and effluent treatment models are intended to be representative of the most common water management and effluent treatment practices employed at the mine and mill in each (sub)sector. They demonstrate the typical technologies and practices currently employed to control effluent quality, to which modifications would then be made to improve effluent quality at the point of discharge. They are **not** intended to be best practices of current mine water management and effluent control technologies, but a generic representation of what the operations reviewed employ at present. The models establish the “base case” mining operations water management practices and effluent treatment systems upon which to generate estimates of the incremental costs associated with the implementation of the technologies under consideration for BAT/BATEA selection.

Finally, as the last subtask in Task 2, a high level analysis of operations practices, effluent treatment systems and effluent quality was conducted to identify relationships between operating practices and effluent quality. Specific factors that were reviewed in this analysis were water management around site features (e.g., mine, waste rock stockpiles, tailings storage facilities and ore stockpiles), ore processing steps, explosives use, type of treatment systems, operator diligence, etc.

5.3 Task 3: Identify Management and Control Technologies which could be Considered BAT

5.3.1 Summary of Task as Defined in MEND’s Terms of Reference

The aims of Task 3 were to identify effluent treatment technologies that could be considered best available technologies (BAT), and for those effluent treatment technologies considered BAT, to establish estimates of capital and operating costs, removal efficiencies and/or achievable concentration levels, the applicability to each (sub)sector, and to discuss the synergies and challenges resulting from the application of the technology for the control of effluent quality.

5.3.2 Approach

The identification of best available technologies has been addressed via two separate approaches. Effluent management practices are identified and discussed in the analysis of the relationships between mine operation practices, water management and effluent quality in Section 6. Effluent treatment technologies are identified in Section 7, described in detail in Section 8, and evaluated in Sections 9 and 10. Effluent management practices considered to be BATEA are also discussed in Section 10.

To generate a list of best available technologies for effluent treatment, Hatch first compiled a list of treatment technologies currently available on the market, both active and passive, that are applicable to the control of effluent quality for those contaminants dictated in MEND’s Terms of Reference: total aluminum, ammonia and its related species, total arsenic, chloride, total copper, cyanide, total iron, total lead, total manganese, total nickel, phosphorus, total selenium, total zinc, TSS and pH. Throughout the report, unless otherwise specified, metals refer to total metals.

The list of treatment technologies currently available for effluent quality control was generated through the use of the following sources, in addition to in-house knowledge:

- Report on Technologies Applicable to the Management of Canadian Mining Effluents, prepared for Environment Canada by SENES Consultants Limited, 1999.
- Review of Available Technologies for the Removal of Selenium from Water, prepared for the North American Metals Council by CH2M Hill, 2010.

- Technical Addendum to the *Review of Available Technologies for the Removal of Selenium from Water,* prepared for JR Simplot, Teck and Rio Tinto by CH2M Hill, 2013.
- *Study on Canadian Coal Mining Effluent Final Report*, prepared for Environment Canada by Stantec Consulting, 2011.
- Identification of Best Available Control Technologies Applicable to Canadian Diamond Mining Effluent, prepared for Environment Canada by WorleyParsons, 2009.
- Evaluation of Treatment Options to Reduce Water-Borne Selenium at Coal Mines in West-Central Alberta, prepared for Alberta Environment by Microbial Technologies, Inc.
- Review of Mine Drainage Treatment and Sludge Management Operations (MEND Report 3.43.1), J. Zinck and W. Griffith, 2013.
- Application of Membrane Separation Technology to Mitigation of Mine Effluent and Acidic Drainage (MEND Report 3.15.1), S. Mortazavi.
- Review of Passive Systems for Treatment of Acid Mine Drainage (MEND Report 3.14.1), Kilborn Inc., 1996.
- *MEND Manual Volume 5 – Treatment* (MEND Report 5.4.2e), G.A. Tremblay and C.M. Hogan, eds., 2000.
- Economic *Evaluation of Acid Mine Drainage Technologies* (MEND Report 5.8.1), by GEOCON, 1995 General handbook and literature review.

A vendor questionnaire was also distributed to Hatch's vendor contacts to solicit input concerning available technologies and existing case studies of their use, as well as capital and operating cost information.

The technologies included in the preliminary technologies list were then screened against the following criteria questions:

1. Can this technique achieve current *MMER* discharge limits?
2. Has this technique been demonstrated at full scale on mining effluent?
3. Has this technique been demonstrated under representative climate conditions?

Those technologies that satisfied all three criteria were considered best available technologies (BAT), and carried forward in the study for consideration as best available technologies economically achievable (BATEA). BAT selection did not consider technical or economic aspects of the effluent treatment technique installation or operation. This screening is presented in Section 7.

A technical description of each of the best available technologies was then generated and is presented in Section 8. In these descriptions, each technology was technically and economically characterized, in terms of contaminant removal mechanisms, removal efficiencies and/or achievable concentrations, major equipment, synergies with other technologies, operational challenges, current application for effluent treatment at Canadian operations, capital and operating cost considerations, and typical range of costs.

For each (sub)sector, this list of BAT technologies was further screened to establish which of the BAT were applicable for the augmentation of the (sub)sector model effluent treatment system. BATs were deemed non-applicable if the technology was already employed in the model effluent treatment system, or if the typical effluent quality rendered the technology unnecessary (e.g., if the concentration of a given contaminant is lower than the achievable concentration for that contaminant by a given technology).

Order of magnitude capital equipment, capital installed and operating cost estimates were then prepared for each BAT technology for each sector (in a few cases only installed costs were estimated where equipment cost information was unavailable). These costs are presented in Section 9. Where relevant, costs include not only the BAT in question but also any auxiliary technology critical to the operation of the BAT technology within the model effluent flow sheet (e.g., to apply reverse osmosis to a model effluent treatment system that has no system for the bulk removal of contaminants, it was assumed a bulk removal system would also be installed for optimal reverse osmosis operation).

To generate these cost estimates, a variety of cost data sources were utilized to identify capital equipment costs (or where equipment costs were unavailable, total installed costs), including:

- Capital and operating cost data collected via the vendor and operations questionnaire.
- Validated capital and operating cost data collected from operations via review of Revision A and Revision 0 of this report. △1
- In-house capital and operating cost information.
- Capital and operating cost data specifically collected from vendors in response to commentary received during review of Revision A and Revision 0 of this report. △1
- Relative contribution of reagents, labour, power, utilities, transportation, sludge management and maintenance to operating costs, reported in the operations questionnaire data.
- Cost data reported in literature.

There were generally less cost data available for those technologies that have seen limited application on mining effluent.

For most effluent treatment technologies, total installed costs were estimated by applying typical factors to equipment costs to incorporate additional direct and indirect costs. Direct cost factors account for shipping and transportation, installation, site preparation and civil works, piping, HVAC, electrical and controls and plant services and utilities costs. Indirect cost factors account for wrap-around engineering, procurement, construction management, temporary construction services, insurance, spares and cold commissioning.

It is important to note that the capital and operating costs presented in this section have been developed on an order-of-magnitude basis (±50%) for the sole purpose of this study. These costs are intended to be generally representative of the incremental capital and operating costs that the model operation would incur to install and operate the studied technologies, to support the BATEA selection in this study. Accordingly, the level of engineering performed to develop these costs was that which was sufficient to produce approximate order-of-magnitude cost estimates while remaining feasible within the time and budget constraints of the study.

For most effluent treatment technologies, total installed costs were estimated by applying typical factors to equipment costs to incorporate additional direct and indirect costs. Direct cost factors account for shipping and transportation, installation, site preparation and civil works, piping, HVAC, electrical and controls and plant services and utilities costs. Indirect cost factors account for wrap-around engineering, procurement, construction management, temporary construction services, insurance, spares and cold commissioning. Where total installed costs were developed from equipment costs utilizing typical factors, total installed costs were determined to be roughly 3 times equipment costs for most technologies. However, one uranium operation in Saskatchewan reported during the Revision A / Revision 0 review period that the ratio of total installed costs to equipment costs for a clarifier installation in 2008 was approximately 5 for site-specific reasons possibly related to high materials and labour costs due to the remote location of the operation. Commentary provided by a coal operation during the Revision A/Revision 0 review period indicated ratios of total installed costs to equipment costs as high as 10 for certain technologies; however, follow-up to seek clarification on this comment was unsuccessful. △1

It is acknowledged that actual costs could vary significantly from the presented figures, depending on numerous site-specific factors including process factors (e.g., effluent parameters of concern and concentrations, pH, temperature, volume/flow rate) and site factors (e.g., site location, shipping costs, electricity costs, existing effluent management and treatment facilities, existing residuals storage/disposal facilities, site layout, available outdoor footprint, available footprint in process buildings, available utilities, available skilled labour, discharge criteria, etc.). For all technologies, it is assumed that sufficient space is available for the incorporation of the necessary equipment into the model system. Site layout may impact the distance to supply effluent, electricity and other utilities to treatment processes, as well as the distance to pump treatment residuals to storage/disposal facilities.

5.4 Task 4: Conclusions

5.4.1 Summary of Task as Defined in MEND's Terms of Reference

Task 4 is the culmination of the MEND BATEA study; the goal of this task is to identify those technologies that can be considered BATEA for the Canadian (sub)sector of the mining industry reviewed, based on the information collected throughout the course of the study, the analysis of this information and the cost estimates generated for this study.

5.4.2 Approach

Utilizing the information collected and the cost estimates generated for this study, a BATEA selection table was generated for each mining (sub)sector. These tables condensed the information concerning each technology into five main considerations:

1. What effluent concentration is achievable by the treatment technology in comparison to the performance of the (sub)sector model flow sheet?
2. What is the capital cost for the addition of this technology to the typical treatment system ($\$/m^3$ installed capacity)?
3. What incremental increase in operating cost above the (sub) sector model flow sheet is this technology anticipated to have ($\$/m^3$ treated)?
4. Can this treatment technology reliably achieve a consistent effluent concentration, given variations in untreated effluent quality (due to seasonal variation or process upsets)?
5. Pertinent risks or opportunities (“challenges” and “synergies”).

Hatch employed best professional judgment based on the summarized information and mining industry experience to establish what could reasonably be considered the BATEA for each (sub)sector. The BATEA evaluation was based on a series of comparisons weighing the cost/benefit of the various BAT technologies:

- Effluent concentrations achievable by the BAT technology were compared against the performance of the (sub) sector model flow sheets to determine the magnitude of reductions in concentration, if any.
- Capital cost and operating cost of the BAT technology was compared against the reported model flow sheet capital and operating cost and the resultant percentage increase in cost noted as either a minor, moderate, or major increase.
- Capital cost of the BAT technology was also compared against the reported range of previous capital investments for upgrades and retrofits to existing (sub) sector effluent treatment systems and the cost noted as either within the range or exceeding the range.

These BATEA selections include a discussion of the rationale for the selection of the technology, applicability across the (sub)sector, and the sensitivity of the BATEA selection to factors such as concentration variations, volume variations, climatic effects, etc. This information is presented in Section 10.

5.5 Limitations

5.5.1 Study Timeline and Budget Limitations

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The study budget for Revision 0 work was established by MEND at CAD$75,000 for a study period originally intended to be from late July 2013 to December 2013. The study timeline for the completion of the draft was later extended to mid-January 2014. As a result of the magnitude of this study, this timeline placed limitations on the effort that could be exerted on the tasks comprising this study. To meet the study budget and timeline goals for Revision 0 work, effort was saved by the approaches summarized below; these approaches were largely retained for Revision 1 work, as the focus of the Revision 1 work was to expand on or validate specific areas of the study rather than the overall approach. Commentary with respect to these approaches within Revision 1 work has been included below.

- Limiting discussion of technologies to the treatment of current and proposed *MMER* “deleterious substance” parameters, although it is acknowledged that a larger set of parameters are present in Canadian mining effluent and are treated via the technologies and techniques discussed. This approach was retained for Revision 1 of this report.

- Focusing (though not limiting) questionnaire follow-up effort to those operations that have higher contaminant levels in effluent and to those employing treatment technologies that are relatively rare. For Revision 1, effort was focused on expanding data received from operations that submitted questionnaires in Revision 0 and operations that had participated in Revision 0 but not provided complete information.

- Utilizing published capital and operating cost information to the maximum extent possible and adjusting the published cost information for currency and time value of money, e.g., applying a 95% CAD/USD currency conversion rate and the appropriate year ratio from the Chemical Engineering Plant Cost Index (CEPCI). CEPCI considers cost escalation for process plants as a composite of four indexes: equipment, construction, labour, buildings, and engineering and supervision. The application of CEPCI is normally limited to a 5 year adjustment and adjustments outside of the 5 year window are less accurate. Some of the applications of CEPCI within the study fall outside of the 5 year window. However, the costs presented in the study are order of magnitude and intended for comparative purposes only. Utilization of CEPCI to adjust costs was retained for Revision 1 of this report.

- Utilizing in-house budgetary quotations to the maximum extent possible and similarly adjusting the quotations for currency and time value of money. This approach was retained for Revision 1 of this report.

- Utilizing representative reagent, consumable, power cost, and total operating cost information provided by operations questionnaire respondents. This approach was retained for Revision 1 of this report. Additional information provided by operations via commentary on the Draft MEND BATEA Study (Revision A) was validated where possible and utilized to update cost estimates for Revision 1.

- Utilizing single vendor-supplied cost estimates where multiple cost estimates from a variety of vendors were not available. This approach was retained for Revision 1 of this report. △1

- These effort-saving measures primarily impact the cost estimates generated in Section 9 (and subsequently incorporated into BATEA selection in Section 10) and the extent of data collection that could be achieved to support (sub)sector summaries and mine operations and effluent treatment practices relationship analysis (Section 6).

- Cost estimates are, as a result, based on cost information that reflect variable site and operational conditions, may include implicit cost estimating factors, incorporate more or less equipment than necessary for the model effluent treatment systems, and may not precisely reflect current equipment costs. These factors ultimately affect the accuracy of the equipment and installed capital cost and operating cost estimates produced for this study. Operating costs estimates, in particular, are highly variable from site to site, and were difficult to establish with significant accuracy due to the limited amount of information available as a design basis (e.g., untreated effluent quality comprising all relevant chemical species, including those not subject to *MMER*, suspended solids particle size distribution, speciation of targeted contaminants, targeted effluent quality, etc.) and the time constraints placed on the study.

- With respect to the amount of information available to support (sub)sector summaries and mine operations and the analysis of relationships between water management practices and effluent quality, substantial effort was expended to collect as much information about mine and mill operations in Canada as possible within the time constraints of the study; however time constraints ultimately limited the extent of this information collection. Collection of additional information in Revision 1 was limited to that required to support activities included in the scope of Revision 1 and an effort to collect additional general information was not undertaken. As a result, not all operations identified as relevant to this study could be reviewed and represented in the subsector summaries (especially those that did not submit Revision 0 questionnaires, Revision 1 mini-surveys or have publicly accessible information), and operations that were reviewed may not have been reviewed for all aspects of mine operations summarized in Section 6 if this information was not available through questionnaires and other resources (e.g., water management practices, explosive use, etc.).

5.5.2 Data Limitations

Data limitations experienced in undertaking this study were the applicability, the quality and amount of information and data available for this study.

Quality and Availability

In some cases, the information provided via the Revision 0 operations questionnaires and which could be collected via independent research lacked detail and clarity, making the complete and accurate incorporation of the information into the study difficult. In these cases, an effort was made to clarify information through additional research or follow-up with mine operations. Additionally, where the scope of Revision 1 allowed, follow-up attempts to clarify Revision 0 questionnaire submissions were made during Revision 1 effort. However, when clarification attempts were not successful, this often left information and data subject to interpretation by the study team during data analysis, summarization and report writing. The quality of information collected via the Revision 1 mini-survey was on average better than that collected by the Revision 0 questionnaire.

Quality limitations in information available via independent research were frequently the result of the public accessibility of operation-specific information. A valuable resource in this study was discharge permits for operations in jurisdictions where they are publicly released online by provincial regulatory bodies. However, some provincial regulatory bodies do not make this information readily available to the public.

As a result, more reliable and detailed information could be collected for analysis for operations in provinces where this information was readily available. In provinces where this information is not publicly available, information concerning water management and effluent treatment practices had to be drawn from more diffuse sources, and was typically less detailed and less reliable. Another example of a valuable information resource that varied geographically was provincial and territorial mine effluent performance summaries, some of which included detail on effluent treatment systems. These were published by some provinces, but not all.

Independent research was also limited by the confidential nature of some of the information requested, e.g., effluent treatment system capital and operating costs, untreated effluent quality, and water management practices. This information is typically only available from mine operations themselves; for those mine operations that did not complete the questionnaire, or elected to not provide cost information, this information was simply not available.

In Revision 0 of this study, weekly/grab sample values for *MMER* Schedule 4 substances were not available to Hatch. For Revision 1 of this study, Hatch received *MMER* Schedule 4 grab data from Environment Canada to compare to the monthly mean values to assess whether the monthly mean concentrations adequately represent grab mining effluent data. There were concerns following Revision A that the use of monthly and quarterly concentration values may “dilute” or “mask” the true variability of untreated and treated effluent quality. An assessment of the differences between the concentration statistics (minimum, average, 95th percentile and maximum) revealed that the differences between the statistics generated through the use of monthly mean data and grab data were minimal. The most significant differences noted were between maximum values; however, the 95th percentiles, which are used throughout the report in analysis of the data and to represent the model effluent treatment systems, were reasonably well aligned. Thus, the monthly mean data used in Revision 0 has been assessed to be adequate to represent the variation in effluent quality and its use will be continued for Revision 1.

The Revision 0 operations questionnaire requested quarterly data to reduce complexity and data entry demands of the participating operations, therefore untreated effluent concentrations provided were on a quarterly basis.

Applicability

The main limitation concerning the applicability of data provided by questionnaire respondents was in the use of reported treated and untreated effluent quality to establish achievable concentrations, and removal efficiencies. Not all questionnaire respondents provided both untreated and treated effluent quality, making determination of site-specific removal efficiencies difficult.

Quality information in some cases also reflects dilution by incident precipitation onto ponds, and total suspended solids settling and natural degradation (e.g., total ammonia) within ponds, which may affect treated effluent concentrations and removal efficiency assessments. In systems where only one technology was employed in the effluent treatment system, the untreated and treated effluent values as provided were used to establish removal efficiencies or achievable concentrations for that technology.

5.5.3 BATEA Selection Limitations

It is important to note that BATEA selection is not universal for each (sub)sector due to site-specific considerations. The BATEA selection is bounded by strict criteria for BAT (e.g., technology/technique has been demonstrated at full scale on mining effluent and under representative climate conditions) and in the context of a model non-greenfield operation with an existing effluent management and treatment system for given nominal and design treatment capacities. **As a result, the BATEA selected in this study may not be universally applicable across all Canadian operations, due to technical and economic constraints that vary from site to site.**

Selected BATEA are upgrades or retrofits to existing equipment for which capital has already been expended and therefore, are associated with sustaining costs rather than initial capital costs. This affects the consideration of what is economically achievable. BATEA selected for greenfield operations may be different than that selected for existing model operations. Selection of BATEA for greenfield operations was not the focus of this study; however, some suggestions for greenfield operations are made. Technologies screened out as BAT and not selected as BATEA in this report could, in fact, prove to be BATEA for some site-specific applications.

Further, the removal efficiency and/or achievable effluent concentrations associated with the technology is based on reported operations data, literature values, and/or vendor data. It is important to note that achievable concentrations are typical and may not be possible for every application.

Ultimately, the best available technology that is economically achievable (BATEA) for any given mining operation is site-specific, as a result of the multitude of geographic and operational factors that influence effluent quality, impact the technical feasibility of treatment technologies, and dictate the financial constraints on the capital and operating expenditures that can be borne by operations while still maintaining economic viability.

6. Existing Effluent Management Techniques and Treatment Technologies at Metal, Diamond, and Coal Mining Operations in Canada

This section summarizes the information collected about mine and mill operations during the MEND BATEA study for each subsector (base metal, precious metal, iron ore, uranium, coal and diamond) via the operations questionnaire, independent research and in-house knowledge. The main purpose of these summaries is to provide an overview of each subsector's current water management and effluent treatment practices, and to establish a model site wide water management model, model effluent treatment process, average and design flow rate and treated effluent quality to carry forward for use in BATEA selection.

The summarized information is also used to identify any significant relationships between operational aspects of Canadian metal mine and mill operations (i.e., ore mining and processing practices, waste management techniques and effluent treatment processes) and resultant untreated and treated effluent quality.

For each subsector, the following is described:

- Subsector Overview:
    - List and summary of subsector operations and operational status.
    - Summary of the number of reviewed mines.
    - Primary and secondary commodities produced by the subsector.
- Untreated Effluent Quality Summary:
    - Typical contaminants.
    - Factors influencing untreated effluent quality.
    - Summary of untreated effluent quality received from Revision 0 questionnaire respondents and Revision 1 mini-survey respondents.
- Water Management Techniques Summary:
    - Mine facility water management techniques.
    - Explosives use.
    - Waste rock disposal methods and water management techniques.
    - Tailings disposal methods and water management techniques.

- Summary of Effluent Treatment Technologies Employed by Operations for Final Effluent Quality Control:
  - Relative use of observed effluent treatment technologies.
  - Discussion of common or typically employed treatment technologies.
- Treated Effluent Quality Summary:
  - Summary of minimum, average, 95th percentile and maximum concentrations of current and proposed *MMER* regulated parameters based on monthly average concentration data reported to Environment Canada as part of *MMER* reporting requirements for base metal, precious metal, uranium and iron ore subsectors, and based on a data set provided by the Coal Association of Canada for coal operations and data reported to Environment Canada by diamond operations. The data was supplemented by independent research where necessary.
- Model Effluent Treatment System:
  - Process flow diagram of a typical effluent treatment system employed by the subsector operations for control of effluent quality on which to base subsequent cost estimates and BATEA selection.
  - Model water management plan.
  - Model effluent treatment system flow rate.
  - Model effluent treatment system effluent quality analysis and summary.

Information collected via the operations questionnaire concerning water management around specific site features (e.g., mine, waste rock stockpiles, tailings storage facility, and ore stockpiles) is presented graphically to demonstrate the relative application of the reported water management technique where a sufficient number of operations provided data. The information presented may not reflect all of the operations surveyed as practices utilized at each site vary and the techniques may not be relevant to each operation (e.g., if an operation does not have mine facilities and therefore has not reported mine water management techniques, or does not actively manage water around a site feature such as the ore stockpiles).

Additionally, the water management techniques reported are not mutually exclusive and operations may have reported multiple techniques. As a result, the total number of operations reflected in the graphical data for each sector or subsector can fluctuate. The intent of the graphs presented in these summaries is to reflect the relative usage of the water management techniques.

6.1 Metals Sector: Base Metal

Operating Canadian base metal operations are, at present, subject to the current *Metal Mining Effluent Regulations,* and per Environment Canada's 10-Year Review of *Metal Mining Effluent Regulations*, would be subject to the proposed changes to *MMER* for metal mines. Base metal operations subject to *MMER* have been identified by Environment Canada as being potentially impacted by the changes in discharge limits proposed for the parameters that are currently regulated (arsenic, copper, cyanide, lead, nickel and zinc), however analysis concerning the potential impact of the additional parameters (ammonia, iron, selenium) proposed by Environment Canada is not available.

The review of the Canadian base metal subsector included a total of 43 mine, mill and smelter sites ("operations"), out of a total of 57 operations identified as relevant to this study (see Section 5.2.2 for details). Of the operations reviewed, 33 submitted questionnaires as part of the data collection portion of the study. Information for an additional 12 operations was collected from independent research efforts and from in-house information. A complete list of the Canadian base metal operations is presented below, in Table 6-1.

Table 6-1: Canadian Base Metal Operations

Operation	Owner/Operator	Location	Status
Restigouche Mine	Blue Note Mining Inc.	Bathurst, MB	Producing
Prairie Creek Mine	Canadian Zinc	Fort Simpson, NT	Development
Bucko Lake Mine	CaNickel Mining Ltd.	Wabowden, MB	Producing
Minto Project	Capstone Mining Corporation	Carmacks, YT	Producing
Lockerby Mine	First Nickel Inc.	Sudbury, ON	Producing
MAX Molybdenum Mine and Mill	FortyTwo Metals Inc.	Trout Lake, BC	Suspended/ Care and Maintenance
Bracemac-MacLeod Mine	Glencore Xstrata	Matagami, QC	Producing
Brunswick Mine	Glencore Xstrata	Bathurst, MB	Closed
Heath Steele Mine	Glencore Xstrata	Newcastle, NB	Closed
Horne Smelter	Glencore Xstrata	Rouyn-Noranda, QC	Producing
Kidd Metallurgical Site	Glencore Xstrata	Timmins, ON	Producing
Kidd Mine Site	Glencore Xstrata	Timmins, ON	Producing
Matagami Mine	Glencore Xstrata	Matagami, QC	Producing
Mattabi Mine	Glencore Xstrata	Ignace, ON	Closed
Montcalm Project	Glencore Xstrata	Timmins, ON	Closed
Perserverance Mine	Glencore Xstrata	Matagami, QC	Closed
Raglan Mine	Glencore Xstrata	Kattiniq, QC	Producing
Sudbury Integrated Nickel Operations	Glencore Xstrata	Sudbury, ON	Producing
Flin Flon Complex	Hudbay Minerals Inc.	Flin Flon, MB	Producing
Lalor Project	HudBay Minerals Inc.	Snow Lake, MB	Development/ Redevelopment
Reed Copper Project	HudBay Minerals Inc.	Flin Flon, MB	Producing
Trout Lake Mine	HudBay Minerals Inc.	Flin Flon, MB	Closed
Niobec Mine	IAMGOLD Corporation	Saint-Honoré, QC	Producing
Huckleberry Mine	Imperials Metals Corporation	Houston, BC	Producing
Morrison Mine	KHGM International	Sudbury, ON	Producing

Operation	Owner/Operator	Location	Status
McCreedy Mine	KHGM International	Sudbury, ON	Producing
Podolsky Mine	KHGM International	Chelmsford, ON	Closed
Victoria Advanced Exploration Project	KHGM International	Whitefish, ON	Development/ Redevelopment
Redstone Mine	Northern Sun Mining Corporation	Timmins, ON	Producing
McWatters Mine	Northern Sun Mining Corporation	Porcupine, ON	Producing
New Afton Mine[6]	New Gold	Kamloops, BC	Producing
Lac des Isles Mine[7]	North American Palladium Ltd.	Thunder Bay, ON	Producing
Cantung Mine	North American Tungsten Corporation Ltd.	Tungsten, NT	Producing
Copper Rand Mine	Nuinsco Resources / CBay Minerals Inc.	Chibougamau, QC	Closed
Langlois Mine	Nyrstar	Lebel-sur-Quévillon, QC	Producing
Myra Falls Operations	Nyrstar	Buttle Lake, BC	Producing
Shakespeare Nickel Mine	Prophecy Platinum	Sudbury, ON	Suspended/ Care and Maintenance
Ming Mine	Rambler Metals and Mining Canada Ltd	Baie Verte, NL	Producing
Complex Metallurgique Sorel-Tracy	Rio Tinto	Sorel-Tracy, QC	Producing
Tio Mine	Rio Tinto	Havre-Saint-Pierre, QC	Producing
ScoZinc Mine-Mill	Selwyn Resources Ltd.	Shubenacadie, NS	Suspended/ Care and Maintenance
Copper Mountain Mine	Similco Mines Ltd.	Princeton, BC	Producing
Tanco Mine (Bernic Lake Mine)	Tantalum Mining Corporation of Canada Ltd.	Lac-du-Bonnet, MB	Producing
Gibraltar Mine	Taseko Mines Ltd.	Williams Lake, MB	Producing
Duck Pond Operations	Teck Resources Ltd.	Millertown, NL	Producing
Highland Valley Copper Mine	Teck Resources Ltd.	Logan Lake, BC	Producing
Endako Mines	Thompson Creek Mining Ltd.	Fraser Lake, BC	Producing
Haley Plant	Timminco Ltd.	Haley, ON	Closed
Caribou Mine-Mill	Trevali Mining Corporation	Bathurst, NB	Suspended/ Care and Maintenance
Birchtree Mine	Vale Canada Ltd.	Thompson, MB	Producing
Copper Cliff Complex	Vale Canada Ltd.	Copper Cliff, ON	Producing
Crean Hill Mine	Vale Canada Ltd.	Sudbury, ON	Producing
Garson Mine	Vale Canada Ltd.	Sudbury, ON	Producing
Thompson Mine	Vale Canada Ltd.	Thompson, MB	Producing

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[6] Classified as a base metal operation since copper production significantly exceeds precious metal production.

[7] Classified as a base metal operation by Environment Canada within *MMER* reporting data.

Operation	Owner/Operator	Location	Status
Totten Mine	Vale Canada Ltd.	Copper Cliff, ON	Producing
Voisey's Bay Mine-Mill	Vale Canada Ltd.	Voisey's Bay, NL	Producing
Wolverine Project	Yukon Zinc Corporation	Ross River, YT	Producing

Effluent discharges at 38 of the 43 operations reviewed were subject to *MMER* in 2012. Those operations that are not subject to *MMER* are either closed or were considered development projects in 2012. Any changes to *MMER* status that may have occurred in 2013 have not been included.

The most common primary commodities produced or processed by the Canadian base metal mines, mills and smelters reviewed are copper, nickel, and zinc. Copper is the most common secondary commodity produced by the base metal subsector. A summary of the primary and secondary commodities mined or processed by the operations reviewed in this study and the number of operations producing these commodities is presented in Figure 6-1. In Figure 6-1, there are several operations reporting precious metal as primary commodities; these operations are classified as base metal operations because they have been classified as such by Environment Canada or they also have a base metal reported as a primary commodity for which the annual production is higher.

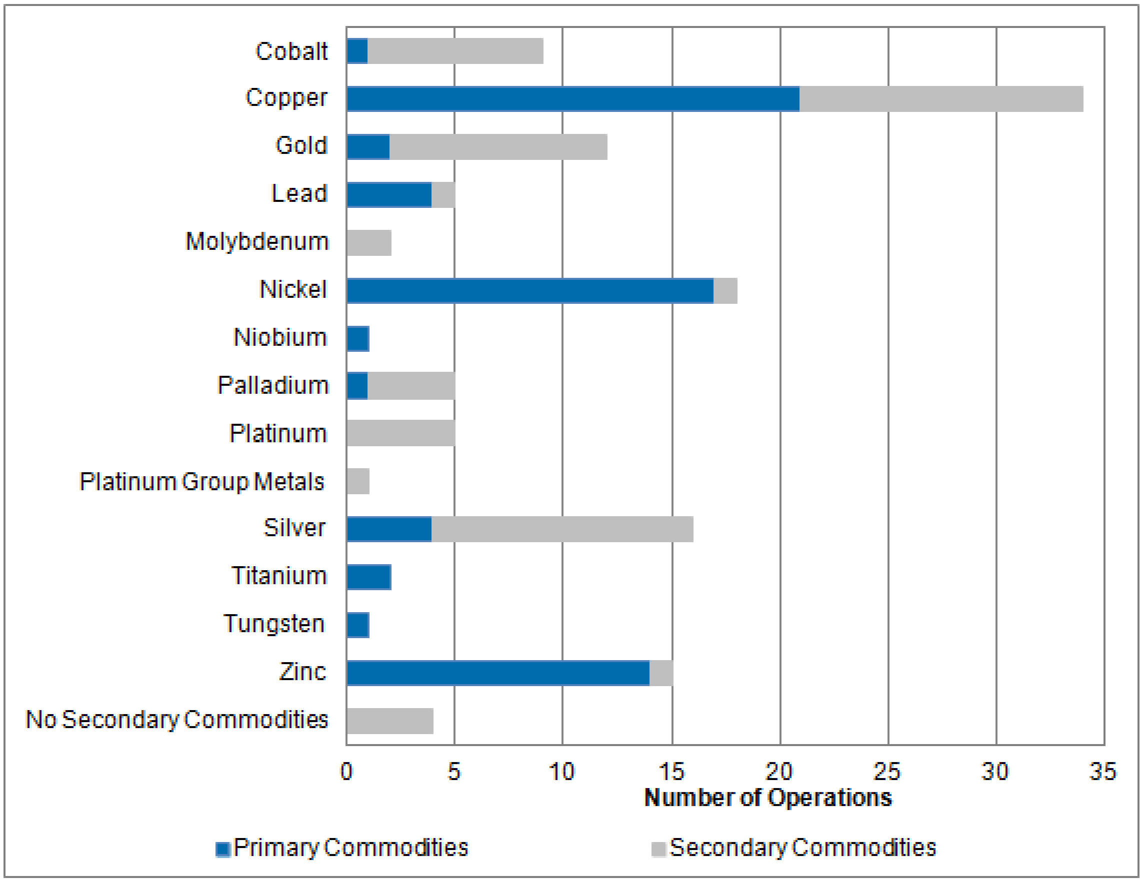

Figure 6-1: Primary and Secondary Commodities Produced at Canadian Base Metal Operations, as reviewed

Base metal operations are dispersed across Canada, though often found in clusters surrounding mineral deposits regions. The operations reviewed in this study are found in British Columbia, Manitoba, New Brunswick, Newfoundland and Labrador, the Northwest Territories, Quebec, Ontario and the Yukon. Figure 6-2 illustrates the geographic distribution of the base metal subsector operations.

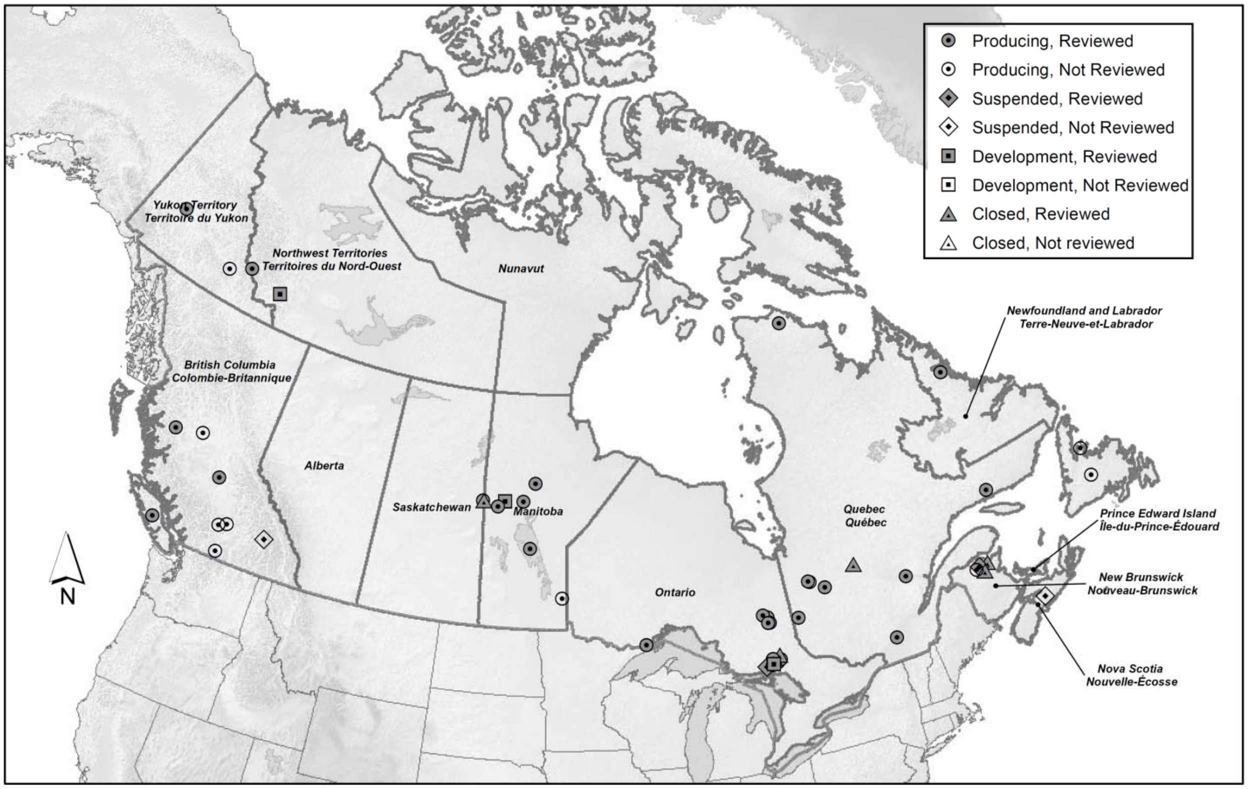

Figure 6-2: Geographic Distribution of the Base Metal Subsector Operations

The majority of sites included in this summary are operational sites; however several closed sites, suspended/care and maintenance sites, and development/redevelopment sites were also reviewed. Figure 6-3 illustrates the status of the base metal operations reviewed in this study.

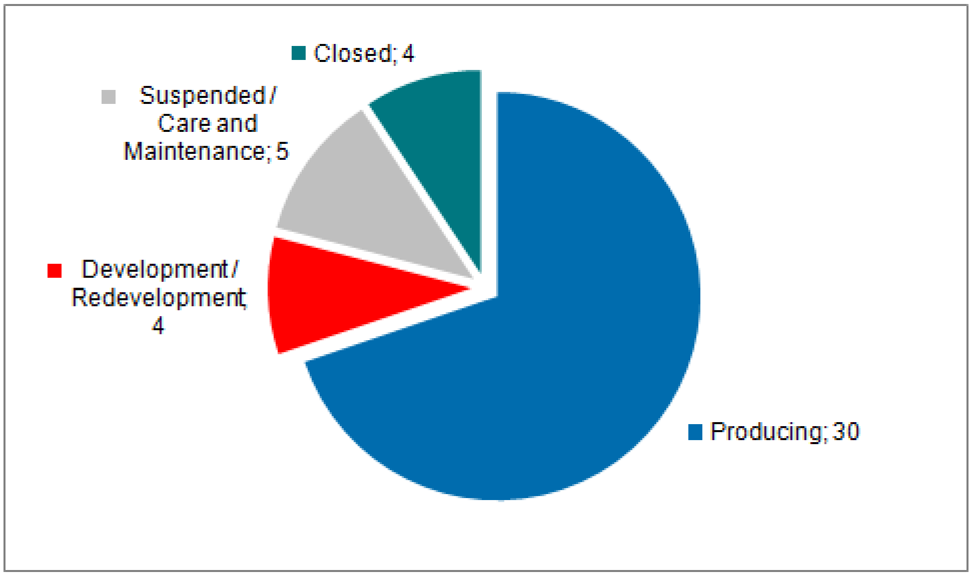

Figure 6-3: Operational Status of Base Metal Operations Reviewed

6.1.1 *Effluent Characteristics*

In general, it is expected that the quality of effluent generated by any mine or mill operation, including base metal operations, will be variable based on site-specific factors, including, but not limited to, what type of mine, mill and waste management facilities are present on site, the operating status of the site (e.g., closed, producing, etc.), local climate, and the mineralogy of the ore and waste rock. However, given the common target elements for extraction from these sites, similar processing technologies and often similarities in mineralization of base metal ores, effluents at these operations generally contain similar contaminants that require management. Table 6-2 summarizes the characteristics of the reviewed base metal operations that may contribute to the typical untreated effluent quality.

Table 6-2: Factors Influencing Base Metal Subsector Untreated Effluent Quality

Ore and Waste Rock Mineralization	Mine and Mill Operational Status and Facilities	Base Metal Processing
The ore and waste rock mineralization at base metal operations is variable. The ore bodies at some operations reviewed are associated with sulfidic mineralizations, and mine wastes at these operations often experience some degree of acid generation. Acid generation in turn encourages metal leaching into site water. Mineralization surrounding ore at other operations may have a net	The operational status, as well as the mining, processing and waste management facilities of the operations reviewed for this subsector vary. The following list characterizes the cohort of base metal operations by status and facility configurations: Closed operations; including those formerly engaged in mining activity only, and those formerly engaged in mining and processing activities (including concentrating, processing, and smelting activities).	Mining Concentrator/Mill • Water applied for ore stockpiles dust suppression can result in TSS generation • Ore size reduction can result in TSS generation and contaminant metal liberation • Froth flotation chemicals, including organic frother compounds, sodium sulfate, copper sulfate activator, and sodium

Ore and Waste Rock Mineralization	Mine and Mill Operational Status and Facilities	Base Metal Processing
neutralizing or alkaline effect, and are often relatively benign in terms of effluent impact.	Developments; including operations that will have mining activity only, and operations that will have both mining and processing activity. Operational sites where the only activity is mining. Operational sites that engage in both mining and processing. Operational sites that engage in only ore processing.	cyanide suppressor, and pH modifiers can impact site water quality. Hydrometallurgy • Acid leaching of ore using sulfuric acid, nitric acid, etc. promoting metal leaching. • Acid neutralization by lime addition and gypsum precipitation. • Ion exchange generates regeneration waste. • Organic solvent extraction. Pyrometallurgy (smelting) • Slag granulation process can generate TSS, and leach metals. • Wet scrubber blowdown (including acid plant blowdown). Electrolysis • Electrowinning and electrorefining bleed stream.

To establish what contaminants of concern are typically found in untreated effluent at base metal operations, parameters included in discharge permits, parameters reported as targeted by effluent treatment processes by questionnaire respondents and parameters reported in untreated effluent data by questionnaire respondents were considered. Figure 6-4 demonstrates the relative frequency of each parameter that appears in effluent discharge permits or is targeted by effluent treatment processes.

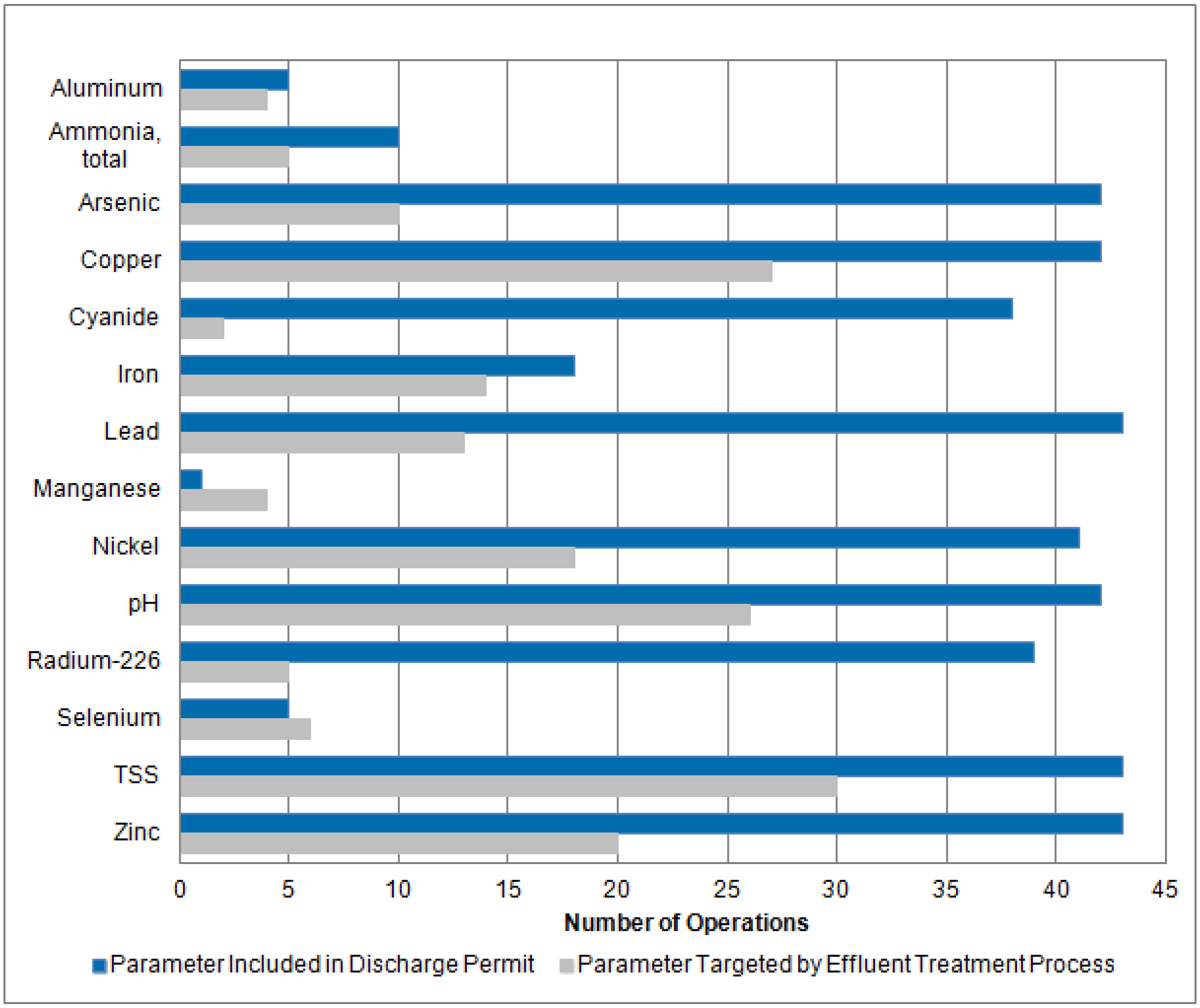

Figure 6-4: Parameters Included in Discharge Permits and Targeted by Effluent Treatment Processes at Reviewed Base Metal Operations[8] (38 Discharge Permits / 27 Effluent Treatment System)

Of the 33 mines that submitted or began questionnaires in support of this study, only 20 elected to provide untreated effluent quality as part of their submittals. The data are summarized in Table 6-3.

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[8] This figure includes information from two planned developments that will treat for selenium.

Table 6-3: Quarterly Average Concentrations of Parameters in Untreated Effluent at Base Metal Operations

1

Parameter	Unit	Minimum	Average	95th Percentile	Maximum	Number of Operations Reporting Untreated Effluent Concentration
pH		2.6	7.2	11.0	12	20
Aluminum	mg/L	0.007	1.8	5.9	16	12
Arsenic	mg/L	0.0005	0.04	0.20	0.21	13
Copper	mg/L	0.0006	1.0	6.0	9.4	17
Cyanide	mg/L	0.002	0.0061	0.02	0.02	4
Iron	mg/L	0.037	10.7	51	135	15
Lead	mg/L	0.00027	0.061	0.279	0.488	14
Nickel	mg/L	0.0019	4.3	23	52	17
Selenium	mg/L	0.0010	0.033	0.124	0.20	10
Zinc	mg/L	0.0010	15	59	64	14
Radium-226	Bq/L	0.010	0.821	2.0	2.0	4
TSS	mg/L	0.758	22	114	227	17
Total Ammonia	mg-N/L	0.010	2.1	11	22	11

Notes:
Values reported as less than the method detection limit have been incorporated at the MDL value.
All metal concentrations are total metal concentrations, i.e., the sum of dissolved and suspended fractions.
TSS data from one operation was removed from the data set as it was extremely high and was skewing the results.

The contaminants that are considered to be typical based on the frequency of occurrence in untreated effluent at base metal operations (see Figure 6-4) are: pH, total suspended solids, zinc, nickel, copper, lead, iron and arsenic. Total suspended solids, pH, nickel, zinc and copper are all targeted by at least half of effluent treatment processes described by questionnaire respondents, and lead, iron and arsenic are targeted by at least a third of effluent treatment processes. Further, these parameters are the most commonly found in discharge permits and in reported untreated water quality.

It is important to note that though cyanide and radium-226 also appear in Figure 6-4 as parameters which are included in most permits (with the exception of the permits for operations that are not subject to *MMER*), they are not considered typical for base metal operations as they do not frequently appear in reported untreated effluent quality or as targeted by effluent treatment processes.

Additional contaminants of note which may be present in base metal operations' untreated effluent and targeted by effluent treatment processes are metals such as aluminum, cadmium, cobalt, manganese, and mercury, and non-metals such as ammonia, sulfate, and selenium.

6.1.2 Effluent Management and Control Techniques

In an effort to control the volume and quality of effluent requiring containment and treatment prior to discharge to the environment, and to minimize the risk of potential contaminants being released to the environment, base metal operations employ a variety of techniques to manage water.

Table 6-4 presents an overview of water management and effluent control techniques used at one or more operations (for water management in and surrounding mines, waste rock stockpiles, ore stockpiles, and tailings storage facilities).

Table 6-4: Overview of Effluent Management and Control Techniques at Base Metal Operations

Volume Control	Quality Control	Minimize Environmental Contact
• Diversion of clean or non-impacted surface and groundwater away from site features which may degrade water quality upon contact. • Recycle of contact water to minimize the volume of water requiring treatment. • Co-disposal or in-pit disposal of waste streams to minimize the total waste storage footprint and thereby minimize contact water run-off volumes generated by precipitation. • Segregation of benign and potentially PAG/PML wastes. • Covers (e.g., soil, vegetation, mine or process waste) on inactive facilities to minimize interaction between precipitation and facilities which may degrade water quality upon contact and to divert precipitation away from impacted percolation/seepage, preventing contamination. • Progressive reclamation of site facilities to minimize footprint requiring water collection. • Indoor storage of ore stockpiles. • Mine waste employed in mine backfill and other construction applications.	• Water cover on mine wastes in waste storage facilities (e.g., tailings storage facility). • Explosives best management plan in place and in practice. • Mine waste blended with neutralizing materials to control acid generation and resultant metal leaching. • Tailings deposition plan specifically designed to minimize acid generation and metal leaching by limiting length of time sulfidic mine wastes are exposed to atmospheric conditions.	• Storage of potentially reactive wastes in dedicated storage facilities with environmental controls (e.g., liners, covers, seepage monitoring and collection, etc.). • Collection of contact water (including run-off and seepage) and isolation from the environment during conveyance to treatment. • Chemical dust suppressants or water applied to tailings and ore stockpiles to minimize dust generation. • Mill facilities are centralized, with two or more mines providing ore for processing to one mill. This arrangement isolates processing activities, which can reduce the potential for deleterious substances that are used for processing or generated by processing to contaminate contact water or to be released to the environment.

The following sections present a more detailed summary of the mining and waste management disposal methods on site at base metal operations and their associated effluent management and control techniques.

It should be noted that in the figures, each operation can employ more than one technique and thus the sum of the number of operations presented in this figure may exceed the number of operations reviewed in this study.

6.1.2.1 *Mine Facilities and Water Management Techniques*

Base metal operations employ a combination of open pit and underground mine facilities; frequently both types of mine facilities are present on a single site. Both active and inactive mining facilities are found at base metal operations. Figure 6-5 illustrates the mining facilities found at base metal operations and their relative prevalence for 41 operations. Operations that reported "none" include closed operations, in development operations and operations with no mining activity on site (i.e., operation comprises processing only).

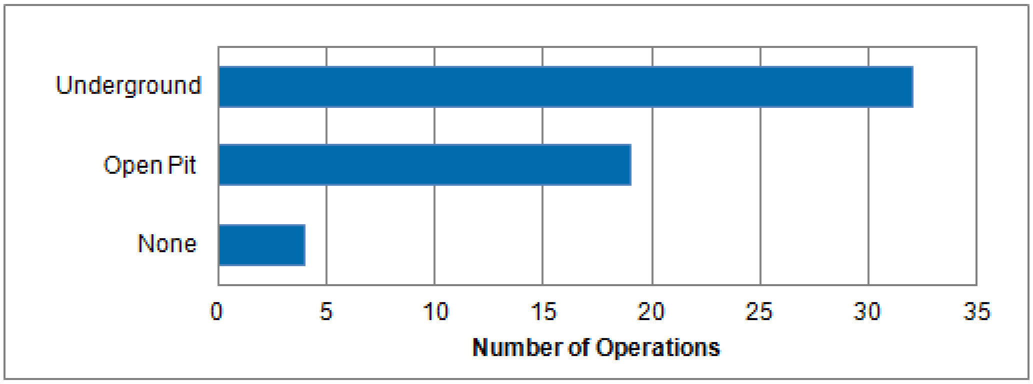

Figure 6-5: Base Metal Subsector Mine Facilities (41 Operations)

Figure 6-6 summarizes the water management techniques utilized by 31 base metal operations to minimize mine-water-environment interactions.

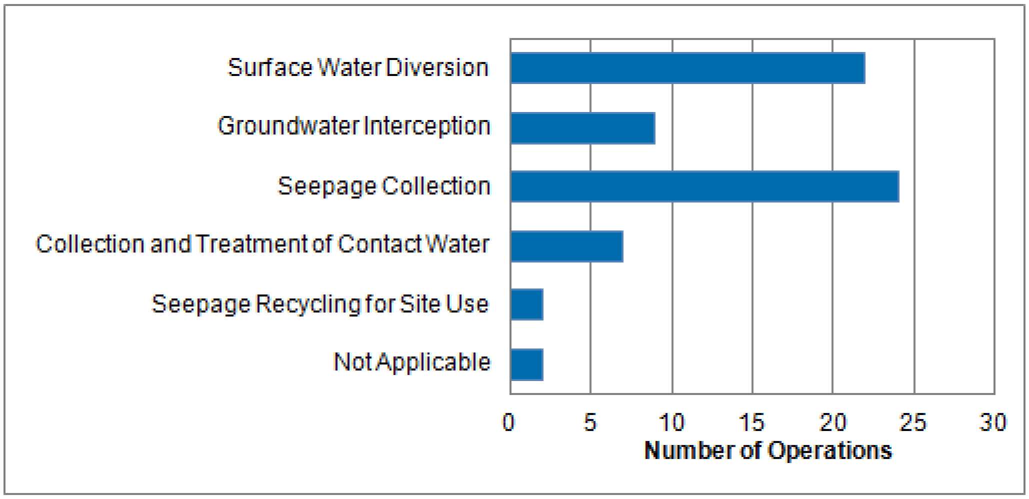

Figure 6-6: Base Metal Subsector Mine-Water-Environment Interaction Minimization Techniques (31 Operations)

Surface water diversion and seepage collection are most commonly used by base metal operations to minimize the volume of water contacting mine workings and to isolate the water that does contact mine workings, respectively. Surface water diversion is employed at 71% of operations (22 of 31) and seepage collection techniques are employed at 77% of operations (24 of 31) reporting mine water management techniques.

Water is diverted away and prevented from contacting mine facilities through the use of diversion ditches, culverts, and channels, berms, and dams. Seepage (groundwater reporting to mine workings) collection is accomplished via capture in sumps and is either conveyed to treatment or recycled for site use.

6.1.2.2 *Explosive Use*

Operations with active mining operations generally use some combination of bulk ammonium nitrate fuel oil (ANFO), packaged ANFO, bulk emulsions and packaged emulsions, and packaged watergel/slurry. 81% of operations (20 of 27 responses) operate or plan to operate under explosives best management plans. No explosives are used at sites with no active mining operations. Figure 6-7 demonstrates the relative frequency of used explosive types as reported by 29 questionnaire respondents.

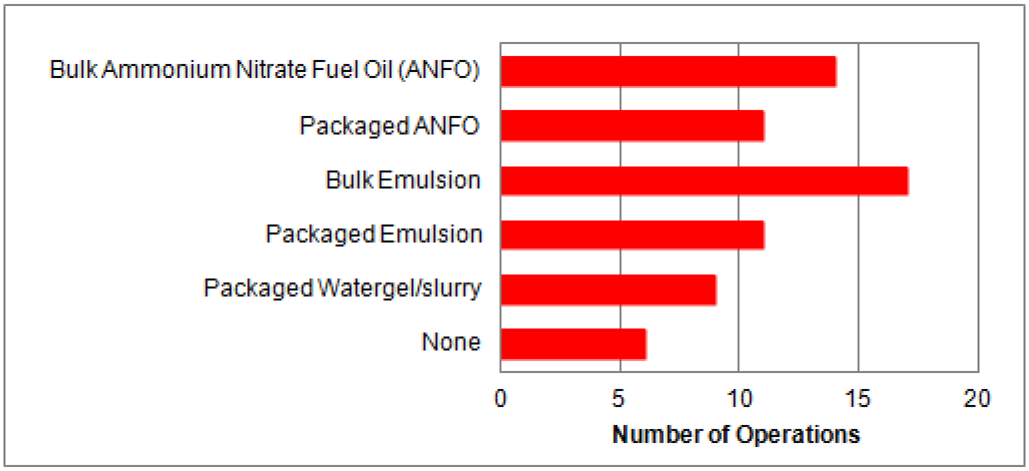

Figure 6-7: Relative Use of Types of Explosives at Base Metal Operations (29 Operations)

6.1.2.3 *Ore Stockpiles and Water Management Techniques*

58% of operations (18 of 31) reported having active ore stockpiles on site. Figure 6-8 summarizes the ore stockpile-water-environment interaction minimization techniques reported by 20 operations, and illustrates the relative frequency of each technique's use. Figure 6-8 reflects answers provided by questionnaire respondents, including details provided outside of the questionnaire answers available for Ore Stockpile(s)-Water-Environment Interaction Minimization Techniques. Water or chemical dust suppressants applied, indoor or barrel storage, collection and treatment of contact water were not provided as responses within the questionnaire; these were provided by respondents.

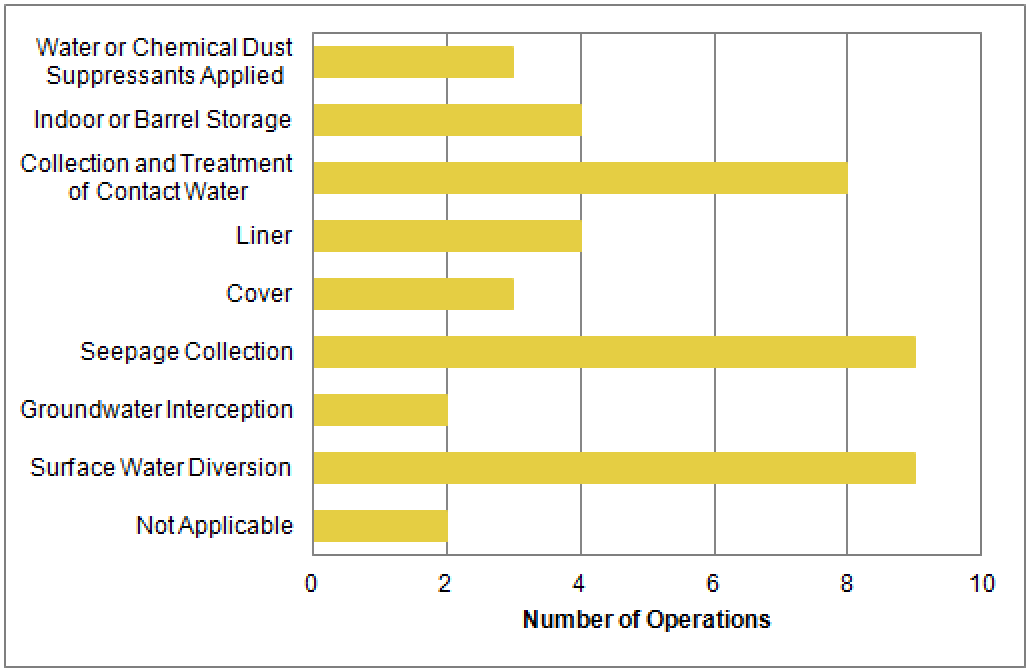

Figure 6-8: Base Metal Subsector Ore Stockpile(s)-Water-Environment Interaction Minimization Technologies (20 Operations)

The most commonly reported techniques are surface water diversion, and collection of seepage and other contact water which is then conveyed to treatment.

Indoor or barrel storage refers to ore stockpiles held in buildings, storage bins or barrels to prevent contact/interaction with water and in some cases, oxygen. Examples of the type of liners and covers employed for isolation of ore stockpiles from environmental interactions are HDPE liners, paved platforms and water cover[9].

Not applicable refers to 1 operation reporting no ore stockpiles on site and 1 operation reporting an ore stockpile that did not provide additional detail.

6.1.2.4 *Waste Rock Disposal Methods and Water Management Techniques*

Waste rock is produced, managed or stored at the majority of operations as reported by questionnaire respondents (26 of 30). Base metal operations employ a variety of means of disposal for waste rock stockpiles. The disposal techniques and relative frequency of the use of these techniques for 26 operations are summarized in Figure 6-9.

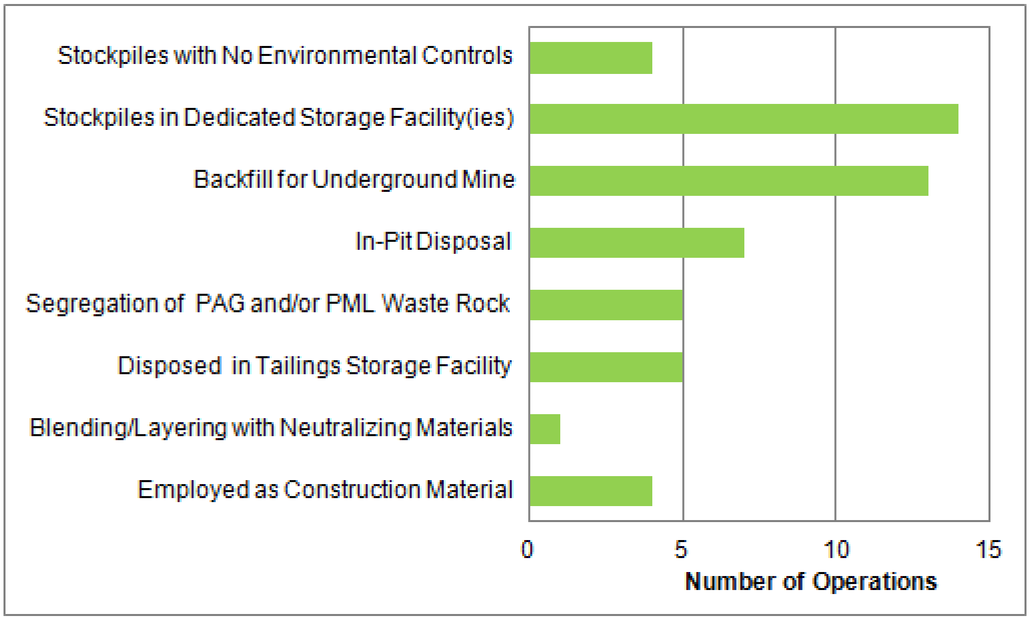

Figure 6-9: Base Metal Subsector Current and Historical Waste Rock Disposal Techniques (26 Operations)

Waste rock stockpiles are most often managed either through disposal in a dedicated storage facility, or used as backfill for underground mines. Figure 6-10 summarizes the waste rock stockpile-water-environment interaction minimization techniques reported by 26 operations via the operations questionnaire, and the frequency of each technique's use.

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[9] In-pit water cover is used to prevent oxidation of ore at one operation under care and maintenance.

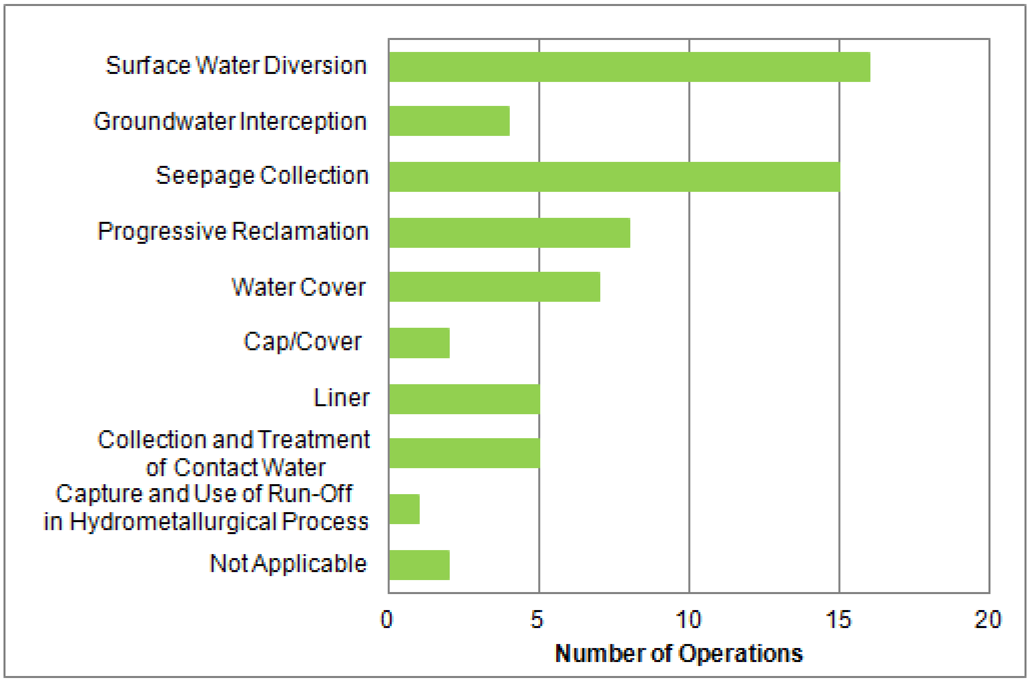

Figure 6-10: Base Metal Subsector Waste Rock-Water-Environment Interaction Minimization Techniques (26 Operations)

With respect to Figure 6-10, collection and treatment of contact water was not an answer provided for Waste Rock-Water-Environment Interaction Minimization within the questionnaire. Figure 6-10 therefore reflects the number of respondents that reported this technique in the 'other' option.

Liners used for isolation of waste rock stockpiles and their run-off from groundwater include clay and bitumen. Waste rock stockpiles covers employed include glacial till and other engineered covers. One operation reported disposal of waste rock in natural water bodies.

The two operations that selected 'Not Applicable' are: an operation that has historical waste rock stockpiles on site but is no longer operational, and an operation that co-disposes of waste rock in a tailings storage facility.

Approximately 20% of operations (5 of 26) with waste rock stockpiles segregate waste rock by characterization as benign or potentially acid generating/metal leaching. Those operations that do not segregate by waste rock type dispose of all waste rock in the same manner; these have identified only one type of waste rock or treat all waste rock as potentially PAG/PML.

Table 6-5 summarizes the disposal methods employed for the types of waste rock present on site.

Table 6-5: Disposal Methods for Different Waste Rock Types at Active Base Metal Operations

Waste Rock Classification	Disposal Method or Use
• PAG and/or PML	• In-pit disposal. • Used in underground mine backfill. • Co-disposal with tailings. • Stored in dedicated storage facilities. • Berm construction material. • Sub-aqueous disposal.
• NML and NAG	• Construction material for dam and road construction, and backfill. • Stored in dedicated storage facilities. • Surface stockpiles with no environmental controls.

6.1.2.5 *Tailings Disposal Methods and Water Management Techniques*

Tailings are produced, managed or stored at two-thirds (20 of 30) of the operations questionnaire respondents. Base metal operations employ a variety of means of disposal for tailings. The disposal techniques and relative frequency of the use of these techniques are summarized for 20 operations in Figure 6-11.

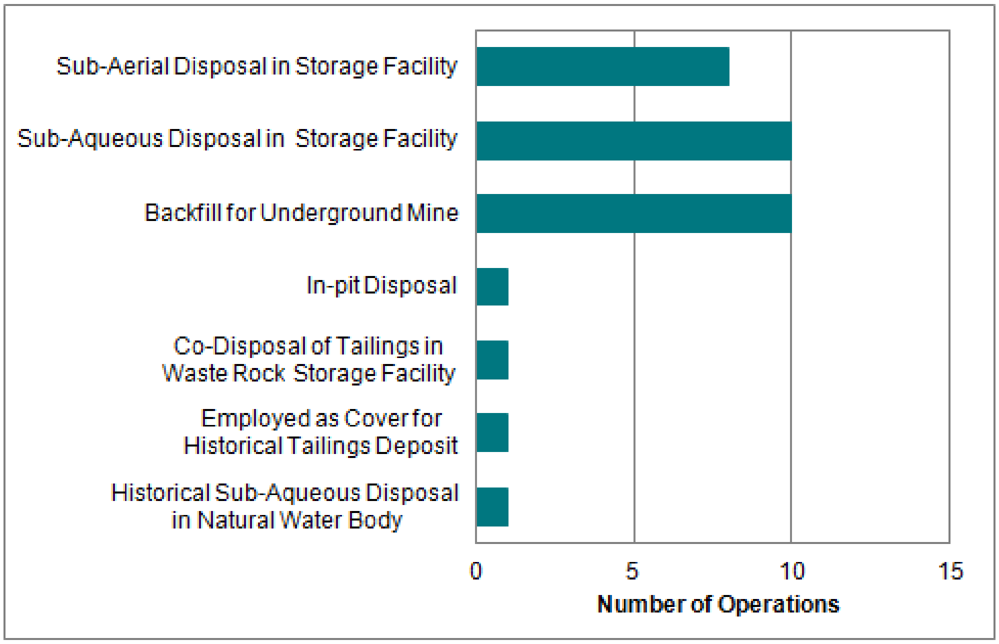

Figure 6-11: Base Metal Subsector Current and Historical Tailings Disposal Methods (20 Operations)

Figure 6-12 summarizes the tailings-water-environment interaction minimization techniques reported as utilized by 18 operations that provided responses concerning tailings management, and the frequency of each technique's use. 2 operations that responded that they managed or stored tailings on site indicated this question was ‘Not Applicable’ to their operations; 1 operation indicated they no longer actively deposited tailings and 1 site did not provide an explanation concerning it was not applicable.

The most common tailings disposal methods are sub-aerial disposal in dedicated storage facilities, sub-aqueous disposal in dedicated storage facilities, and utilization of tailings as a backfill material for underground mines. Some other notable strategies for the minimization of tailings from the environment and water are:

- Tailings deposition plans are specifically designed to minimize tailings-environment interactions by depositing fresh tailings over older deposits, shortening the duration of tailings exposure to oxidative atmospheric conditions.
- Solid tailings covers are employed (e.g., soil, vegetation, wood mulch, process waste materials, impermeable covers).

44% (8 of 18) of operations reported dewatering of tailings prior to disposal. Most operations reported depositing tailings at below 50% solids, though 6 reported depositing tailings at greater than 50%, with 3 of these 6 reporting greater than 70% solids at the point of deposition. 5 operations neutralize tailings prior to disposal, and 1 operation reported desulfurization of tailings prior to disposal.

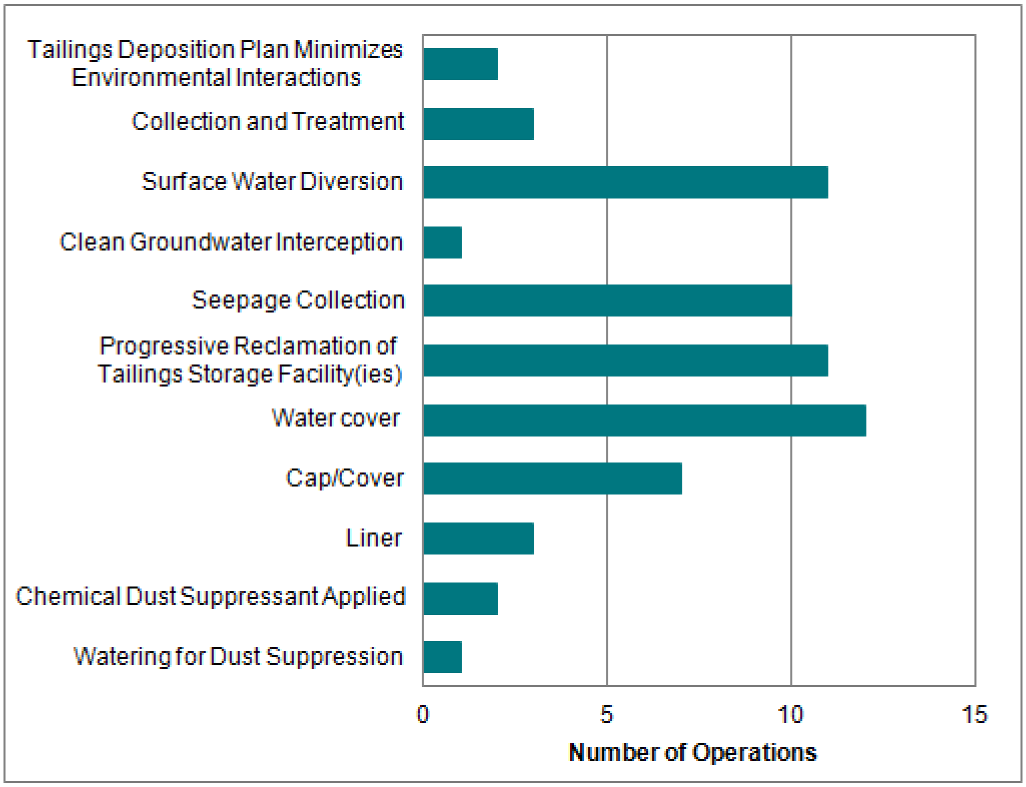

Figure 6-12: Techniques Employed to Minimize Tailings-Environment-Water Interactions (18 Operations)

6.1.3 *Effluent Treatment Technologies*

Base metal operations employ a wide range of technologies for effluent treatment and target a large number of parameters. Technologies employed at base metal operations include hydroxide precipitation, sulfide precipitation, co-precipitation and coagulation, natural degradation and passive treatment, ion exchange, oxidation, membrane size/charge exclusion, air stripping, and solid/liquid separation for the removal of metals, cyanide, ammonia, and TSS. A list of the chemical and physical processes reported in effluent treatment systems at base metal operations are summarized in Table 6-6.

Table 6-6: Treatment Techniques in Effluent Treatment Processes at Base Metal Operations

Chemical and Biological Processes	Physical Processes
• Hydroxide Precipitation • Lime-based (high density sludge, simple sludge recycle, conventional low density sludge, multi-stage low density sludge) • Pond-based lime addition • Sodium hydroxide-based (simple sludge recycle, conventional low density sludge) • Lime-based tailings neutralization. **Co-precipitation/Coagulation** • Ferric iron coagulation/co-precipitation (arsenic removal) • Barium sulfate co-precipitation (radium-226 removal). **Sulfide Precipitation** • Biologically generated sulfide • Proprietary polymeric organosulfide reagents • Sulfide precipitation followed by lime precipitation (planned). **Natural Degradation/Passive Treatment** • Natural degradation of ammonia, cyanide, and thiosalts • Enhanced natural degradation via pond aeration • Solid/Liquid Separation • Coagulant and/or polymer-aided pond settling. **Final pH adjustment** • Sulfuric acid • Gaseous CO2 • Sodium hydroxide. **Ion Exchange** • Selective ion exchange (metals and ammonia removal)	**Solid/Liquid Separation** • Screening • Pond-based settling/sedimentation • Pond silt curtains • Clarification (Conventional, Lamella) • Ballasted flocculation/ sedimentation • Media filtration. **Air Stripping** **Membrane Separation** • Reverse osmosis • Nanofiltration • Other • Oil/water separation • Pre-treatment equalization or holding pond.

Chemical and Biological Processes	Physical Processes
• Selective ion exchange using zeolite (ammonia removal). **Oxidation** • Hydrogen peroxide oxidation (cyanide, thiosalt destruction) • Oxygen bubbling into reactors (thiosalt oxidation). **Active aerobic biological oxidation** • Moving bed biofilm (MBBR) (ammonia removal, planned) • Marsh/wetland/bog polishing.	

The treatment technologies employed at base metal operations depend on a host of factors, including discharge limits and/or objectives established by provincial or territorial regulatory bodies, volume of effluent requiring treatment, contaminants present in the untreated effluent and their concentrations, and to some extent, the age of the mine and legacy effluent treatment infrastructure.

The stringency of discharge limits and/or objectives established by provincial or territorial regulatory bodies appears to drive the extent of treatment and the technologies employed on many of the operations reviewed. Often operations employing polishing steps such as reverse osmosis or ion exchange need to achieve low concentrations to comply with their discharge permits, licences, certificates of authorization or environmental compliance approvals.

Whether contaminants in mine effluent are themselves commodities (e.g., nickel, copper) and are present in concentrations that make recovery from effluent financially feasible also impacts the technologies employed. For example, sulfide precipitation is employed at operations where metals removed from the effluent can be recovered to the process.

The volume of water requiring treatment appears to also be related to the treatment process in use. Those operations treating larger volumes of effluent frequently use pond-based technologies.

Finally, at base metal operations with operational periods spanning many decades, effluent treatment systems have evolved over time. Some treatment systems present today are a combination of legacy effluent treatment infrastructure and upgrades added as necessary to achieve discharge limits.

6.1.4 *Effluent Quality*

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Table 6-7 summarizes the effluent quality at the final discharge points of all the base metal operations subject to *MMER* between 2008 and 2010. These effluent quality ranges utilize the same data set as employed by Environment Canada for the 10-Year Review of *Metal Mining Effluent Regulations*. The data was employed to generate the summary of treated effluent quality as it is a more complete data set than that generated by the questionnaire submittal, as operations are legally obliged to provide this information to Environment Canada.

The summary in Table 6-7 for Schedule 4 parameters (pH, arsenic, copper, lead, nickel, radium-226 zinc and TSS) uses monthly average concentration data generated by Environment Canada from grab data reported by operations. An assessment of the extent that the monthly average data adequately represents the grab data was performed for Revision 1 of this study and it was determined that for the most significant statistics (i.e., the 95th percentile), the difference between the monthly mean data and the grab data was minimal. Therefore, in Revision 1, the monthly mean data are carried forward for analysis. A more detailed assessment of the monthly mean data versus the grab data for each subsector is appended to this report in Appendix D.

Table 6-7: Treated Effluent Summary for the Base Metal Subsector

Parameters	Units	Effluent Concentration Basis	Minimum	Average	95th Percentile	Maximum
pH		Monthly Mean	3.7	7.8	9.0	12.3
Aluminum	mg/L	Grab/Composite	0.00005	0.11	0.39	28.1
Ammonia, total	mg-N/L	Grab/Composite	0.0015	0.94	3.95	39.1
Arsenic	mg/L	Monthly Mean	0.00005	0.0035	0.02	0.061
Copper	mg/L	Monthly Mean	0.0008	0.02	0.06	4.2
Cyanide	mg/L	Monthly Mean	0.0005	0.031	0.052	2.6
Iron	mg/L	Grab/Composite	0.001	0.64	1.82	104
Lead	mg/L	Monthly Mean	0.00002	0.005	0.015	0.2
Nickel	mg/L	Monthly Mean	0.00025	0.091	0.38	14.7
Radium-226	Bq/L	Monthly Mean	0.005	0.025	0.106	0.736
Selenium[10]	mg/L	Grab/Composite	0.00005	0.006	0.024	0.073
Zinc	mg/L	Monthly Mean	0.0001	0.06	0.25	17.5
TSS	mg/L	Monthly Mean	0.01	4.3	13	106

Notes:
Values reported as less than the method detection limit have been incorporated at 50% of the MDL value.
All metal concentrations are total metal concentrations, i.e., the sum of dissolved and suspended fractions.

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[10] Compiled from grab and composite selenium concentrations reported through Schedule 5 for 2012.

6.1.5 Model Water Management and Effluent Treatment Systems

6.1.5.1 Model Water Management System

Based on this review of water management techniques employed by base metal subsector operations, a model water management plan to represent the typical water management practices employed at these operations has been generated. This model is presented in Figure 6-13.

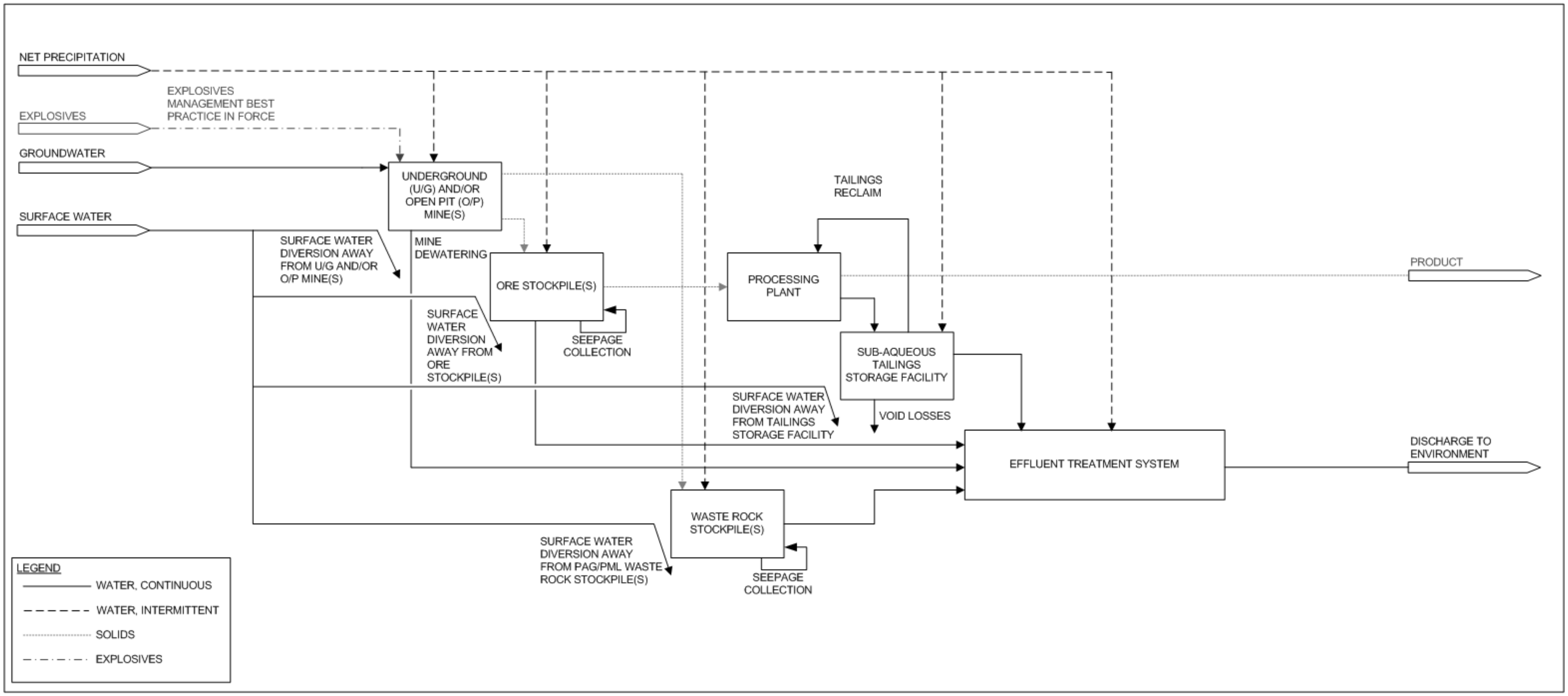

Figure 6-13: Base Metal Subsector Water Management Model

6.1.5.2 *Model Effluent Treatment System Process Flow Diagram*

Because a wide variety of technologies are employed by base metal operations for effluent treatment, the first step in establishing a model effluent treatment system was to establish what technologies are most frequently employed. From this narrowed list of technologies, the relative frequency of use of the technologies was examined and a typical effluent treatment system for base metal operations was established.

Figure 6-14 illustrates the relative frequency of use of the treatment technologies used at 43 base metal operations.

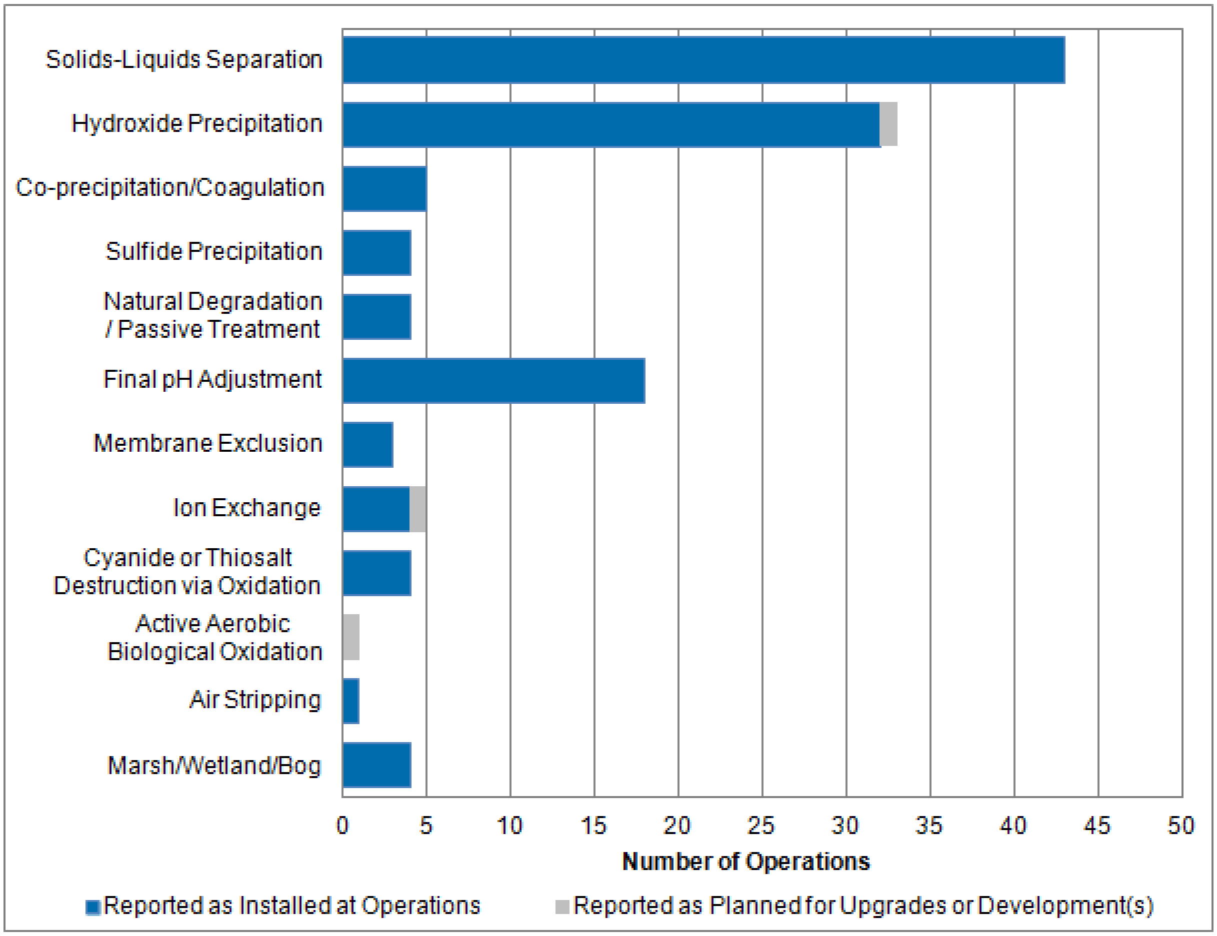

Figure 6-14: Relative Frequency of Use of Effluent Treatment Technologies at Base Metal Operations (43 Operations)

From Figure 6-14, it is apparent that the majority of base metal operations employ hydroxide precipitation, solid/liquid separation, and final pH adjustment. The other technologies identified are each used at five or fewer operations; these technologies are therefore not considered typical of the effluent treatment systems employed at base metal operations.

The relative frequency of use of the variations of common technologies utilized in effluent treatment systems by the base metal subsector for 49 effluent treatment systems are presented in Figure 6-15.

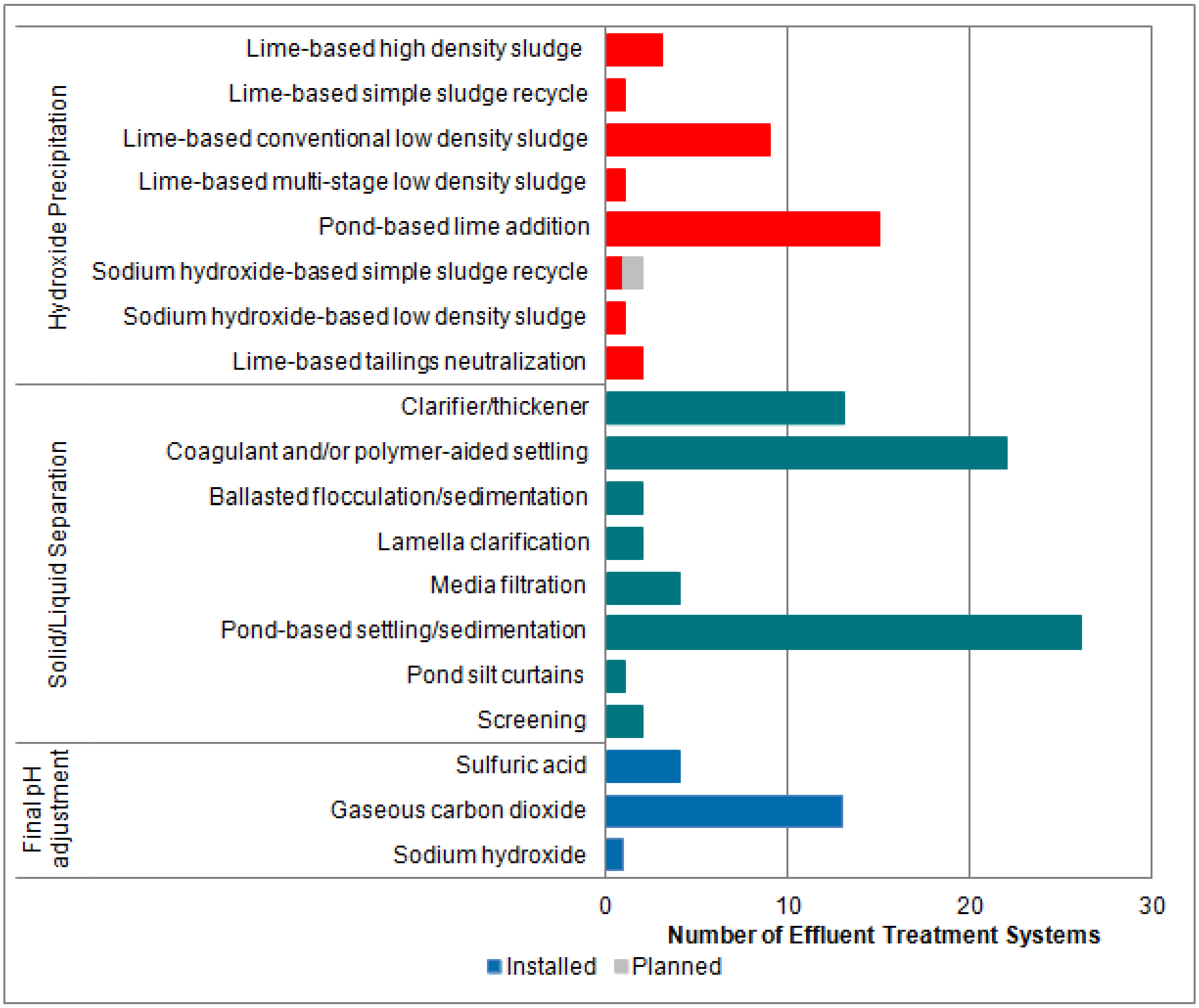

Figure 6-15: Relative Frequency of Use of Hydroxide Precipitation, Solid/Liquid Separation, and Final pH Adjustment Technologies at Base Metal Operations[11] (49 Effluent Treatment Systems)

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[11] NB: Some effluent management and treatment systems employ more than one technique.

The most frequently used hydroxide precipitation technique is pond-based lime addition, followed closely by conventional lime-based low density sludge hydroxide precipitation. Three of the effluent treatment systems reflected in the counts in Figure 6-15 use both pond-based and a reactor-based treatment step (either hydroxide or sulfide precipitation). In total, 12 operations use only pond-based lime precipitation. By contrast, 9 operations employ conventional low density sludge lime hydroxide precipitation. Though the number of operations employing pond-based lime hydroxide precipitation and reactor-based lime hydroxide precipitation is comparable, by this analysis the most common technique used by the operations reviewed for this study is pond-based lime hydroxide precipitation.

- From Figure 6-15, it is also apparent that the most commonly employed solid/liquid separation step is pond settling with the aid of coagulant and flocculant. pH is most often adjusted by gaseous carbon dioxide prior to discharge to reduce the pH to within *MMER* limits (6.0 to 9.5).
- The selected model effluent treatment system is a lime-based hydroxide precipitation process, utilizing coagulant and flocculant to aid pond-based settling/sedimentation, and pH adjustment at the end of the process via carbon dioxide addition. It is acknowledged that though by the analysis presented in this section, this technology is considered the most common, it nonetheless only represents a quarter of the operations reviewed in this study, largely due to the wide variety of technologies utilized by base metal operations.
- To establish the details of the model treatment system, those operations utilizing pond-based hydroxide precipitation were reviewed, to identify:
- The number of ponds employed in the treatment process.
- The location of lime, flocculant and coagulant addition.
- The design, average and maximum flow rates/volumes that pond systems treat.

Based on these considerations, the model effluent treatment system was established as the process illustrated in Figure 6-16. In this model, effluent is treated via hydroxide precipitation and bulk TSS removal via pond-based settling. The lime addition/holding/settling pond(s) also allows time for passive natural degradation of ammonia. The effluent is dosed with coagulant and flocculant before precipitates and TSS are then allowed to settle in the settling pond. Pond decant is pH adjusted with carbon dioxide to meet *MMER* pH limits and/or un-ionized ammonia/toxicity requirements prior to discharge to the environment.

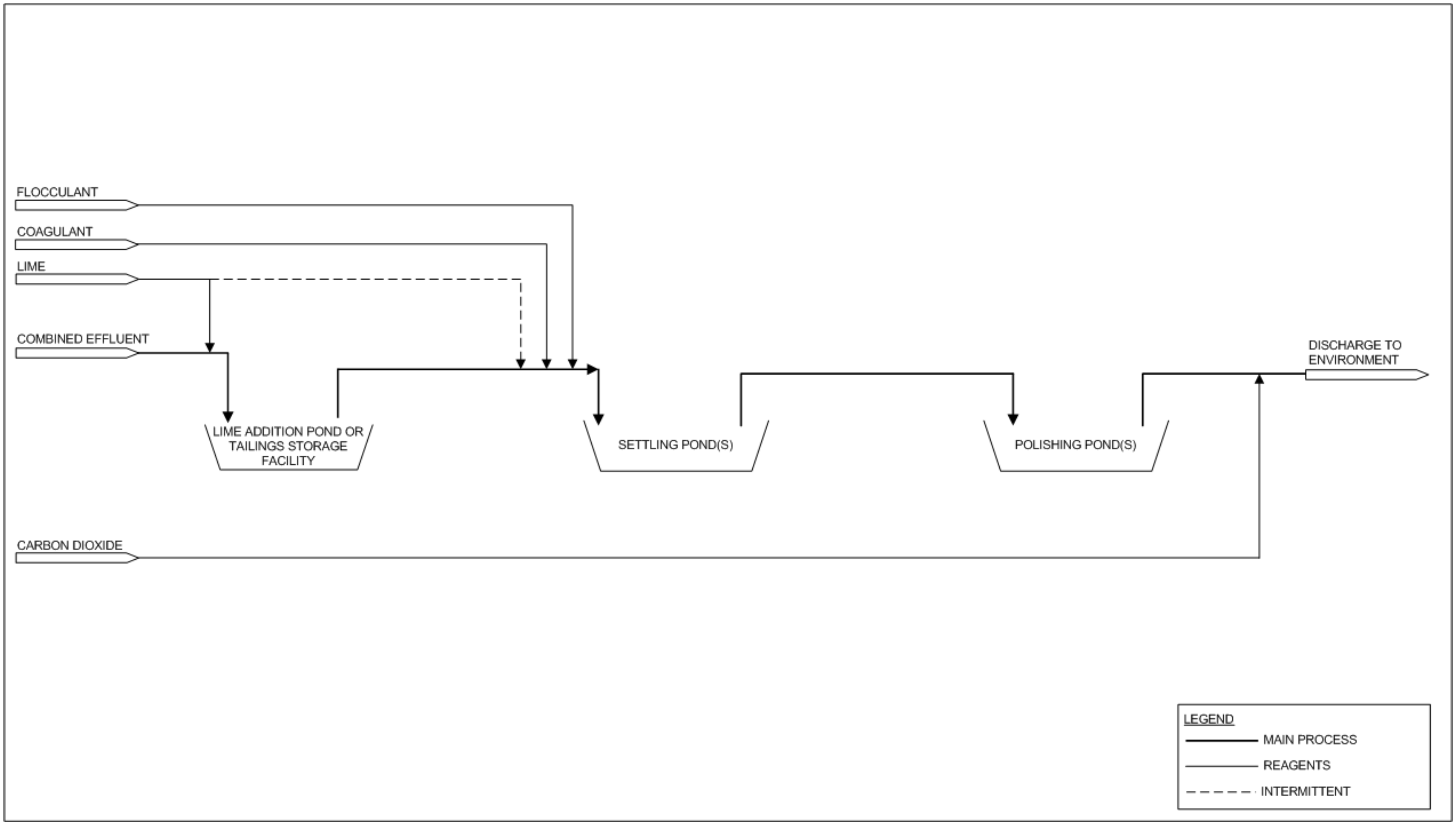

Figure 6-16: Base Metal Subsector Model Effluent Treatment Process

6.1.5.3 *Model Effluent Treatment System Flow Rate*

For Revision 0 of this report, to establish a flow rate for the model effluent treatment system, two sources of treatment system flow rate and discharge volume information were used:

- Final discharge point flow rates reported to Environment Canada as part of *MMER* reporting for 2008 – 2010 (the analysis of which generated data set “A” in Table 6-8), and
- Average and design flow rates for effluent treatment systems reported by questionnaire respondents (the analysis of which generated data sets “B” and “C”, respectively in Table 6-8).

The Environment Canada *MMER* reported data set is a complete set of monthly discharge volumes for all mines subject to *MMER* during 2008 – 2010, and thus is a valuable data source as it provides several years of discharge volumes, and additionally, data for those operations that did not participate in the study questionnaire. This data set, however, presents total discharge volumes from operations to the environment at the final discharge point(s) from the site and does not necessarily reflect the volume of water treated prior to discharge, nor the design capacities of effluent treatment systems, which are of significance when considering the costs of modifications/augmentations to effluent treatment systems.

The discharge volumes reported to Environment Canada may differ from the treated volumes as they may include incident precipitation to ponds downstream of effluent treatment systems or streams that do not require treatment. Nonetheless, due to the completeness of this data set compared to the data received via the questionnaire, in terms of time span of data collection and operation participation, it was considered valuable in the selection of a typical design flow rate. This monthly reported data was used to calculate the total annual discharge volume from operations, from which rough average annual hourly flow rates were calculated assuming continuous discharge (24 hours/day, 365 days/year). These values are presented later in Table 6-8. This approach may not accurately represent flow rates treated by effluent treatment systems for the following reasons:

- This approach summed the discharge volumes from all final discharge points associated with an operation; for sites with multiple final discharge points, this approach overestimates the total volume requiring treatment by any one treatment system; however, if all final discharge points at an operation were to require augmentation of their effluent treatment systems, this may be representative of the total sum of the capacities of augmentative technologies for a single operation.
- This approach may account for volume that is not actively treated in an effluent treatment system (e.g., accounts for volumes treated only by settling ponds).
- This approach assumes that treatment occurs 365 days a year, for 24 hours a day. This approach could underestimate the treatment system flow rates for those sites that only treat for a portion of the year (e.g., in summer only) or day (e.g., during day shift only).

The second source of data reviewed in the process of establishing the model treatment system was treatment flow rate data provided via the Revision 0 operations questionnaire. As part of the questionnaire, operations were prompted to provide the average, design, maximum and minimum treatment flow rates for their effluent treatment systems. This data set is limited to those operations that provided this information as part of their questionnaire responses, and is thus a less complete data set as compared to the Environment Canada *MMER* reported discharges volumes. However, this data set is a valuable source of information concerning design capacities of treatment technologies, which are not apparent from reported discharge volumes. The average flow rates reported via the questionnaire were used to informally cross-check the questionnaire-reported values against the Environment Canada *MMER* reported values, and the design flow rates are used in the consideration of the typical effluent treatment system design flow rate, or the equipment capacity that would need to be installed for new equipment.

Following the release of Revision 0, two additional sources of treatment system flow rate and discharge volume information were available for review. These sources of treatment system flow rate and discharge volume information and the analysis performed on them are summarized below:

- Environment Canada provided monthly flow rate data reported through *MMER* for 2005 – 2012. The methodology undertaken by Environment Canada to analyze this flow rate data was as follows:
    - To generate approximate average hourly discharge volumes, Environment Canada analyzed the data by calculating the average daily flow rates by month for each discharge point reporting to *MMER*, then assuming that discharge occurs over 24 hours a day. This method identifies the average discharge flow rate from each site based on seven years of Schedule 4 data (this analysis generated data set “D” in Table 6-8).
    - To generate approximate maximum hourly discharge volumes for the highest monthly discharge, Environment Canada analyzed the data by first identifying the highest monthly discharge volume for each discharge point reporting to *MMER*, then assuming that discharge occurs continuously over the whole month, for 24 hours a day. This method identifies an approximate hourly discharge flow rate for the highest monthly discharge from each site based on seven years of Schedule 4 data (this analysis generated data set “E” in Table 6-8).
    - The approaches described above may not accurately represent flow rates treated by effluent treatment systems as they assume that treatment occurs over the entire month, for 24 hours a day. This approach could underestimate the treatment system flow rates for those sites that only treat for a portion of the year (e.g., in summer only) or day (e.g., during day shift only).
- The MEND Report 3.43.1, Review of Mine Drainage and Sludge Management Operations, contains all data collected by the survey associated with the report, including operation subsector classifications and maximum, average and minimum treatment flow rates (1). Treatment system flow rate data are included for 25 Canadian base metal operations (the analysis of which generated data sets “F” and “G”).

The range, average and median values for the data sets described above are presented in Table 6-8. In selecting a flow rate for the typical model effluent treatment system based on the flow rate statistics in Table 6-8, greater consideration was given to the reported design flow rates, as opposed to average flow rates, as design values reflect the installed capacity required to accommodate design events (e.g., years with higher precipitation or extreme precipitation events) to avoid uncontrolled discharge and bypassing or short-circuiting of effluent treatment systems. These values are expected to be more representative of the installed capacities required of additional technology installed to augment existing systems.

Table 6-8: Summary of Reviewed Discharge and Treatment Flow Rates for the Base Metal Subsector

Data Set		Methodology	Range (m^3/h)	Average (m^3/h)	Median (m^3/h)
Data Sets Informing Selection of Nominal Model Effluent Treatment System Flow Rates					
A	**Estimated Average Annual Hourly Discharge Volume: Sum of All Final Discharge Points per Site**	Annual discharge volumes for each final discharge point and each site were calculated (based on the sum of annual discharge volumes at all final discharge points) utilizing Schedule 4 reported monthly discharge volumes as reported by operations to Environment Canada. The maximum, minimum, average and median annual site discharge volumes were then calculated, assuming discharge continuously over 365 days a year and 24 hours a day to generate hourly maximum, minimum, average and median flow rates.	3 – 8,010	863	256
B	**Questionnaire Reported Average Treatment System Flow Rate**	The average treatment flow rate volumes provided by operations via the operations questionnaire were used to calculated maximum, minimum, average and median values.	7 – 5,100	870	560
D	**EC Analysis: Estimated Average Hourly Flows per Final Discharge Point**	Schedule 4 monthly flow volume data reported to Environment Canada from 2005 – 2012 was used to calculate an average daily discharge volume for each final discharge point. It was assumed that treatment and discharge occurred continuously over 24 hours per day. Maximum, minimum, average and median values were then calculated for the approximate hourly flow rates determined in this fashion.	1 – 6,475	487	76
F	**MEND Report 3.43.1 AMD Database (Appendix D): Average Flow Rates**	Maximum, minimum, average and median values were calculated for the average treatment system flow rates reported for all Canadian Base Metal in the AMD Database. This includes 27 operations that reported that they treat effluent prior to discharge; both operating and closed sites were included in this evaluation. No indication of whether the operations are subject to *MMER* was included in this database.	4.1 – 5,481	681	394.5
Data Sets Informing Selection of Design Model Effluent Treatment System Flow Rates					
C	**Questionnaire Reported Design/Maximum Treatment System Flow Rate**	Operations were prompted for their design and maximum treatment flow rates as part of the operations questionnaire. The maximum of these two numbers was used to generate a data set for the maximum/design treatment values for the subsector. Maximum, minimum, average and median values were then calculated for the subsector data set.	20 – 19,790	2,230	600

Data Set		Methodology	Range (m^3/h)	Average (m^3/h)	Median (m^3/h)
E	**EC Analysis: Estimated Average Max Hourly Flows per Final Discharge Point**	Schedule 4 monthly flow volume data reported to Environment Canada from 2005 – 2012 was used to calculate a maximum monthly discharge volume for each final discharge point. It was assumed that treatment and discharge occurred continuously over the entire month to generate approximate maximum hourly discharge volumes. Maximum, minimum, average and median values were then calculated for the hourly flow rates determined in this fashion.	2 – 11,379	1,135	264
G	**MEND Report 3.43.1 AMD Database (Appendix D): Maximum Flow Rates**	Maximum, minimum, average and median values were calculated for the maximum treatment system flow rates reported for all Canadian Base Metal in the AMD Database. This includes 27 operations that reported that they treat effluent prior to discharge; both operating and closed sites were included in this evaluation. No indication of whether the operations are subject to *MMER* was included in this database.	4.3 – 9,458	1,457	942

In Revision 0, data sets “A”, “B” and “C” in Table 6-8 were considered in determining the nominal and design flow rates for the model effluent treatment system. The average value of the reported average treatment system rates (870 m^3/h, data set “B”) was in accordance with the *MMER* reported data (863 m^3/h, data set “A”). The selected value for the design capacity of the base metal subsector model effluent treatment system was 2,000 m^3/h. This value was utilized for capital cost estimating for system augmentation. The selected value for the nominal flow rate of the base metal model effluent treatment system was 870 m^3/h, based on the *MMER* reported data (data set “A”) and the questionnaire reported data (data set “B”). This value was utilized for operating cost estimating for system augmentation.

In Revision 1, data sets “D” and “F” were considered in addition to data sets “A”, “B” to review the nominal model effluent treatment system flow rates utilized in Revision 0.

Data set “D”, based on Environment Canada’s analysis of Schedule 4 flow rate data from 2005 – 2012, provides an alternate approach to selecting a nominal treatment flow rate for the model effluent treatment system, as it identifies the average daily discharge for each final discharge point and from this generates an approximate average hourly flow rate volume. The average volume calculated by this method (487 m^3/h) is lower than the nominal value used in Revision 0 (870 m^3/h, data set “B”) and the average of the reported nominal flow rates in the operations questionnaire (863 m^3/h, data set “A”).

Data set “F” is based on the average treatment system flow rates from the AMD Database (Appendix D) of MEND report 3.43.1. The values in this database are from 27 anonymous base metal operations, eight (8) that are operating and nineteen (19) that are closed. The average treatment system flow rate based on this data set (681 m^3/h) is somewhat lower than the nominal value used in Revision 0 (870 m^3/h, data set “B”) and the average of the reported nominal flow rates in the operations questionnaire (863 m^3/h, data set “A”).

There is some variability between the average treatment flow rates that could be used for the model effluent treatment system by the analysis of these four data sets, ranging between 500 m^3/h and 900 m^3/h. However, the impact to cost estimates for augmentative technologies is expected to fall within the estimate accuracy (e.g., +/-50%) of Revision 0 estimates, and there is no anticipated impact on BATEA selection if a midrange value of the data set averages was used as the model effluent treatment system treatment average flow rate. Therefore, for Revision 1, the average treatment system flow rate remains 870 m^3/h and is used for operating cost estimates for augmentative technologies.

In Revision 1, data sets “E”, and “F” were considered in addition to data set “C” to review the design model effluent treatment system flow rates utilized in Revision 0.

Data set “E”, based on Environment Canada’s analysis of Schedule 4 flow rate data from 2005 – 2012, provides an alternate approach to selecting a design treatment flow rate for the model effluent treatment system, as it identifies the maximum volume discharged from each final discharge point over seven years of data and generates an approximate maximum hourly discharge volume from the data. The average of this data set (1,135 m^3/h) is lower than the average of the reported design flow rates via the operations questionnaire (2,230 m^3/h, data set “C”).

Data set “F” is based on the maximum treatment system flow rates from the AMD Database (Appendix D) of MEND Report 3.43.1. The values in this database are from 27 anonymous base metal operations, eight that are operating and nineteen that are closed. The maximum treatment system flow rate based on this data set (1,457 m^3/h) is somewhat lower than the design value used in Revision 0 (2,000 m^3/h).

The difference between the values established by Environment Canada based on maximum monthly discharge volumes, and those reported by operations (to support MEND Report 3.43.1 and this report) could be due to the possibility that self-reported data could be more representative of sites with larger effluent treatment system capacities, if these operations submitted completed questionnaires while operations with smaller effluent treatment system capacities did not. The differences could also be due to the possibility that effluent treatment systems are designed and installed with a capacity capable of handling extreme precipitation events, and that the volumes associated with extreme precipitation events that are not reflected in Schedule 4 data (e.g., probable maximum precipitation events or extreme wet years). It is ultimately unknown whether the seven years of Schedule 4 data accurately reflect treatment flow rates required for extreme precipitation events or wet years for base metal operations. Additionally, it is possible that effluent treatment systems do not operate 24 hours a day over the entire month.

Given the uncertainties associated with design values generated by analysis of each of the data sets, there is no clear indication that one value is more representative of base metal operations than the others. Additionally, the impact to cost estimates as a result of lowering the design flow rate for the model effluent treatment system to a mid-range value of the average values from each data set is expected to be within the estimate accuracies (+/-50%), and no impact on BATEA selection is anticipated. Therefore, for Revision 1, the design flow rate remains 2,000 m^3/h and is used for estimating additional equipment and installation costs associated with augmentative technologies.

6.1.5.4 Model Effluent Treatment System Effluent Quality

In Revision 0 of this report, the 95th percentile of the treated effluent quality for the entire base metal subsector for each parameter (as summarized in Table 6-7) was used to represent the effluent quality that was produced by the model effluent treatment system. It was assumed that for each parameter, the 95th percentile would reflect the concentration in treated effluent at the majority of sites and that the 95th percentile value associated with the complete data set would be weighted to reflect the most common effluent treatment technologies (and therefore the model effluent treatment system), as the most common effluent treatment systems would contribute a larger fraction of the concentration values than other systems.

Feedback received from industry indicated two main concerns with the use of 95th percentile values as representative of the model effluent treatment system, as follows:

1. The total cohort of final discharge effluent quality data for the subsector originates from a variety of effluent treatment systems, and not just systems very similar or equivalent to the model effluent treatment system. This could skew the 95th percentile values, as other types of effluent treatment systems may achieve higher or lower concentrations than the model. Thus, using the total cohort of final discharge effluent quality data for the

subsector may not be representative of the concentrations specifically achieved by the model effluent treatment system.

2. Using the total cohort of final discharge effluent quality data for the subsector may result in average and 95th percentile values that are skewed low by the inclusion of concentration data from effluent treatment systems that do not target or remove a given parameter (i.e., where the concentration of a given parameter in untreated effluent is compliant with existing *MMER* without treatment). Using the total cohort of final discharge effluent quality data does not consider which concentration values reflect concentrations achievable by treatment, and thus, may not be representative of the concentration achieved by any given treatment system.

To better reflect the concentrations achieved by subsector effluent treatment systems similar or equivalent to the model effluent treatment system for systems that target the removal of the parameters in question, Hatch compared concentration statistics for subsets of Schedule 4 and Schedule 5 data. The subsets were organized according to type of effluent treatment system and targeted parameters. Effluent treatment system information was collected during Revision 0 work via questionnaire and independent research, and augmented with additional data collected during Revision 1 work. The purpose of this effort was to narrow the total cohort of final discharge effluent quality data down to the concentration values that are more representative of concentrations achieved by systems similar to the model effluent treatment system. 1

Two types of effluent treatment systems utilized by base metal subsector operations were of interest for this analysis: systems similar to the model effluent treatment system (referred to as “model effluent treatment systems”) and systems that are not exactly like the model effluent treatment system but utilize a process that can achieve similar effluent quality to model effluent treatment systems (referred to “model equivalent effluent treatment systems”). For the base metal subsector, these types of treatment systems are defined as follows:

- **Model Effluent Treatment Systems**: Pond-based lime hydroxide precipitation system where lime addition is followed by settling in a pond.
- **Model Equivalent Effluent Treatment Systems:** Lime hydroxide precipitation systems including low density sludge systems, high density sludge systems, reactor/pond based lime systems, batch lime additions, etc.

For the base metal subsector, the critical parameters for which concentration statistics were developed were arsenic, copper, lead, nickel, zinc, radium-226, total suspended solids (TSS), aluminum, iron, selenium and total ammonia. Cyanide was not reviewed as this parameter is typically not a concern in effluent at base metal operations. Also, pH was not reviewed as pH adjustment systems are well defined for this subsector. For each of these parameters, treated effluent quality statistics have been developed for the subsets of the total cohort, according to:

1. Model effluent treatment systems.
2. Model effluent treatment systems and model equivalent effluent treatment systems.
3. Effluent treatment systems that target the parameter.

4. Model effluent treatment systems that target the parameter.
5. Model effluent treatment systems and model equivalent effluent treatment systems that target the parameter.

Effluent treatment systems targeting parameters were identified per self-reporting by operations via the Revision 0 questionnaire and the Revision 1 mini-survey; this self-reported information was confirmed to the extent possible using paired untreated effluent and treated effluent quality data provided by operations where available. Where information provided in the Revision 0 questionnaire differed from the information provided in the Revision 1 questionnaire, the operation was contacted to ensure a correct understanding of the information.

A comparison between the concentration statistics for each subset of data was performed to assess the extent to which the utilization of the total cohort of base metal subsector effluent quality data may skew the concentration statistics in comparison to data associated with model or model equivalent effluent treatment systems that target the parameter. The number of final discharge points associated with each data set is also provided. As the 95th percentile values are used in augmentative BAT cost estimation and BATEA selection later in this report, the agreement between the data subsets for this statistic (95th percentile) is considered more heavily than the other concentration statistics (minimum, average and maximum). For each parameter, a final model effluent treatment system effluent concentration is estimated based on this assessment.

6.1.5.4.1 Arsenic

For the base metal subsector, Table 6-9 summarizes the arsenic effluent concentration statistics for data subsets analyzed. Observations on these statistics and conclusions for the base metal subsector are summarized below.

Table 6-9: Arsenic Concentration Statistics for the Base Metal Subsector

	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00005	0.003	0.020	0.061	76
Model(s)	0.00025	0.003	0.008	0.033	13
Model(s) and Model Equivalent(s)	0.00025	0.004	0.020	0.035	27
Self-Identified as Targeting	0.00025	0.003	0.009	0.036	10
Model(s) that Self-Identify as Targeting	0.00025	0.003	0.008	0.019	3
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.00025	0.002	0.008	0.019	5

- Operations that self-indented as treating for arsenic and utilize model or model equivalent treatment systems have similar average effluent concentrations to the total cohort but much lower 95th percentile concentrations than the total cohort.
- The arsenic concentration achieved by effluent treatment systems similar to or equivalent to the model effluent treatment system (based on the 95th percentile) is estimated to be <0.01 mg/L.

6.1.5.4.2 Copper

For the base metal subsector, Table 6-10 summarizes the copper effluent concentration statistics for data subsets analyzed. Observations on these statistics and conclusions for the base metal subsector are summarized below.

Table 6-10: Copper Concentration Statistics for the Base Metal Subsector

	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00008	0.020	0.06	4.2	76
Model(s)	0.0003	0.008	0.02	0.07	13
Model(s) and Model Equivalent(s)	0.0003	0.018	0.06	0.29	27
Self-Identified as Targeting	0.0003	0.021	0.06	0.29	22
Model(s) that Self-Identify as Targeting	0.0030	0.007	0.01	0.03	3
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.0010	0.026	0.19	0.29	7

- Operations that self-indented as treating for copper and utilize model or model equivalent treatment systems have higher 95th percentile concentrations than the other data subsets. Further review of the data indicates that the 95th percentile of this data subset is significantly higher due to the inclusion of one operation which has higher relative copper concentrations.

- The copper concentration achieved by effluent treatment systems similar to or equivalent to the model effluent treatment system (based on the 95th percentile) is estimated to be <0.06 mg/L.

6.1.5.4.3 Lead

For the base metal subsector, Table 6-11 summarizes the lead effluent concentration statistics for the data subsets analyzed. Observations on these statistics and conclusions for the base metal subsector are summarized below.

Table 6-11: Lead Concentration Statistics for the Base Metal Subsector

	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00002	0.005	0.015	0.200	76
Model(s)	0.00006	0.004	0.015	0.043	13
Model(s) and Model Equivalent(s)	0.00003	0.007	0.015	0.043	27
Self-Identified as Targeting	0.00010	0.007	0.015	0.200	11
Model(s) that Self-Identify as Targeting	0.00010	0.002	0.004	0.015	4
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.00010	0.003	0.008	0.016	6

- The 95th percentile concentrations calculated for the total cohort, the operations using the exact model, the operations using the model and model equivalent(s) and the operations targeting lead for removal regardless of treatment systems are the same.
- Operations that self-identified as treating for lead and utilize model or model equivalent treatment systems have 95th percentile concentrations 2 to 3 times lower than the other data subsets.
- The lead concentration achieved by effluent treatment systems similar to or equivalent to the model effluent treatment system (based on the 95th percentile) is estimated to be <0.015 mg/L.

6.1.5.4.4 Nickel

For the base metal subsector, Table 6-12 summarizes the nickel effluent concentration statistics for the data subsets analyzed. Observations on these statistics and conclusions for the base metal subsector are summarized below.

Table 6-12: Nickel Concentration Statistics for the Base Metal Subsector

	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00025	0.091	0.38	14.7	76
Model(s)	0.00025	0.067	0.29	1.0	13
Model(s) and Model Equivalent(s)	0.00025	0.076	0.32	1.0	27
Self-Identified as Targeting	0.00042	0.123	0.36	0.68	20
Model(s) that Self-Identify as Targeting	0.00100	0.077	0.31	0.46	4
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.00042	0.087	0.33	0.53	9

- The statistics calculated for the operations using the exact model and the operations using the model and model equivalent are very similar to the average and 95th percentile concentrations of the total cohort.

- Operations that self-identified as treating for nickel and utilize model or model equivalent treatment systems have 95th percentile concentrations very similar to the other data subsets.

- The nickel concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on the 95th percentile) is estimated to be <0.36 mg/L.

6.1.5.4.5 Zinc

For the base metal subsector, Table 6-13 summarizes the zinc effluent concentration statistics for the data subsets analyzed. Observations on these statistics and conclusions for the base metal subsector are summarized below.

Table 6-13: Zinc Concentration Statistics for the Base Metal Subsector

	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.0001	0.06	0.25	17.5	76
Model(s)	0.0001	0.06	0.26	0.62	13
Model(s) and Model Equivalent(s)	0.0001	0.08	0.31	0.62	27
Self-Identified as Targeting	0.0001	0.10	0.32	0.62	16
Model(s) that Self-Identify as Targeting	0.0001	0.05	0.20	0.62	6
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.0001	0.08	0.31	0.62	10

- The statistics calculated for the operations using the exact model and the operations using the model and model equivalent are very similar to the average and 95th percentile concentrations of the total cohort.
- Operations that self-identified as treating for zinc and utilize model or model equivalent treatment systems have 95th percentile concentrations very similar to the other data subsets.
- The zinc concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on the 95th percentile) is estimated to be <0.30 mg/L.

6.1.5.4.6 Total Suspended Solids (TSS)

For the base metal subsector, Table 6-14 summarizes the TSS effluent concentration statistics for the data subsets analyzed. Observations on these statistics and conclusions for the base metal subsector are summarized below.

Table 6-14: TSS Concentration Statistics for the Base Metal Subsector

	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.01	4.3	13.0	106	76
Model(s)	0.11	2.1	5.9	22	13
Model(s) and Model Equivalent(s)	0.11	2.6	7.3	22	27
Self-Identified as Targeting	0.01	3.5	10.8	40	26
Model(s) that Self-Identify as Targeting	0.11	2.1	7.1	22	5
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.11	2.8	8.0	22	8

- The statistics calculated for the operations using the exact model and the operations using the model and model equivalent are slightly lower than the average and 95th percentile concentrations of the total cohort.

- Operations that self-identified as treating for TSS and utilize model or model equivalent treatment systems have 95th percentile concentrations very similar to the other data subsets.

- The TSS concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on the 95th percentile) is estimated to be <10 mg/L.

6.1.5.4.7 Radium-226

For the base metal subsector, Table 6-15 summarizes the radium-226 effluent concentration statistics for the data subsets analyzed. Observations on these statistics and conclusions for the base metal subsector are summarized below.

Table 6-15: Radium-226 Concentration Statistics for the Base Metal Subsector

	Minimum (Bq/L)	Average (Bq/L)	95th Percentile (Bq/L)	Maximum (Bq/L)	# of Final Discharge Points
All Data	0.0005	0.025	0.106	0.736	76
Model(s)	0.0005	0.008	0.026	0.070	13
Model(s) and Model Equivalent(s)	0.0005	0.021	0.100	0.300	27
Self-Identified as Targeting	0.0050	0.117	0.412	0.736	4
Model(s) that Self-Identify as Targeting	No data.				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	No data.				0

- The statistics calculated for the operations using the exact model and the operations using the model and model equivalent are slightly lower than the average and 95th percentile concentrations of the total cohort.
- There are no operations identified which use the exact model treatment system and self-identified as targeting or demonstrated that they remove radium-226. This was also the case for the operations that use the model or model equivalent.
- Of the operations that target for radium-226, the concentrations achieved are higher than the total cohort data, both the average concentration and the 95th percentile. The data appears to be skewed by one of the four operations which appears to have had problems with its system early in the period examined which were resolved by the end of the period examined. Removing this operation from the data set results in a 95th percentile of 0.2 Bq/L and an average 0.08 Bq/L for the operations that target radium-226.
- Radium-226 is not removed by the model effluent treatment system. However, the radium concentrations in the effluent from the model or equivalent to the model effluent treatment system (based on the 95th percentile) is estimated to be <0.11 Bq/L.

6.1.5.4.8 Aluminum

For the base metal subsector, Table 6-16 summarizes the aluminum effluent concentration statistics for the data subsets analyzed. Observations on these statistics and conclusions for the base metal subsector are summarized below.

Table 6-16: Aluminum Concentration Statistics for the Base Metal Subsector

	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00005	0.11	0.39	28.1	78
Model(s)	0.0005	0.09	0.39	0.93	13
Model(s) and Model Equivalent(s)	0.0005	0.09	0.34	2.1	27
Self-Identified as Targeting	0.0028	0.20	0.59	1.7	7
Model(s) that Self-Identify as Targeting	0.0028	0.22	0.79	0.93	3
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.0028	0.20	0.76	0.93	6

- The statistics calculated for the operations using the exact model and the operations using the model and model equivalent are similar to the average and 95th percentile concentrations of the total cohort.
- Operations that self-identified as treating for aluminum and utilize model or model equivalent treatment systems have 95th percentile concentrations almost double the other data subsets.
- The aluminum concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on the 95th percentile) is estimated to be <0.79 mg/L.

6.1.5.4.9 Iron

For the base metal subsector, Table 6-17 summarizes the iron effluent concentration statistics for the data subsets analyzed. Observations on these statistics and conclusions for the base metal subsector are summarized below.

Table 6-17: Iron Concentration Statistics for the Base Metal Subsector

	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.001	0.633	1.82	104	78
Model(s)	0.001	0.25	0.9	5.0	13
Model(s) and Model Equivalent(s)	0.001	0.25	0.9	5.0	27
Self-Identified as Targeting	0.001	0.27	2.0	5.0	17
Model(s) that Self-Identify as Targeting	0.001	0.35	1.1	5.0	8
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.001	0.28	1.0	5.0	15

- The statistics calculated for the operations using the exact model and the operations using the model and model equivalent are approximately half of the average and 95th percentile concentrations of the total cohort.
- Operations that self-identified as treating for iron and utilize model or model equivalent treatment systems have 95th percentile concentrations very similar to the other data subsets, with the exception of the total cohort data.
- The iron concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on the 95th percentile) is estimated to be <1.05 mg/L.

6.1.5.4.10 Total Ammonia (as Nitrogen)

For the base metal subsector, Table 6-18 summarizes the total ammonia effluent concentration statistics for the data subsets analyzed. Observations on these statistics and conclusions for the base metal subsector are summarized below.

Table 6-18: Total Ammonia Concentration Statistics for the Base Metal Subsector

	Minimum (mg-N/L)	Average (mg-N/L)	95th Percentile (mg-N/L)	Maximum (mg-N/L)	# of Final Discharge Points
All Data	0.0015	0.94	3.9	39.1	78
Model(s)	0.0100	0.7	2.9	5.1	13
Model(s) and Model Equivalent(s)	0.0015	1.0	4.2	8.1	27
Self-Identified as Targeting	0.0022	0.5	3.0	5.1	11
Model(s) that Self-Identify as Targeting	0.0250	1.2	4.0	5.1	3
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.0022	0.9	3.2	5.1	6

- The statistics calculated for the operations using the exact model and the operations using the model and model equivalent are similar to the average and 95th percentile concentrations of the total cohort.
- Operations that self-identified as treating for ammonia and utilize model or model equivalent treatment systems have average and 95th percentile concentrations very similar to the other data subsets.
- Total ammonia is not actively removed by the model effluent treatment system nor model equivalents. Some reduction in total ammonia concentrations may be achieved as ammonia may volatilize during the elevated pH step(s) (i.e., hydroxide precipitation) and/or naturally degrade in ponds
- Total ammonia concentrations in the effluent from the model or equivalent to the model effluent treatment systems (based on the 95th percentile) is estimated to be <4.0 mg-N/L.

6.1.5.4.11 Selenium

For the base metal subsector, Table 6-19 summarizes the selenium effluent concentration statistics for the data subsets analyzed. Observations on these statistics and conclusions for the base metal subsector are summarized below.

Table 6-19: Selenium Concentration Statistics for the Base Metal Subsector

	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00005	0.006	0.024	0.073	66
Model(s)	0.0004	0.011	0.037	0.059	12
Model(s) and Model Equivalent(s)	0.0001	0.009	0.029	0.073	24
Self-Identified as Targeting	0.0003	0.012	0.037	0.041	5
Model(s) that Self-Identify as Targeting	0.0032	0.018	0.039	0.041	3
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.0032	0.014	0.038	0.041	4

- The statistics calculated for the operations using the exact model and the operations using the model and model equivalent are slightly higher than the average and 95th percentile concentrations of the total cohort.
- Operations that self-identified as treating for ammonia and utilize model or model equivalent treatment systems have average and 95th percentile concentrations very similar to the other data subsets, with the exception of the entire cohort which has lower average and 95th percentile concentrations.
- The selenium concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on the 95th percentile) is estimated to be <0.04 mg/L.

6.1.5.4.12 Model Effluent Treatment System Effluent Concentration Summary

The 95th percentile concentrations achieved by model and model equivalent effluent treatment systems are summarized in Table 6-20. These will be used as representative of the concentrations produced by the model effluent treatment system for augmentative technology costing and BATEA selection.

Table 6-20: Concentrations Achieved by the Model Effluent Treatment System in the Base Metal Subsector

Parameter	Concentration
Arsenic	<0.01 mg/L
Copper	<0.06 mg/L
Lead	<0.015 mg/L
Nickel	<0.36 mg/L
Zinc	<0.30 mg/L
Radium-226	<0.11 Bq/L[12]
Cyanide	<0.05 mg/L[13]
TSS	<10 mg/L
Aluminum	<0.79 mg/L
Iron	<1.05 mg/L
Selenium	<0.04 mg/L
Total Ammonia (as nitrogen)	<4 mg-N/L[14]

6.2 Metals Sector: Precious Metal

Operating Canadian precious metal operations are at present subject to the current *Metal Mining Effluent Regulations,* and per Environment Canada's 10-Year Review of *Metal Mining Effluent Regulations*, would be subject to the proposed changes to *MMER* for metal mines. Precious metal operations subject to *MMER* have been identified by Environment Canada as being potentially impacted by the changes in discharge limits proposed for the parameters that are currently regulated (arsenic, copper, cyanide, lead, nickel and zinc), however analysis concerning the potential impact of the additional parameters (ammonia, iron, selenium) proposed by Environment Canada is not available.

Current Canadian precious metal operations are listed in Table 6-21. A total of 57 mine and mill operations were identified as relevant to this study. The review of the Canadian precious metal subsector for this study included a total of 40 precious metal mine operations, 31 of which began or completed questionnaires during the data collection portion of this study. Information for an additional 10 operations was collected from independent research efforts and from in-house information.

Effluent discharges from 37 of the operations reviewed are currently subject to the *Metal Mining Effluent Regulations*. Those operations that are not subject to *MMER* are either closed

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[12] Radium-226 is not removed by the model effluent treatment system. The radium concentration in the effluent from the model effluent treatment system is from Table 6-15.

[13] From Table 6-7 - Cyandie is typically not a concern in effluent at base metal operations.

[14] Total ammonia is not actively removed by the model effluent treatment system. The total ammonia concentration in the effluent from the model effluent treatment system is from Table 6-18.

sites, or were still development projects in 2012 changes to *MMER* status that may have occurred in 2013 have not been included.

Table 6-21: Canadian Precious Metal Operations

Operation	Owner/Operator	Location	Status
Barry Mine	Métanor Resources Inc.	Lebel-sur-Quévillon, QC	Suspended/Care and Maintenance
Beaufor Mine	Richmont Mines Ltd.	Val d'Or, QC	Producing
Bell Creek Mine-Mill	Lake Shore Gold Corporation	Porcupine, ON	Producing
Bellekeno Mine	Alexco Resource Corporation	Keno Hill, YT	Suspended/Care and Maintenance
Black Fox Mine-Mill Complex	Primero Gold Canada Inc.	Matheson, ON	Producing
Bralorne Gold Mine	Bralorne Gold Mines Ltd.	Pemberton, BC	Producing
Camflo Mill	Richmont Mines Ltd	Malartic, QC	Producing
Canadian Malartic Mine	Osisko Mining Corporation	Malartic, QC	Producing
Casa Berardi Mine	Hecla Mining	La Sarre, QC	Producing
Clavos Mine	St Andrew Goldfields Ltd.	Timmins, ON	Development/ Redevelopment
Con Mine	Newmont Canada Corporation	Yellowknife, YT	Closed
Detour Lake Mine	Detour Gold Corporation	Cochrane, ON	Producing
Doyon Mine	IAMGOLD Corporation	Cadillac, QC	Closed
Eagle River Complex	Wesdome Gold Mine Ltd.	Wawa, ON	Producing
Eleonore Project	Goldcorp Canada Ltd.	James Bay, QC	Development/ Redevelopment
Equity Silver Mine	Goldcorp Canada Ltd.	Houston, BC	Closed
Francoeur Mine	Richmont Mines Ltd.	Rouyn-Noranda, QC	Producing
Géant Dormant Mine	North American Palladium Ltd.	Amos, QC	Closed
Giant Mine	Indian and Northern Affairs Canada	Yellowknife, NT	Closed
Golden Giant Mine	Newmont Canada Corporation	Marathon, ON	Closed
Goldex Mine	Agnico-Eagle Mines Ltd	Val d'Or, QC	Development/ Redevelopment
Hemlo-William Mine	Barrick Gold Corporation	Marathon, ON	Producing
Hinge Mine	San Gold Corporation	Bissett, MB	Producing
Hislop Mine	St Andrew Goldfields Ltd.	Matheson, ON	Producing
Holloway Mine	St Andrew Goldfields Ltd.	Matheson, ON	Producing
Holt Mine-Mill	St Andrew Goldfields Ltd.	Matheson, ON	Producing
Island Gold Project	Richmont Mines Ltd.	Debreuville, ON	Producing
Jolu Mill	Golden Band Resources Inc.	Brabant Lake, SK	Suspended/Care and Maintenance
Kemess South	AuRico Gold Inc.	Smithers, BC	Closed

Operation	Owner/Operator	Location	Status
Mine			
Kiena Complex	Wesdome Gold Mine Ltd.	Val d'Or, QC	Suspended/Care and Maintenance
Lac Bachelor Mine	Métanor Resources Inc.	Desmaraisville, QC	Producing
Lac Herbin Mine and Aurbel Mill	QMX	Val d'Or, QC	Producing
Lapa Mine	Agnico-Eagle Mines Ltd.	Rivière-Héva, QC	Producing
LaRonde Mine	Agnico-Eagle Mines Ltd.	Rouyn-Noranda, QC	Producing
Lupin Operations	Lupin Mines Inc.	Cambridge Bay, NT	Closed
Macassa Mine	Kirkland Lake Gold Inc.	Kirkland Lake, ON	Producing
McAlpine Mill	SMC (Canada) Ltd.	Cobalt, ON	Producing
McGarry Mine	Armistice Resource Group	Kirkland Lake, ON	Producing
Meadowbank Mine	Agnico-Eagle Mines Ltd.	Baker Lake, NU	Producing
Mount Polley Mine	Imperial Metals Corporation	Williams Lake, BC	Producing
Mouska Mine	IAMGOLD Corporation	Cadillac, QC	Producing
Musselwhite Mine	Goldcorp Canada Ltd.	Pickle Lake, ON	Producing
Nugget Pond Mine	Rambler Metals and Mining Canada Ltd.	Snook's Arm, NL	Producing
Phoenix Project	Rubicon Minerals	Red Lake, ON	Development/ Redevelopment
Pine Cove Gold Mine	Anaconda Mining Inc	Baie Verte, NL	Producing
Porcupine Mine	Goldcorp Canada Ltd.	South Porcupine, ON	Producing
QR Mine-Mill	Barkerville Gold Mines Ltd.	Quesnel, BC	Producing
Red Lake Gold Mines	Goldcorp Canada Ltd.	Red Lake, ON	Producing
Rice Lake Gold Mine	San Gold Corporation	Balmertown, ON	Producing
Seabee and Santoy 8 Complex	Claude Resources Inc.	La Ronge, SK	Producing
Sigma-Lamaque Mine	White Tiger Gold Ltd.	Val d'Or, QC	Closed
Silvana Mine	Klondike Silver	Nelson, BC	Producing
Snow Lake Mine	QMX	Snow Lake, MB	Suspended/Care and Maintenance
Timmins West Complex	Lake Shore Gold Corporation	Timmins, ON	Producing
Vezza Mine	North American Palladium Ltd.	Matagami, QC	Producing
Yellowjacket Gold Mine	Eagle Plains Resources Ltd.	Atlin, BC	Development/ Redevelopment
Young-Davidson Mine	AuRico Gold Inc.	Kirkland Lake, ON	Producing

The most common primary commodities produced by Canadian precious metal mines, mills and smelters reviewed are gold and silver. A summary of the primary and secondary commodities mined or processed by the operations reviewed in this study and the number of operations producing these commodities is presented in Figure 6-17.

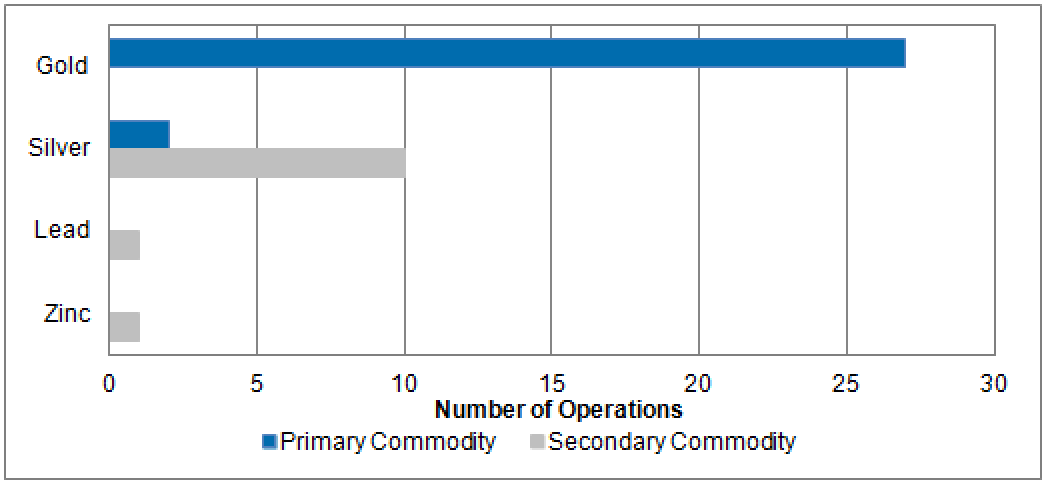

Figure 6-17: Primary and Secondary Commodities Produced by Precious Metal Operations

Precious metal operations are dispersed across Canada, though often found in clusters surrounding mineral deposits regions. The operations reviewed in this study are located in British Columbia, Newfoundland and Labrador, the Northwest Territories, Nunavut, Ontario, Quebec and Saskatchewan. Figure 6-18 illustrates the geographic distribution of the precious metal subsector operations.

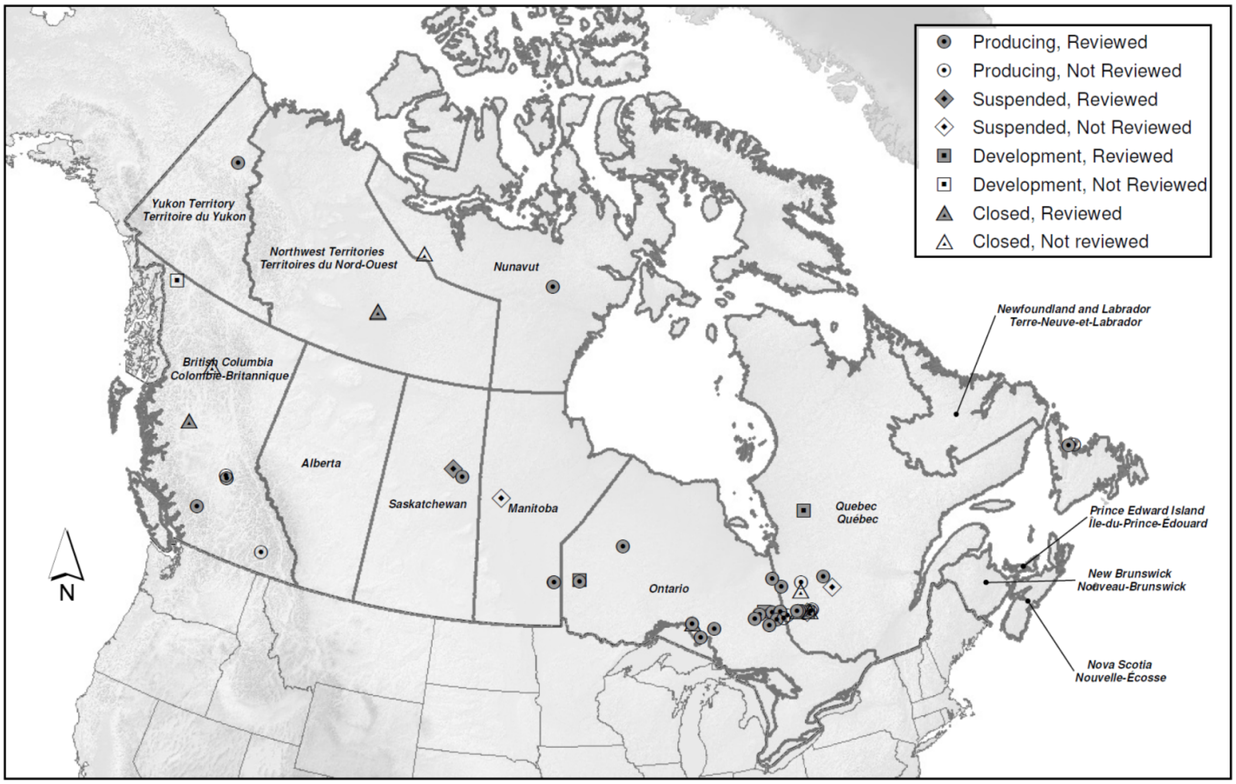

Figure 6-18: Geographic Distribution of Precious Metal Subsector Operations

Figure 6-19 illustrates the status of the precious metal operations reviewed in this study. The majority of operations reviewed are in production.

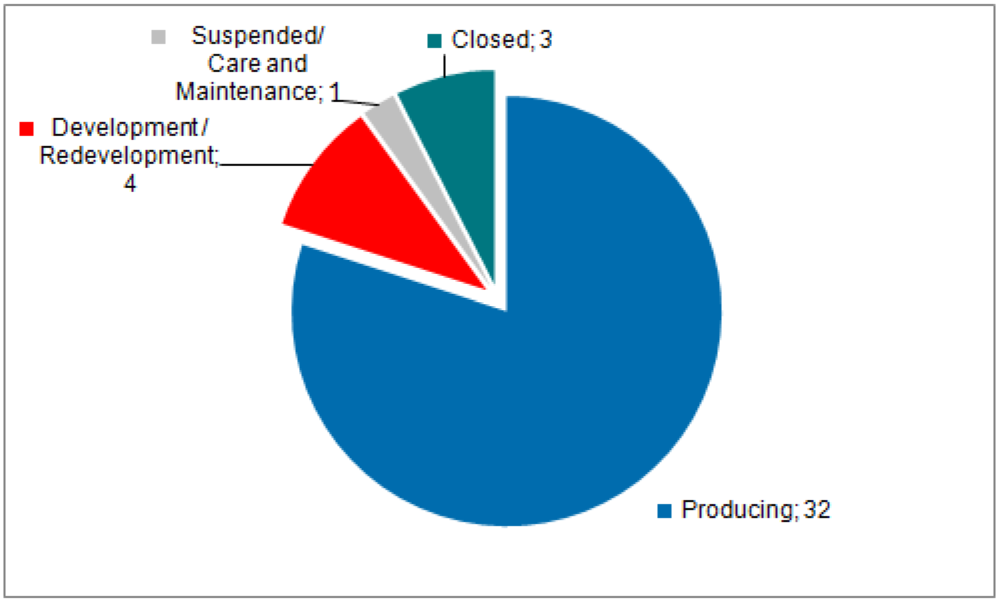

Figure 6-19: Status of Operations Reviewed for the Precious Metal Subsector

6.2.1 *Effluent Characteristics*

In general, it is expected that the quality of effluent generated by any operation will be variable based on site-specific factors, including, but not limited to mine, mill and waste management facilities present on site, the operating status of the site (e.g., closed, producing, etc.), and the mineralogy of the ore and waste rock. However, it is also expected that given the common target element for extraction from these operations, and common ore processing steps, effluent at precious mine and mills will share some similarities.

Table 6-22 summarizes factors that can influence untreated effluent quality at precious metal operations.

Table 6-22: Factors Influencing Precious Metal Subsector Untreated Effluent Quality

Ore and Waste Rock Mineralization	Mine and Mill Operational Status and Facilities	Precious Metal (Gold and Silver) Processing
The ore and waste rock mineralization at precious metal operations is variable. The ore bodies at many of the operations reviewed are associated with sulfidic and metallic mineralizations, and mine wastes at these operations exhibit some degree of acid generation and metal leaching tendencies.	Mine and mill facilities appear in various configurations at precious metal operations reviewed in this study. Operational status of facilities is also variable. Mining is typically from open pit or underground. The mine and mill facility configurations and operational statuses of the sites reviewed include: • Operating mines with associated waste rock management facilities but no milling or tailings management facilities. • Operating and suspended mine and mill/concentrator sites with waste rock and tailings management facilities. • Operating mill sites with tailings management facilities but no mining operations or waste rock management facilities. • Closed mine sites with no active mining or processing, but continued waste rock and tailings management activities.	Concentrator/Mill • Water applied for ore stockpiles dust suppression can result in TSS generation • Ore grinding and size reduction can result in TSS generation and contaminant metal liberation • Froth flotation chemicals, including cyanide, can impact site water quality Pressure Oxidation • Liberation of metals • Sulfuric acid generation • Acid neutralization by lime addition and gypsum precipitation Leaching • Leaching reagents – acid, sodium cyanide, thiosulfate • Cyanide destruction – copper sulfate reagent, residual cyanide, cyanate/ammonia.

To establish what contaminants of concern are typically found in untreated effluent at precious metal operations, parameters included in discharge permits, parameters reported as targeted by effluent treatment processes by questionnaire respondents and parameters reported in untreated effluent data by questionnaire respondents were considered. Figure 6-20 demonstrates the relative frequency of each parameter that appears in effluent discharge permits or is targeted by effluent treatment processes.

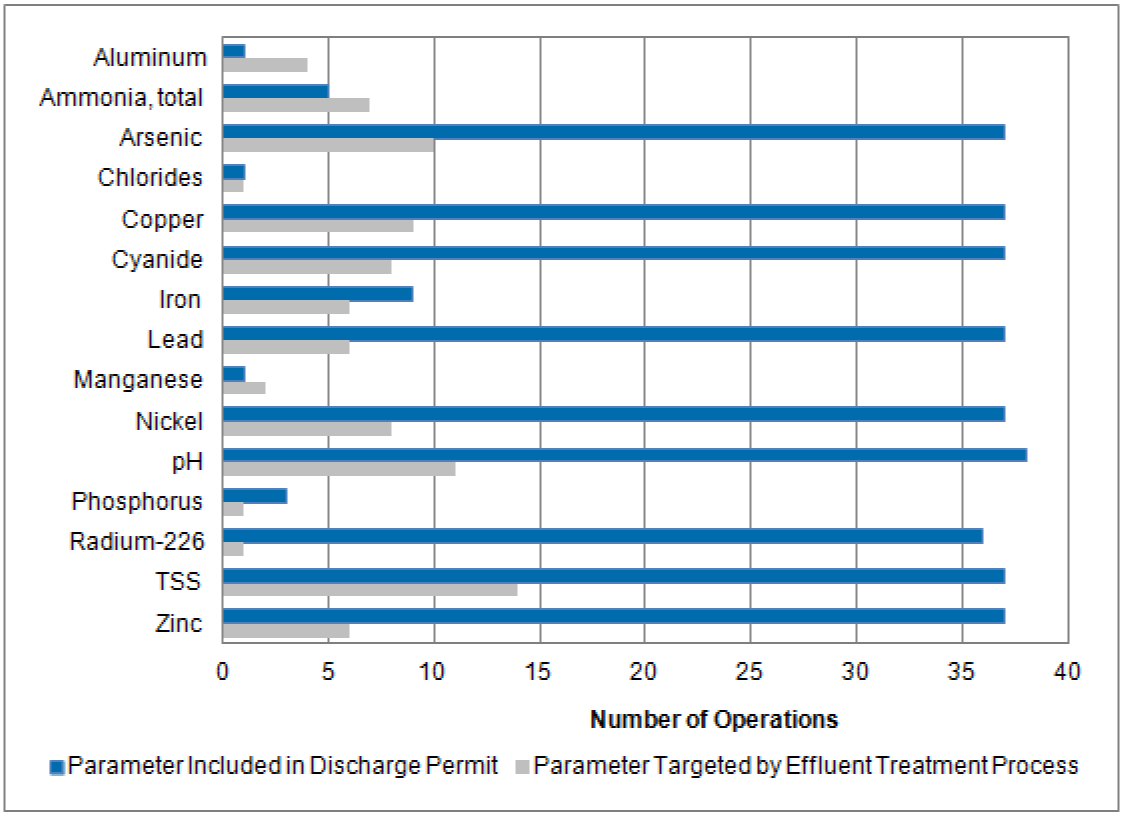

Figure 6-20: Parameters included in Discharge Permits and Targeted by Effluent Treatment Processes at Reviewed Precious Metal Operations (38 Operations Discharge Permits / 21 Effluent Treatment Systems)

Of the 31 mines that began or completed questionnaires to support this study, only 18 elected to provide untreated effluent quality in their submittals. The data are summarized in Table 6-23.

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Table 6-23: Quarterly Average Concentrations of Parameters in Untreated Effluent at Precious Metal Operations

Parameter	Unit	Minimum	Average	95th Percentile	Maximum	Number of Operations Reporting Untreated Effluent Concentration
pH		2.51	7.52	9.23	10.21	16
Aluminum	mg/L	0.001	110.5	717.9	1,080	10
Arsenic	mg/L	0.001	0.89	2.94	27.90	17
Copper	mg/L	0.0003	7.31	51.9	81.15	17
Cyanide	mg/L	0.002	13.3	36.6	250.0	11
Iron	mg/L	0.003	112.0	749.1	1,194	17
Lead	mg/L	0.00001	0.018	0.15	0.27	15
Nickel	mg/L	0.002	0.79	4.43	7.05	16
Selenium	mg/L	0.00029	0.14	0.96	1.20	11
Zinc	mg/L	0.001	9.58	112.0	164.89	18
TSS	mg/L	2.0	48.9	160.7	536.0	13
Total Ammonia	mg-N/L	2.20	20.03	42.5	45.0	11

Notes:
Values reported as less than the method detection limit have been incorporated at the MDL value.
All metal concentrations are total metal concentrations, i.e., the sum of dissolved and suspended fractions.

Many different contaminants are present in untreated effluent at precious metal operations and their presence at any given operation is highly variable. The most commonly reported contaminants in untreated effluent in concentrations above *MMER* limits and targeted by effluent treatment plants are pH (above or below discharge limits), total suspended solids, arsenic, copper, nickel and cyanide.

6.2.2 *Effluent Management and Control Techniques*

In an effort to control the volume and quality of effluent requiring containment and treatment prior to discharge to the environment, and to minimize the risk of potential contaminants being released to the environment, precious metal operations employ a variety of techniques to manage water. These techniques and their relative frequency of employment are presented in this section.

Table 6-24 presents an overview of water management and effluent control techniques used at precious metal operations (for water management in and surrounding mines, waste rock stockpiles, ore stockpiles, and tailings storage facilities).

Table 6-24: Overview of Effluent Management and Control Techniques Used at Precious Metal Operations

Volume Control	Quality Control	Minimize Environmental Contact
• Diversion of clean or non-impacted surface and groundwater away from site features which may degrade water quality upon contact. • Recycle of contact water to reduce the volume of water requiring treatment. • Co-disposal or in-pit disposal of waste streams to minimize the total waste storage footprint and thereby minimize contact water run-off volumes generated by precipitation. • Segregation of benign and potentially reactive wastes. • Vegetative cover of closed facilities to separate clean run-off from impacted percolation/seepage.	• Explosives best management plan in force. • Mine waste employed in mine backfill applications. • Water cover on mine wastes in waste storage facilities (e.g., tailings storage facility).	• Storage of potentially reactive wastes in dedicated storage facilities with environmental controls (e.g., liners, covers, seepage monitoring and collection, etc.). • Collection of contact water (run-off and seepage) and isolation from the environment during conveyance to treatment. • Mill facilities are centralized, with two or more mines providing ore for processing to one mill. This arrangement isolates processing activities, which can reduce the potential for deleterious substances that are used for processing (e.g., cyanide) or generated by processing to contaminate contact water or to be released to the environment.

6.2.2.1 *Mine Facilities and Water Management Techniques*

Precious metal operations employ a combination of open pit and underground mine facilities; frequently both types of mine facilities are present on a single site. Both active and inactive mine facilities are found at precious metal operations. Figure 6-21 illustrates the mining facilities found at 27 precious metal operations and their relative prevalence. 24 operations reported open pit and/or underground mine facilities, 3 operations indicated there are no mine facilities present on site.

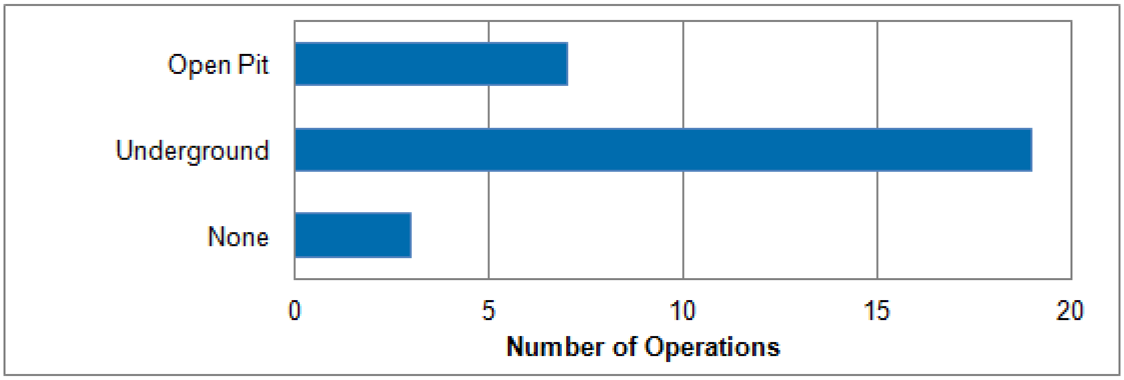

Figure 6-21: Precious Metal Subsector Mine Facilities (27 Operations)

Figure 6-22 summarizes the mine-water-environment interaction minimization techniques utilized by the 22 operations that reported mine facilities and the frequency of each technique's use. 2 operations reporting mine facilities did not provide information concerning mine-water-environment interaction minimization techniques. 3 operations reported that this information was 'Not Applicable' but did not provide any further detail.

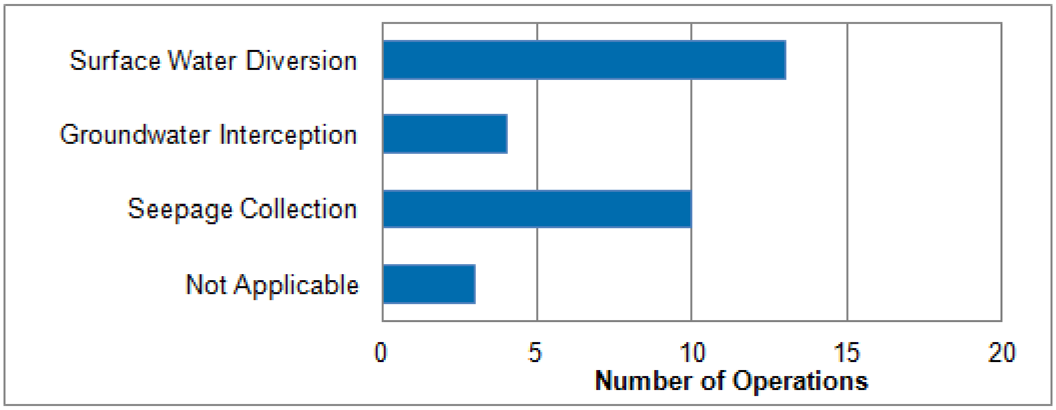

Figure 6-22: Precious Metal Subsector Mine-Water-Environment Interaction Minimization Techniques (22 Operations)

The most commonly reported water management and effluent control techniques are seepage collection and surface water diversion. Seepage collection is used at 42% of operations with mine facilities (10 of 24), and surface water diversion is used at 54% of mine facilities (13 of 24).

6.2.2.2 *Explosives Use*

Operations with active mining operations generally use some combination of bulk ammonium nitrate fuel oil (ANFO), packaged ANFO, packaged emulsions and packaged watergel/slurry, though some operations use only one type of explosives. Figure 6-23 illustrates the relative frequency of used explosive types as reported by 23 questionnaire respondents. 76% of operations reported operating under an explosives best management plan (16 of 21 respondents).

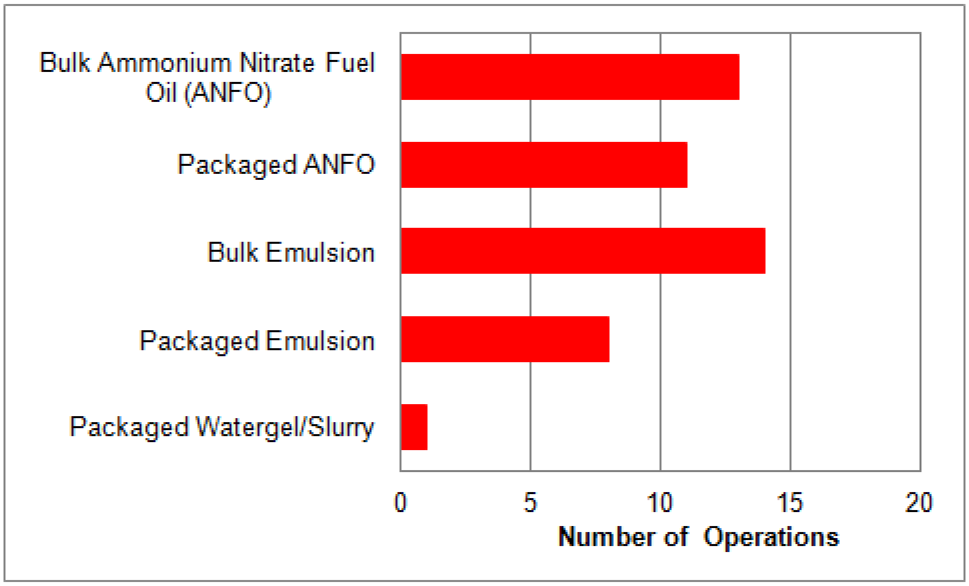

Figure 6-23: Relative Use of Types of Explosives at Precious Metal Operations (23 Operations)

6.2.2.3 *Ore Stockpiles and Water Management Techniques*

Of the operations that provided information via questionnaire, 22 have active ore stockpiles on site. Figure 6-24 shows the techniques employed to minimize ore-water-environment interactions, and their frequency of use.

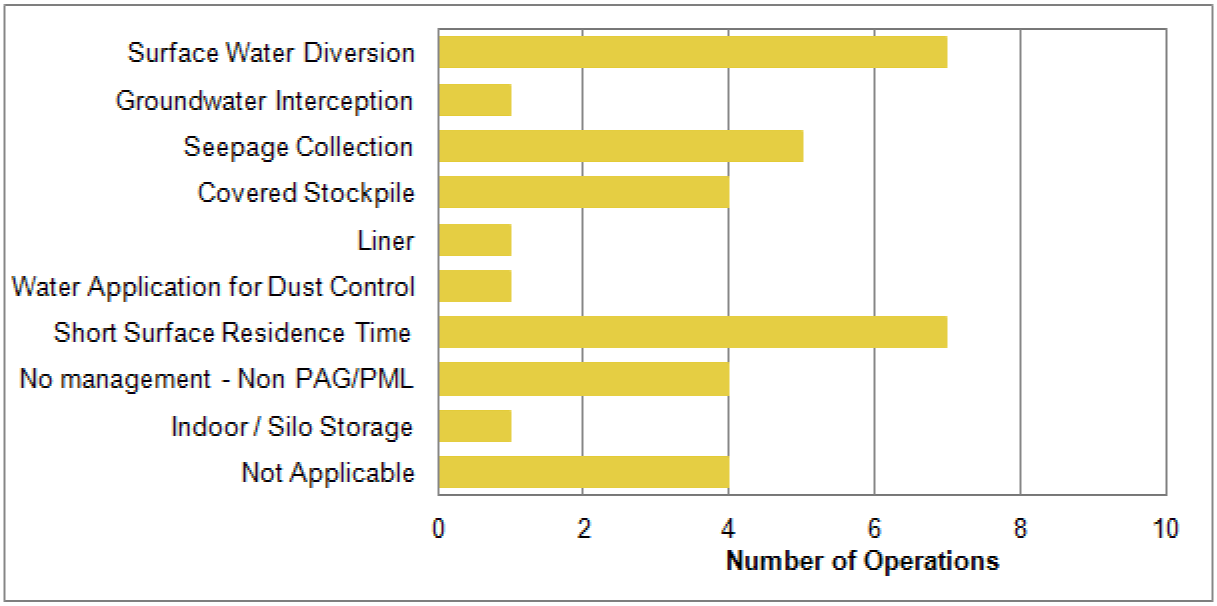

Figure 6-24: Precious Metal Subsector Ore Stockpile(s)-Water-Environment Interaction Minimization Techniques (22 Operations)

The most commonly reported methods of minimizing ore stockpile-water-environment interactions were diverting surface water around ore stockpiles and minimizing surface residence time to minimize the length of time ore is exposed to the atmosphere, and as a consequence minimizing exposure to oxygen and water via precipitation. 4 operations that reported stockpiles on site indicated the question surrounding ore stockpile(s)-water-environment interaction minimization was 'Not Applicable' but did not provide any additional information.

6.2.2.4 Waste Rock Disposal Methods and Water Management Techniques

Figure 6-25 summarizes the variety and relative frequency of waste rock disposal methods employed at the 21 precious metal operations that reported that they produce, manage or dispose of waste rock on site. Waste rock is most frequently disposed in dedicated storage facilities or used as backfill for underground mines.

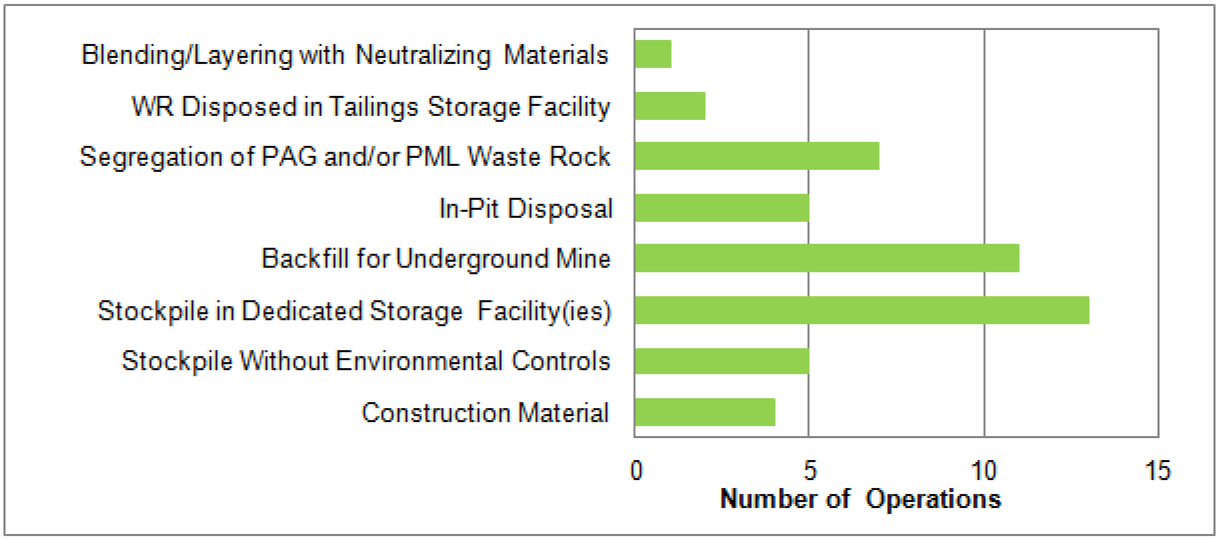

Figure 6-25: Precious Metal Subsector Active and Historical Waste Rock Disposal Techniques (21 Operations)

Various techniques are used to minimize potential interactions between waste rock stockpiles, water and the environment. Figure 6-26 summarizes the waste rock stockpile-water-environment interaction minimization techniques reported as utilized by 21 operations, and the frequency of each technique's use.

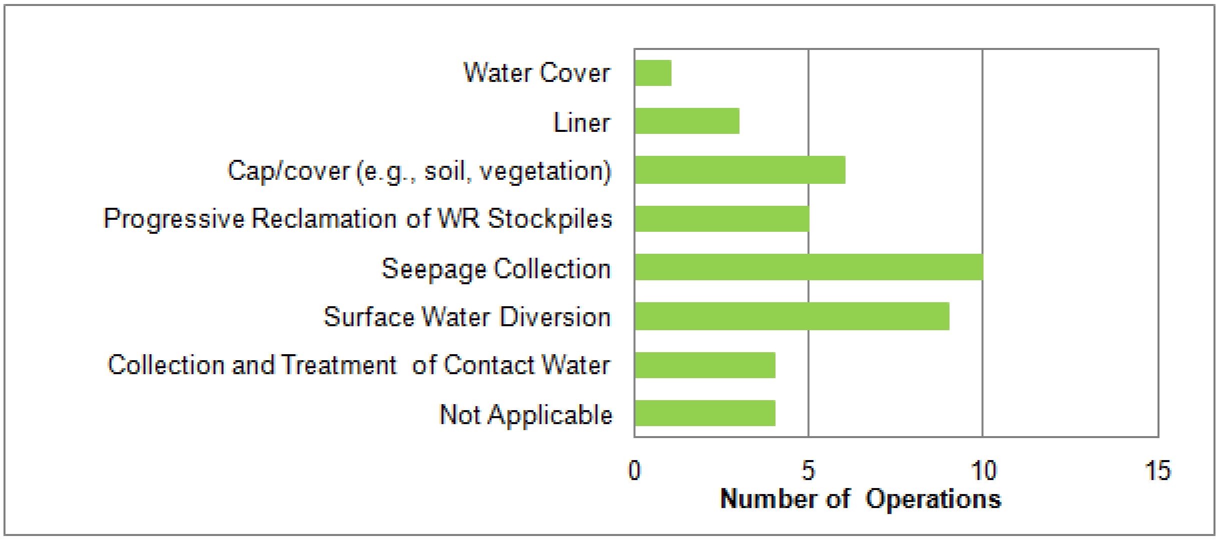

Figure 6-26: Precious Metal Subsector Waste Rock-Water-Environment Interaction Minimization Techniques (21 Operations)

The most common techniques employed to minimize these interactions are surface water diversion and seepage collection. 4 operations reporting waste rock stockpiles on site indicated the questionnaire question concerning Waste Rock-Water-Environment Interaction Minimization techniques was not applicable. 3 operations provided no explanation for this, while 1 operation indicated it was because the waste rock was all benign and used for construction purposes.

Several active operations with waste rock stockpiles segregate waste rock by characterization as benign or potentially acid generating/metal leaching. Those operations that do not segregate by waste rock type may dispose of all waste rock in the same manner have identified only one type of waste rock or treat all waste rock as potentially reactive.

Table 6-25 summarizes the disposal methods employed for the types of waste rock present on site.

Table 6-25: Disposal Methods for Different Waste Rock Types at Operating Precious Metal Operations

Waste Rock Classification	Disposal Method or Use
• PAG and/or PML	• In-pit disposal under water cover. • Used in underground mine backfill. • Temporary surface stockpiles (ultimately used as backfill). • Stored in stockpiles in dedicated storage facilities. • Stored in stockpile without environmental controls (historical waste rock).
• NML and NAG	• Construction material for dam and road construction, and backfill. • Stored in dedicated storage facilities. • Surface stockpiles with no environmental controls.

6.2.2.5 *Tailings Disposal Methods and Water Management Techniques*

22 operations reported that tailings were managed or disposed on site. Figure 6-27 summarizes the variety and relative frequency of tailings disposal methods employed at 20 of these precious metal operations; 2 operations did not provide responses for this question. Tailings are most frequently disposed in dedicated storage facilities, either sub-aqueously or sub-aerially, or are used as backfill for underground mines.

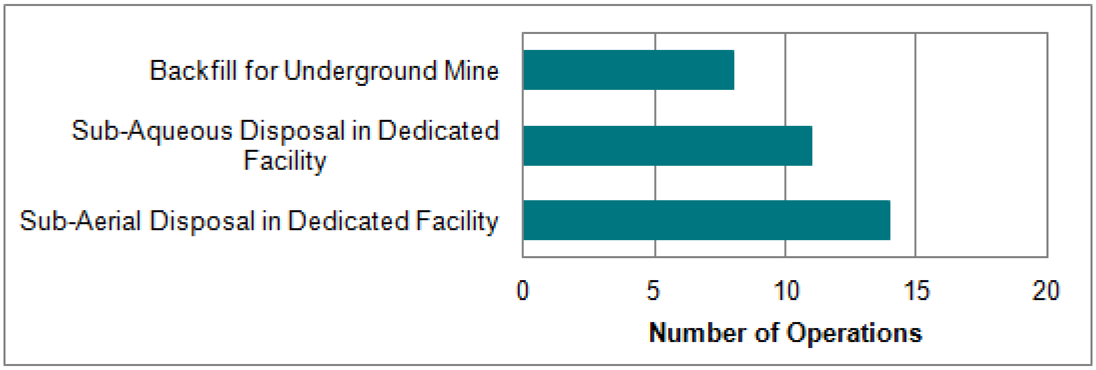

Figure 6-27: Precious Metal Subsector Active and Historical Tailings Disposal Methods (20 operations)

Various techniques are used to minimize potential interactions between tailings, water and the environment. Figure 6-28 summarizes tailings water-environment interaction minimization techniques reported as utilized by the 20 operations reporting tailings on site, and the frequency of each technique's use.

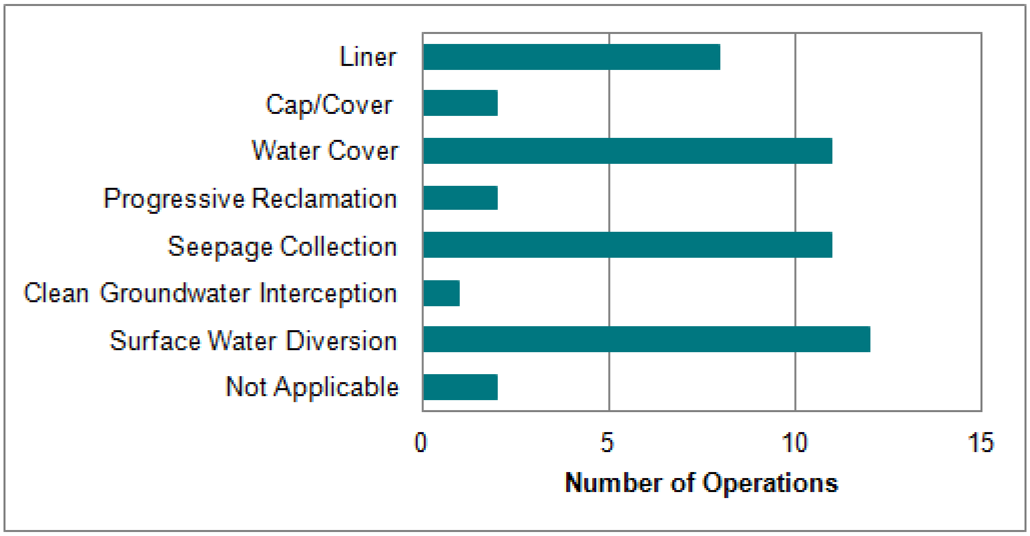

Figure 6-28: Precious Metal Subsector Tailings-Water-Environment Interaction Minimization Techniques

The most common techniques employed to minimize potential interaction between tailings, water and the environment are sub-aqueous disposal (water cover), liners, seepage collection and surface water collection.

Two sites indicated the question concerning Tailings-Water-Environment Interaction Minimization Techniques was 'Not Applicable'.1 site explained that the tailings are used to reclaim a closed site, while the other did not provide an explanation.

Most precious metal operations do not dewater tailings prior to final disposal (only approximately 21% of operations (4 of 15) reported via the questionnaire that they dewater tailings). As a result, tailings are typically disposed at solids content less than 50%, though those operations that dewater achieve up to greater than 70% solids prior to disposal. Tailings dewatering allows the direct recycle of tailings water to the process.

Cyanide destruction for precious metal tailings is the most common chemical tailings treatment process employed, as cyanide is used in the gold extraction process. Cyanide destruction was reported as utilized at half of operations reporting (11 of 22). Cyanide is often managed by destruction prior to tailings disposal to minimize the risk of environmental release of cyanide. Other treatment methods reported were desulfurization, and neutralization, both used in addition to cyanide destruction.

6.2.3 Effluent Treatment Technologies

Precious metal operations employ a wide range of technologies for effluent treatment and target a large number of parameters. Technologies employed at precious metal operations include hydroxide precipitation, co-precipitation and coagulation, natural degradation and passive treatment, ion exchange, oxidation, cyanide destruction, air stripping, and solid/liquid separation for the removal of metals, cyanide, ammonia, and TSS. A list of the chemical and physical separation processes reported in effluent treatment systems at precious metal operations are summarized in Table 6-26.

Table 6-26: Treatment Technologies Utilized in Effluent Treatment Processes at Precious Metal Operations

Chemical and Biological Processes	Physical Processes
Hydroxide Precipitation • Lime-based (high density sludge, conventional low density sludge, multi-stage low density sludge). • Pond-based lime addition. • Sodium hydroxide-based multi-stage simple sludge recycle. • Lime-based tailings neutralization. **Co-precipitation/Coagulation** • Ferric iron coagulation/co-precipitation (arsenic removal). • Solid/Liquid Separation • Coagulant and/or polymer-aided pond settling. **Cyanide Destruction** • INCO SO2/air. • Hydrogen peroxide. **Natural Degradation/Passive Treatment** • Natural degradation of cyanide and ammonia.	**Solid/Liquid Separation** • Pond-based settling/sedimentation. • Sump-based settling/sedimentation. • Pond silt curtains. • Clarification (conventional). • Ballasted flocculation/sedimentation. • Media filtration. **Membrane Separation** • Reverse osmosis (planned). • Other • Oil/water separation. • Pre-treatment equalization or holding pond.

Chemical and Biological Processes	Physical Processes
Final pH adjustment • Sulfuric acid. • Gaseous CO2. **Ion Exchange** • Selective ion exchange (metals and ammonia removal). **Active aerobic biological oxidation** • Moving bed biofilm reactor (MBBR). **Active anaerobic biological oxidation** **Air Stripping (ammonia removal)** • Wetland polishing.	

Which treatment technologies are employed at precious metal operations largely depends on what activities are taking place on site. Those operations that have only mining activity employ treatment process similar to that of base metal operations, as the contaminants present in untreated effluent are likely those metals and compounds often found associated with gold ore (e.g., arsenic, sulfates). Those operations that process gold and silver typically use cyanide in their process. At these operations, additional technologies (e.g. cyanide destruction via INCO SO_2/air process or hydrogen peroxide oxidation) are often employed to manage cyanide in effluent, though some operations rely solely on natural degradation of cyanide. Operations managing cyanide may also require technologies to manage ammonia in effluent, as ammonia is a product of cyanide destruction.

Other factors that affect treatment technologies are discharge limits and/or objectives established by provincial or territorial regulatory bodies, volume of effluent requiring treatment, and to some extent, the age of the mine and legacy effluent treatment infrastructure.

6.2.4 *Effluent Quality*

Table 6-27 summarizes the effluent quality (maximum, minimum, average monthly mean and 95th percentile concentrations) at the final point of discharge for all precious metal mines subject to *MMER* in 2008 – 2010. These effluent quality ranges utilize the same data set as employed by Environment Canada for the 10-Year Review of *Metal Mining Effluent Regulations*. The data was employed to generate the summary of treated effluent quality as it is a more complete data set than that generated by the questionnaire submittal, as operations are legally obliged to provide this information to Environment Canada.

This summary in Table 6-27 for Schedule 4 parameters (pH, arsenic, copper, lead, nickel, radium-226 zinc and TSS) uses monthly average concentration data generated by Environment Canada from grab data reported by operations. An assessment of the extent that the monthly average data adequately represents the grab data was performed for Revision 1 of this study and it was determined that for the most significant statistics (i.e., the 95th percentile), the difference between the monthly mean data and the grab data was minimal. Therefore, in Revision 1, the monthly mean data are carried forward for analysis. A more detailed assessment of the monthly mean data versus the grab data for each subsector is appended to this report in Appendix D.

Table 6-27: Treated Effluent Summary for Precious Metal Subsector

1

Parameters	Unit	Effluent Concentration Basis	Minimum	Average	95th Percentile	Maximum
pH		Monthly Mean	5.9	7.6	8.3	9.3
Aluminum	mg/L	Grab/Composite	0.0001	0.23	0.71	42
Ammonia, total	mg-N/L	Grab/Composite	0.0016	3.09	12	36
Arsenic	mg/L	Monthly Mean	0.0005	0.03	0.17	0.55
Copper	mg/L	Monthly Mean	0.0003	0.01	0.04	0.96
Cyanide	mg/L	Monthly Mean	0.0003	0.03	0.09	1.28
Iron	mg/L	Grab/Composite	0.0005	0.33	0.95	13.9
Lead	mg/L	Monthly Mean	0.00002	0.002	0.005	0.079
Nickel	mg/L	Monthly Mean	0.00005	0.02	0.07	0.30
Radium-226	Bq/L	Monthly Mean	0.0005	0.01	0.05	0.43
Selenium[15]	mg/L	Grab/Composite	0.000095	0.006	0.021	0.11
TSS	mg/L	Monthly Mean	0.3	4.7	13	58
Zinc	mg/L	Monthly Mean	0.0002	0.02	0.07	0.56

Notes:
Values reported as less than the method detection limit have been incorporated at 50% of the MDL value.
All metal concentrations are total metal concentrations, i.e., the sum of dissolved and suspended fractions.

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[15] Compiled from grab and composite selenium concentrations reported through Schedule 5 for 2012.

6.2.5 *Model Water Management and Effluent Treatment Systems*

6.2.5.1 *Model Water Management System*

Based on this review of water management techniques employed by precious metal subsector operations, a model water management plan to represent the typical water management practices employed at these operations has been generated. This model is presented in Figure 6-29.

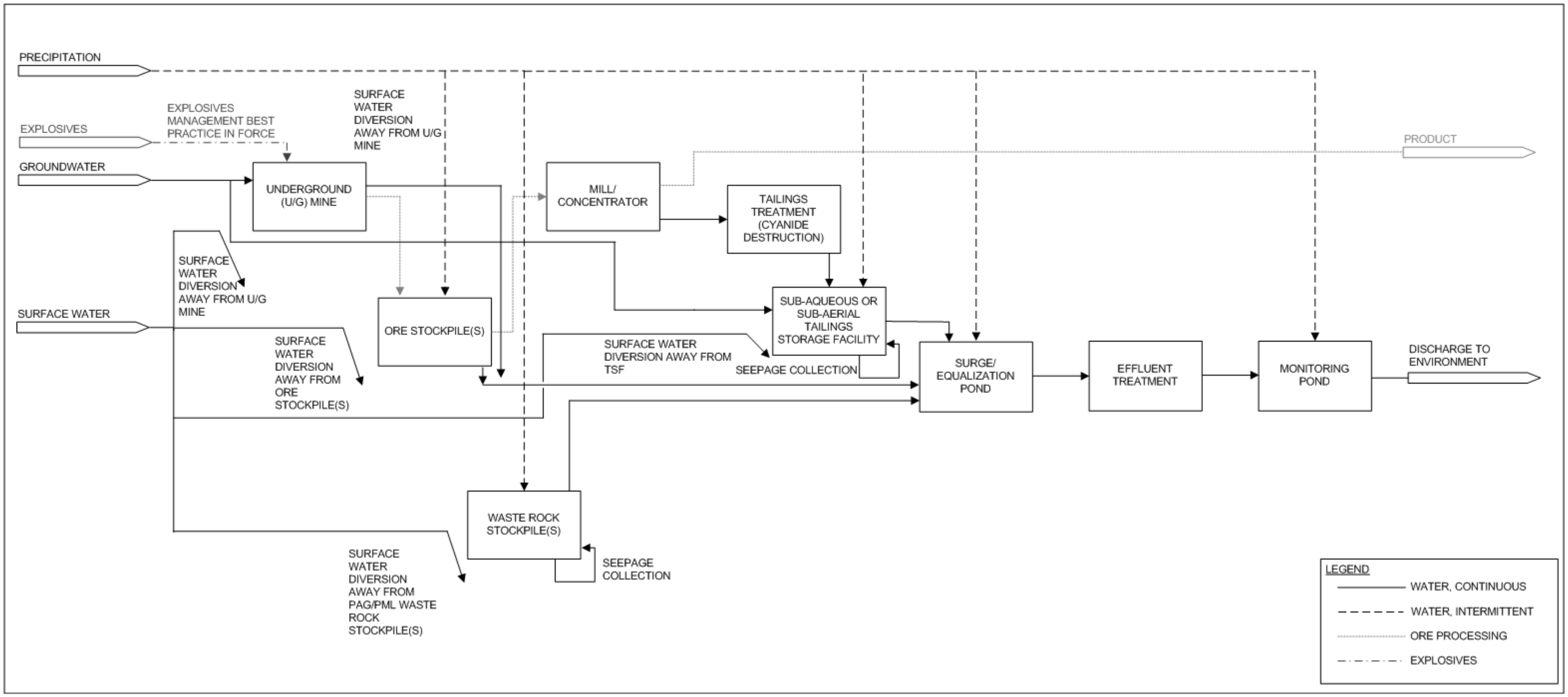

Figure 6-29: Precious Metal Subsector Water Management Model

6.2.5.2 *Model Treatment System Process Flow Diagram*

To establish a model ‘typical’ effluent treatment system, the list of technologies employed by precious metal operations for effluent treatment was first narrowed down to those most commonly used within the subsector. The relative frequency of the use of effluent treatment technologies at precious metal operations (previously presented in Table 6-26) is summarized in Figure 6-30.

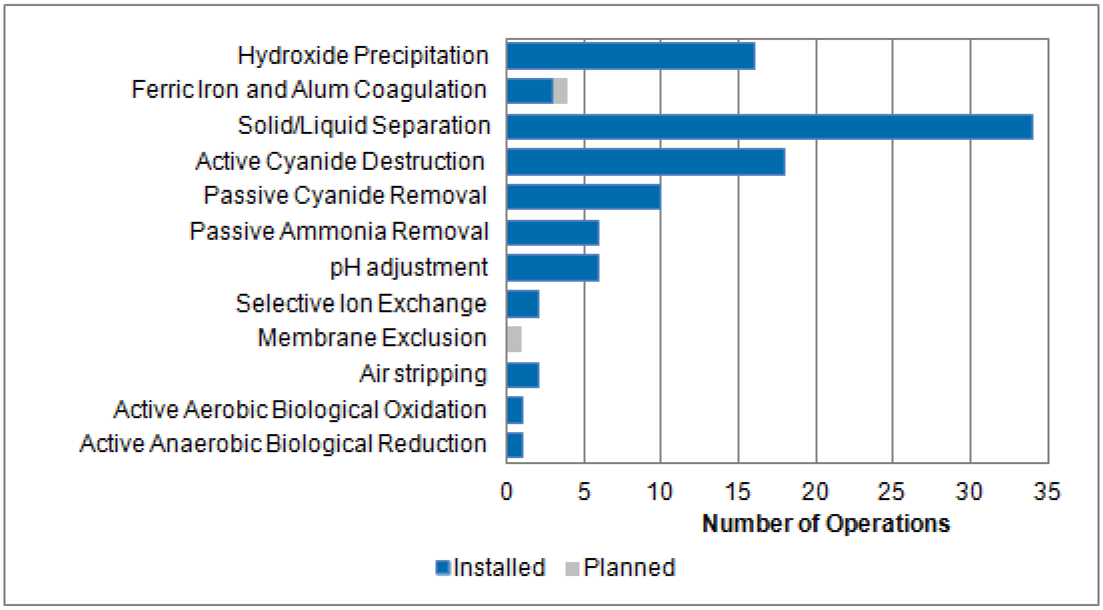

Figure 6-30: Relative Frequency of Use of Effluent Treatment Technologies at Precious Metal Operations (35 Operations)

The majority of precious metal operations reviewed employ solid/liquid separation, hydroxide precipitation and active or passive cyanide destruction/removal (some employ both). The high frequency of use of these technologies is consistent with what would be expected to be applied for the management of typical untreated effluent contaminants (TSS, arsenic, copper, nickel and cyanide). Other technologies that are employed by precious metal operations are ferric iron and alum coagulation for the removal of arsenic and other metals, ion exchange for selective metals removal, and air stripping, active aerobic and active anaerobic biological oxidation for the removal of ammonia. These technologies are each employed at select operations and are not considered typical of precious metal operations.

Cyanide destruction/removal technologies are employed by those precious metal operations that process their gold or silver-containing ore on site utilizing cyanide. The technologies used for cyanide management are passive cyanide removal (employed at 34% of operations managing cyanide) INCO SO_2/air cyanide destruction (employed at 45% of operations managing cyanide) and hydrogen peroxide oxidation (employed at 21% of operations managing cyanide). Operations that employ active cyanide destruction also often employ natural degradation for the secondary removal of cyanide from effluent prior to discharge.

Passive cyanide removal occurs typically in tailings storage facilities and subsequent polishing ponds, as the cyanide in the tailings slurry is volatilized (as hydrogen cyanide) and degraded by chemical or biological processes.

The INCO SO_2/air cyanide destruction process can either be applied to tailings slurry prior to disposal in a tailings storage facility, or to effluent prior to polishing and discharge. Precious metal operations most often apply this process to the tailings prior to discharge to the tailings storage facility, though it is also used at some operations solely for effluent treatment. It was also noted that some operations apply INCO SO_2/air to both tailings slurry and effluent prior to discharge.

Hydrogen peroxide cyanide destruction is typically applied to mine effluent as part of a final effluent treatment process prior to polishing ponds.

The use of a hydroxide precipitation processes for effluent treatment occurs at approximately half of all precious metal operations reviewed; pond-based and conventional/low density sludge lime hydroxide precipitation are used equally at operations that employ hydroxide precipitation. Of those operations that use cyanide destruction systems, again approximately half use lime hydroxide precipitation as an additional effluent treatment step.

The INCO SO_2/air process is able to remove some metals as it is carried out at alkaline pH, however it may not achieve high removal efficiencies for those metals where the lowest solubility occurs at pHs higher than optimal for cyanide removal. Additionally, the copper added to catalyze the INCO SO_2/air process may increase the copper concentrations to higher than the allowable discharge limits requiring further treatment to meet discharge limits. Other cyanide destruction/removal processes do not remove metals and require supplemental treatment where metals are present in untreated effluent. Of the operations employing cyanide destruction/removal processes, hydroxide precipitation using conventional, or low density sludge systems is most common. The most commonly employed solid/liquid separation technology is pond-based settling; this is employed either as the main solid/liquid removal technology, or to supplement active removal technologies as a polishing step.

The process of establishing a typical effluent treatment process for the precious metal subsector is difficult as there is a wide variety of effluent treatment processes applied at these operations. The two main distinctions among effluent treatment systems reviewed that must be addressed in the establishment of a typical model effluent treatment system are: whether cyanide destruction/removal is employed on site (as required by the use of cyanide in the gold or silver ore milling process), and, if cyanide destruction/removal is required on site, which cyanide destruction/removal technology is employed.

For the purpose of this study, one typical model effluent treatment system must be established. The majority of operations reviewed utilize cyanide in their ore processing, and therefore the base case for precious metal operations will be one that must manage cyanide, either actively or passively. Though all three cyanide destruction/removal technologies are employed with comparable frequency at precious metal operations, INCO SO_2/air is nonetheless the most commonly employed technology with nearly half of all operations that manage cyanide in effluent utilizing this process. Hydroxide precipitation is utilized at just over half of precious metal operations reviewed, and will also be carried forward.

The typical model effluent treatment system for precious metal operations carried forward in this study is INCO SO_2/air cyanide destruction applied to tailings prior to final deposition, followed by low density sludge lime hydroxide precipitation for treatment of tailings run-off, tailings supernatant and mine and waste rock untreated effluent prior to discharge. This treatment process is illustrated in Figure 6-31. It is acknowledged that due to the high variability in treatment processes among operations, this process is not representative of the majority of the effluent treatment systems reviewed. However, this process is expected to achieve an effluent quality similar to systems employing other cyanide destruction processes and so provides a system representative of the achievable effluent concentrations.

Additionally, the typical model effluent treatment process illustrated in Figure 6-31 varies somewhat from the water management scheme at operations using both INCO SO_2/air destruction on tailings and hydroxide precipitation. A trend among operations employing INCO SO_2/air cyanide destruction on tailings is that they often treat their mine and waste rock effluent separately from tailings effluent; tailings effluent receives treatment primarily by application of the INCO SO_2/air process to the tailings slurry, while mine water and waste rock run-off are treated separately by a lime hydroxide precipitation process. The resultant treated effluent streams are conveyed to a common polishing pond prior to discharge. However, establishing this type of system, with two separate effluent treatment plants as the typical/model effluent treatment system, is beyond the means and resources of this study. The flow sheet presented in Figure 6-31 ultimately is intended to represent a treatment system discharge and effluent that has received cyanide destruction via INCO SO_2/air and metals removal via hydroxide precipitation, in the configuration most appropriate to site-specific factors.

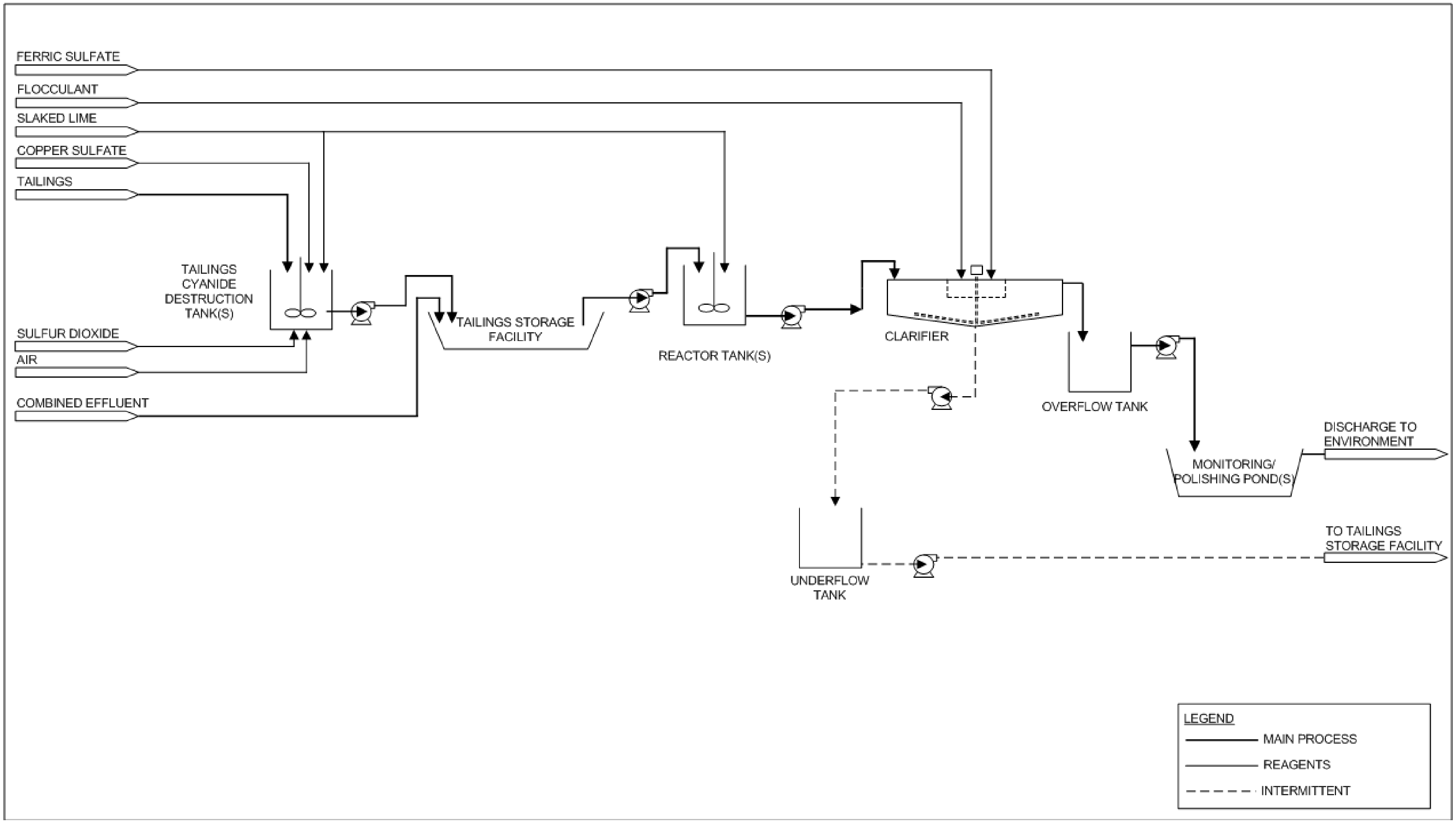

Figure 6-31: Precious Metal Subsector Model Effluent Treatment Process

6.2.5.3 *Model Effluent Treatment System Flow Rate*

For Revision 0, to establish a flow rate for the model effluent treatment system, two sources of treatment system flow rate and discharge volume information were used:

- Final discharge point flow rates reported to Environment Canada as part of *MMER* reporting for 2008 – 2010 (the analysis of which generated data set "A" in Table 6-28), and
- Average and design flow rates for effluent treatment systems reported by questionnaire respondents (the analysis of which generated data sets "B" and "C", respectively in Table 6-28).

The Environment Canada *MMER* reported data set is a complete set of monthly discharge volumes for all mines subject to *MMER* during 2008 – 2010, and thus is a valuable data source as it provides several years of discharge volumes, and additionally, data for those operations that did not participate in the study questionnaire. This data set, however, presents total discharge volumes from operations to the environment at the final discharge point(s) from the site and does not necessarily reflect the volume of water treated prior to discharge, nor the design capacities of effluent treatment systems, which are of significance when considering the costs of modifications/augmentations to effluent treatment systems.

The discharge volumes reported to Environment Canada may differ from the treated volumes as they may include incident precipitation to ponds downstream of effluent treatment systems or streams that do not require treatment. Nonetheless, due to the completeness of this data set compared to the data received via the questionnaire, in terms of time span of data collection and operation participation, it was considered valuable in the selection of a typical design flow rate. This monthly reported data was used to calculate the total annual discharge volume from operations, from which rough average annual hourly flow rates were calculated assuming continuous discharge (24 hours/day, 365 days/year). These values are presented in Table 6-28. This approach may not accurately represent flow rates treated by effluent treatment systems for the following reasons:

- This approach summed the discharge volumes from all final discharge points associated with an operation; for sites with multiple final discharge points, this approach overestimates the total volume requiring treatment by any one treatment system; however, if all final discharge points at an operation were to require augmentation of their effluent treatment systems, this may be representative of the total sum of the capacities of augmentative technologies for a single operation.
- This approach may account for volume that is not actively treated in an effluent treatment system (e.g., accounts for volumes treated only by settling ponds).
- This approach assumes that treatment occurs 365 days a year, for 24 hours a day. This approach could underestimate the treatment system flow rates for those sites that only treat for a portion of the year (e.g., in summer only) or day (e.g., during day shift only).

The second source of data reviewed in the process of establishing the model treatment system was treatment flow rate data provided via the Revision 0 operations questionnaire. As part of the questionnaire, operations were prompted to provide the average, design, maximum and minimum treatment flow rates for their effluent treatment systems. This data set is limited to those operations that provided this information as part of their questionnaire responses, and is thus a less complete data set as compared to the Environment Canada *MMER* reported discharges volumes. However, this data set is a valuable source of information concerning design capacities of treatment technologies, which are not apparent from reported discharge volumes. The average flow rates reported via the questionnaire were used to informally cross-check the questionnaire-reported values against the Environment Canada *MMER* reported values, and the design flow rates are used in the consideration of the typical effluent treatment system design flow rate, or the equipment capacity that would need to be installed for new equipment.

Following the release of Revision 0, two additional sources of treatment system flow rate and discharge volume information were available for review. These sources of treatment system flow rate and discharge volume information and the analysis performed on them are summarized below:

- Environment Canada provided monthly flow rate data reported through *MMER* for 2005 – 2012. The methodology undertaken by Environment Canada to analyze this flow rate data was as follows:
    - To generate approximate average hourly discharge volumes, Environment Canada analyzed the data by calculating the average daily flow rates by month for each discharge point reporting to *MMER*, then assuming that discharge occurs over 24 hours a day. This method identifies the average discharge flow rate from each site based on seven years of Schedule 4 data (this analysis generated data set "D" in Table 6-28).
    - To generate approximate maximum hourly discharge volumes for the highest monthly discharge, Environment Canada analyzed the data by first identifying the highest monthly discharge volume for each discharge point reporting to *MMER*, then assuming that discharge occurs continuously over the whole month, for 24 hours a day. This method identifies an approximate hourly discharge flow rate for the highest monthly discharge from each site based on seven years of Schedule 4 data (this analysis generated data set "E" in Table 6-28).
    - The approaches described above may not accurately represent flow rates treated by effluent treatment systems as they assume that treatment occurs over the entire month, for 24 hours a day. This approach could underestimate the treatment system flow rates for those sites that only treat for a portion of the year (e.g., in summer only) or day (e.g., during day shift only).
- The MEND Report 3.43.1, Review of Mine Drainage and Sludge Management Operations, contains all data collected by the survey associated with the report, including operation subsector classifications and maximum, average and minimum treatment flow rates (1). However, the size of this data set is substantially smaller than the other data sets available. Flow rate information from this report is only available for six precious metal mines located in Canada. Therefore, for the precious metal subsector, this data set was not considered in flow rate evaluation for Revision 1.

The range, average and median values for the data sets described above are presented in Table 6-28. In selecting a flow rate for the typical model effluent treatment system based on the flow rate statistics in Table 6-28, greater consideration was given to the reported design flow rates, as opposed to average flow rates, as design values reflect the installed capacity required to accommodate design events (e.g., years with higher precipitation or extreme precipitation events) to avoid uncontrolled discharge and bypassing or short-circuiting of effluent treatment systems. These values are expected to be more representative of the installed capacities required of additional technology installed to augment existing systems.

Table 6-28: Summary of Reviewed Discharge and Treatment Flow Rates for the Precious Metal Subsector

Data Set		Data Set Generation Methodology	Range (m^3/h)	Average (m^3/h)	Median (m^3/h)
Data Sets Informing Selection of Nominal Model Effluent Treatment System Flow Rates					
A	**Estimated Average Annual Hourly Discharge Volume: Sum of All Final Discharge Points per Site**	Annual discharge volumes for each final discharge point and each site were calculated (based on the sum of annual discharge volumes at all final discharge points) utilizing Schedule 4 reported monthly discharge volumes as reported by operations to Environment Canada. The maximum, minimum, average and median annual site discharge volumes were then calculated, assuming discharge continuously over 365 days a year and 24 hours a day to generate hourly maximum, minimum, average and median flow rates.	0 – 1,563	179	94
B	**Questionnaire Reported Average Treatment System Flow Rate**	The average treatment flow rate volumes provided by operations via the operations questionnaire were used to calculated maximum, minimum, average and median values.	10 – 1,200	330	230
D	**EC Analysis: Estimated Average Hourly Flows per Final Discharge Point**	Schedule 4 monthly flow volume data reported to Environment Canada from 2005 – 2012 was used to calculate an average daily discharge volume for each final discharge point. It was assumed that treatment and discharge occurred continuously over 24 hours per day. Maximum, minimum, average and median values were then calculated for the approximate hourly flow rates determined in this fashion.	2 – 1,482	206	99
Data Sets Informing Selection of Design Model Effluent Treatment System Flow Rates					
C	**Questionnaire Reported Design/Maximum Treatment System Flow Rate**	Operations were prompted for their design and maximum treatment flow rates as part of the operations questionnaire. The maximum of these two numbers was used to generate a data set for the maximum/design treatment values for the subsector. Maximum, minimum, average and median values were then calculated for the subsector data set.	0 – 5,000	840	404
E	**EC Analysis: Estimated Average Maximum Hourly Flows per Final Discharge Point**	Schedule 4 monthly flow volume data reported to Environment Canada from 2005 – 2012 was used to calculate a maximum monthly discharge volume for each final discharge point. It was assumed that treatment and discharge occurred continuously over the entire month to generate approximate maximum hourly discharge volumes. Maximum, minimum, average and median values were then calculated for the hourly flow rates determined in this fashion.	4 – 4,971	561	283

In Revision 0, data sets “A”, “B” and “C” in Table 6-28 were considered in determining the nominal and design flow rates for the model effluent treatment system. The average value of the reported average treatment system rates (330 m^3/h, data set “B”) was roughly in accordance with the *MMER* reported data (179 m^3/h, data set “A”) though the questionnaire reported data skewed slightly higher, as reflected by the average and median values. To account for and attempt to correct this skew, the value for the design capacity of the precious metal subsector model effluent treatment system was selected to be 600 m^3/h, lower than the average 840 m^3/h design flow rate reported by questionnaire respondents. This value was utilized for capital cost estimating for system augmentation. The selected value for the nominal flow rate of the precious metal subsector model effluent treatment system was 180 m^3/h, based on the average flow rate value from data set “A”. This value was utilized for operating cost estimating for system augmentation.

In Revision 1, data set “D” was also considered in addition to data sets “A”, “B”, to review the nominal model effluent treatment system flow rates utilized in Revision 0.

Data set “D”, based on Environment Canada’s analysis of Schedule 4 flow rate data from 2005 – 2012 provides an alternate approach to selecting a nominal treatment flow rate for the model effluent treatment system, as it identifies the average daily discharge for each final discharge point and from this generates an average hourly flow rate volume. The average value calculated by this method (206 m^3/h) is very close to the nominal value used in Revision 0 (179 m^3/h).

Given the minimal difference between the average annual hourly flow rate calculated in Revision 0 and the average hourly flow rate calculated in Environment Canada’s analysis, and given that this change would not be expected to impact BATEA selection, there is insufficient reason to change the nominal model effluent treatment system for the precious metal subsector for Revision 1. The nominal flow rate selected for the model effluent treatment system remains 180 m^3/h.

In Revision 1, data set “E” was also considered in addition to data set “C”, to review the design model effluent treatment system flow rates utilized in Revision 0.

Data set “E”, based on Environment Canada’s analysis of Schedule 4 flow rate data from 2005 – 2012, provides an alternate approach to selecting a design treatment flow rate for the model effluent treatment system, as it identifies the maximum volume discharged from each final discharge point over seven years of data and generates an approximate maximum hourly discharge volume from the data. The average of this data set (840 m^3/h, data set “E”) is lower than the average of the reported design flow rates via the operations questionnaire (561 m^3/h, data set “C”).

This could be due to the possibility that the operations questionnaire data reflects sites with larger effluent treatment system capacities; however, it could also be a result of effluent treatment systems being designed and installed with a capacity capable of handling extreme precipitation events that are not reflected in Schedule 4 data (e.g., probable maximum precipitation events or extreme wet years). It is ultimately unknown whether the seven years of Schedule 4 data accurately reflect treatment flow rates required for extreme precipitation events or wet years over the highly variable climates of all operations in Canada.

Given the minimal difference between the average of the maximum hourly flow rates calculated by Environment Canada (561 m^3/h, data set “C”) and the selected design flow rate for Revision 0 (600 m^3/h), and given that this change would not be expected to impact BATEA selection, there is insufficient reason to change the design flow rates for the model effluent treatment system for the precious metal subsector for Revision 1. The design flow rate selected for the precious metal model effluent treatment system remains 600 m^3/h.

6.2.5.4 *Model Effluent Treatment System Effluent Quality*

1

In Revision 0 of this report, the 95th percentile of the effluent quality summary for the entire precious metal subsector (as summarized in Table 6-64) for each parameter was used to represent the effluent quality that was produced by the model effluent treatment system. It was assumed that for each parameter, the 95th percentile would reflect the concentration in the effluent at the majority of sites and that the 95th percentile value associated with the complete data set would be weighted to reflect the most common effluent treatment technologies (and therefore the model effluent treatment system), as the most common effluent treatment systems would contribute a larger fraction of the concentration values than other systems.

Feedback received from industry indicated two main concerns with the use of 95th percentile values as representative of the model effluent treatment system, as follows:

1. The total cohort of final discharge effluent quality data for the subsector originates from a variety of effluent treatment systems, and not just systems very similar or equivalent to the model effluent treatment system. This could skew the 95th percentile values, as other types of effluent treatment systems may achieve higher or lower concentrations than the model. Thus, using the total cohort of final discharge effluent quality data for the subsector may not be representative of the concentrations specifically achieved by the model effluent treatment system.

2. Using the total cohort of final discharge effluent quality data for the subsector may result in average and 95th percentile values that are skewed low by the inclusion of concentration data from effluent treatment systems that do not target or remove a given parameter (i.e., where the concentration of a given parameter in untreated effluent is compliant with existing *MMER* without treatment). Using the total cohort of final discharge effluent quality data does not consider which concentration values reflect concentrations achievable by treatment, and thus, may not be representative of the concentration achieved by any given treatment system.

To better reflect the concentrations achieved by subsector effluent treatment systems similar or equivalent to the model effluent treatment system for systems that target the removal of the parameters in question, Hatch compared concentration statistics for subsets of Schedule 4 and Schedule 5 data. The subsets were organized according to type of effluent treatment system and targeted parameters. Effluent treatment system information was collected during Revision 0 work via questionnaire and independent research, and augmented with additional data collected during Revision 1 work. The purpose of this effort was to narrow the total cohort of final discharge effluent quality data down to the concentration values that are more representative of concentrations achieved by systems similar to the model effluent treatment system.

Two types of effluent treatment systems utilized by precious metal subsector operations were of interest for this analysis: systems similar to the model effluent treatment system (referred to as “model effluent treatment systems”) and systems that are not exactly like the model effluent treatment system but utilize a process that can achieve similar effluent quality to model effluent treatment systems (referred to “model equivalent effluent treatment systems”). For the precious metal subsector, these types of treatment systems are defined as follows:

- **Model Effluent Treatment Systems**: Operations whose effluent treatment system comprises an INCO SO_2/air cyanide destruction process applied to tailings followed by a reactor-based lime hydroxide precipitation system for treatment of effluent, with ferric sulfate addition as a coagulant and solid/liquid separation occurring in a clarifier.
- **Model Equivalent Effluent Treatment Systems:** Operations whose effluent treatment system comprises of only an INCO SO_2/air cyanide destruction process applied to tailings and/or effluent, or an INCO SO_2/air cyanide destruction process applied to tailings and/or effluent and any lime hydroxide precipitation system. INCO SO_2/air cyanide destruction processes alone have been included as the pH is elevated in these systems and thus some metals removal would be expected to occur by lime hydroxide precipitation.

For the precious metal subsector, the critical parameters for which concentration statistics were developed were arsenic, copper, lead, nickel, zinc, cyanide, total suspended solids (TSS), aluminum, iron, selenium and total ammonia. Radium-226 was not reviewed as this parameter is typically not a concern in effluent at precious metal operations[16]. For each of these parameters, effluent quality statistics have been developed for the subsets of the total cohort, according to:

1. Model effluent treatment systems.
2. Model effluent treatment systems and model equivalent effluent treatment systems.
3. Effluent treatment systems that target the parameter.
4. Model effluent treatment systems that target the parameter.
5. Model effluent treatment systems and model equivalent effluent treatment systems that target the parameter.

Effluent treatment systems targeting parameters were identified per self-reporting by operations via the Revision 0 questionnaire and the Revision 1 mini-survey; this self-reported information was confirmed to the extent possible using paired untreated effluent and treated effluent quality data provided by operations where available. Where information provided in the Revision 0 questionnaire differed from the information provided in the Revision 1 questionnaire, the operation was contacted to ensure a correct understanding of the information.

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[16] The 95th percentile values for the total precious metal effluent quality data cohort have been used to represent the radium-226 concentration present in the model effluent treatment system effluent.

A comparison between the concentration statistics for each subset of data was performed to assess the extent to which the utilization of the total cohort of precious metal subsector effluent quality data may skew the concentration statistics in comparison to data associated with model or model equivalent effluent treatment systems that target the parameter. The number of final discharge points associated with each data set is also provided. As the 95th percentile values are used in augmentative BAT cost estimation and BATEA selection later in this report, the agreement between the data subsets for this statistic (95th percentile) is considered more heavily than the other concentration statistics (minimum, average and maximum). For each parameter, a final model effluent treatment system effluent concentration is estimated based on this assessment.

6.2.5.4.1 Arsenic

Table 6-29 summarizes the arsenic concentration statistics for subsets of the precious metal subsector final discharge effluent quality data; observations on these statistics and conclusions for the precious metal subsector are summarized below.

Table 6-29: Arsenic Concentration Statistics for the Precious Metal Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00005	0.028	0.17	0.55	86
Model(s)	0.0019	0.069	0.23	0.29	3
Model(s) and Model Equivalent(s)	0.00025	0.052	0.22	0.45	9
Self-Identified as Targeting	0.00025	0.085	0.32	0.50	10
Model(s) that Self-Identify as Targeting	0.0019	0.069	0.23	0.29	3
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.00025	0.054	0.22	0.29	4

- Operations that self-identified as targeting arsenic have slightly higher average and 95th percentile concentrations than the average and 95th percentile values of the total cohort of final discharge effluent quality. However, the differences are minor for the 95th percentile values and more significant for the average values.

- The arsenic concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on 95th percentile values) is estimated to be <0.3 mg/L.

6.2.5.4.2 Copper

Table 6-30 summarizes the copper concentration statistics for subsets of the precious metal subsector final discharge effluent quality data; observations on these statistics and conclusions for the precious metal subsector are summarized below.

Table 6-30: Copper Concentration Statistics for the Precious Metal Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00025	0.010	0.04	0.96	86
Model(s)	0.0017	0.020	0.09	0.12	3
Model(s) and Model Equivalent(s)	0.00091	0.030	0.11	0.76	9
Self-Identified as Targeting	0.00084	0.010	0.05	0.12	12
Model(s) that Self-Identify as Targeting	0.0017	0.021	0.107	0.12	2
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.0017	0.022	0.093	0.12	3

- The average values for all subsets are minorly different. The model effluent treatment systems and equivalent systems that self-identify as targeting copper have higher 95th percentile values than the other data subsets.
- The copper concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on 95th percentile values) is estimated to be <0.11 mg/L.

6.2.5.4.3 Cyanide

Table 6-31 summarizes the cyanide concentration statistics for subsets of the precious metal subsector final discharge effluent quality data; observations on these statistics and conclusions for the precious metal subsector are summarized below.

Table 6-31: Cyanide Concentration Statistics for the Precious Metal Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00025	0.029	0.09	1.28	86
Model(s)	0.0005	0.041	0.084	0.10	3
Model(s) and Model Equivalent(s)	0.0005	0.048	0.11	0.74	9
Self-Identified as Targeting	0.0005	0.049	0.18	0.74	11
Model(s) that Self-Identify as Targeting	0.0005	0.040	0.084	0.10	3
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.0005	0.048	0.11	0.74	9

- The differences between the average and 95th percentile values for all subsets are minimal.
- The cyanide concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on 95th percentile values) is estimated to be <0.1 mg/L.

6.2.5.4.4 Lead

Table 6-32 summarizes the lead concentration statistics for subsets of the precious metal subsector final discharge effluent quality data; observations on these statistics and conclusions for the precious metal subsector are summarized below.

Table 6-32: Lead Concentration Statistics for the Precious Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.000016	0.0019	0.0053	0.079	86
Model(s)	0.00005	0.0018	0.0046	0.014	3
Model(s) and Model Equivalent(s)	0.00005	0.0012	0.0042	0.014	9
Self-Identified as Targeting	0.000038	0.0017	0.0045	0.014	8
Model(s) that Self-Identify as Targeting	0.00044	0.0029	0.0056	0.014	2
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.00005	0.0020	0.0049	0.014	3

- The differences in concentration statistics between these data subsets are minor for the average and 95th percentile values.

- The lead concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on 95th percentile values) is estimated to be <0.006 mg/L.

6.2.5.4.5 Nickel

Table 6-33 summarizes the nickel concentration statistics for subsets of the precious metal subsector final discharge effluent quality data; observations on these statistics and conclusions for the precious metal subsector are summarized below.

Table 6-33: Nickel Concentration Statistics for the Precious Metal Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00005	0.019	0.071	0.30	86
Model(s)	0.013	0.050	0.11	0.15	3
Model(s) and Model Equivalent(s)	0.00025	0.026	0.073	0.15	9
Self-Identified as Targeting	0.00025	0.015	0.050	0.09	9
Model(s) that Self-Identify as Targeting	0.013	0.033	0.070	0.11	2
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.0013	0.030	0.050	0.11	3

- The differences in concentration statistics between these data subsets are minor for the 95th percentile and average values.
- The nickel concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment systems (based on 95th percentile values) is estimated to be <0.1 mg/L.

6.2.5.4.6 Zinc

Table 6-70 summarizes the zinc concentration statistics for subsets of the precious metal subsector final discharge effluent quality data; observations on these statistics and conclusions for the precious metal subsector are summarized below.

Table 6-34: Zinc Concentration Statistics for the Precious Metal Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.0002	0.018	0.069	0.56	86
Model(s)	0.00088	0.0086	0.027	0.031	3
Model(s) and Model Equivalent(s)	0.0005	0.0086	0.028	0.069	9
Self-Identified as Targeting	0.00025	0.015	0.052	0.087	8
Model(s) that Self-Identify as Targeting	0.00088	0.0042	0.0078	0.027	2
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.0005	0.0049	0.012	0.027	3

- The differences in concentration statistics between these data subsets are significant for the 95th percentile values, with the highest value generated by the total cohort and the lowest value representing the model effluent treatment systems that target zinc for removal. The average values are similar.
- The zinc concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment systems (based on 95th percentile values) is estimated to be <0.03 mg/L.

6.2.5.4.7 Total Suspended Solids

Table 6-46 summarizes the total suspended solids concentration statistics for subsets of the precious metal subsector final discharge effluent quality data; observations on these statistics and conclusions for the precious metal subsector are summarized below.

Table 6-35: Total Suspended Solids Concentration Statistics for the Precious Metal Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.25	4.69	12.68	58.0	86
Model(s)	0.5	2.51	7.98	9.18	3
Model(s) and Model Equivalent(s)	0.5	4.39	9.73	24.1	9
Self-Identified as Targeting	0.5	4.77	13.15	37.4	14
Model(s) that Self-Identify as Targeting	0.5	1.87	7.98	9.18	3
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.50	4.73	12.04	24.1	4

- The differences in TSS concentration statistics between these data subsets are relatively minor for the average and 95th percentile values. Average values range between 2 – 5 mg/L while 95th percentile values range between 8 – 13 mg/L.

- The TSS concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment systems (based on 95th percentile values) is estimated to be <12.0 mg/L.

6.2.5.4.8 Aluminum

Table 6-73 summarizes the aluminum concentration statistics for subsets of the precious metal subsector final discharge effluent quality data; observations on these statistics and conclusions for the precious metal subsector are summarized below.

Table 6-36: Aluminum Concentration Statistics for the Precious Metal Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.0001	0.23	0.71	42	67
Model(s)	0.0005	0.02	0.06	0.12	3
Model(s) and Model Equivalent(s)	0.00025	0.68	1.06	42	11
Self-Identified as Targeting	0.0001	0.01	0.02	0.05	3
Model(s) that Self-Identify as Targeting	0.0043	0.02	0.04	0.05	1
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.0043	0.02	0.04	0.05	1

- There are significant differences in the 95th percentile and average values of the subsets; the model and model equivalent subset is substantially higher than the other subsets. This appears to be the result of effluent quality data from one operation; the 42 mg/L also appears to be anomalous amongst the aluminum concentration for that operation.
- The aluminum concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment systems (based on 95th percentile values) is estimated to be <0.05 mg/L.

6.2.5.4.9 Iron

Table 6-37 summarizes the iron concentration statistics for subsets of the precious metal subsector final discharge effluent quality data; observations on these statistics and conclusions for the precious metal subsector are summarized below.

Table 6-37: Iron Concentration Statistics for the Precious Metal Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.0005	0.33	0.95	13.9	67
Model(s)	0.01	0.48	1.08	1.23	3
Model(s) and Model Equivalent(s)	0.005	0.30	0.89	1.23	11
Self-Identified as Targeting	0.0005	0.34	1.15	1.75	5
Model(s) that Self-Identify as Targeting	0.16	0.27	0.34	0.342	1
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.025	0.29	0.78	1.2	3

- The differences in concentration statistics between these data subsets are minimal for the average values, and moderately different between the 95th percentile values. Only one model effluent treatment system reported targeting iron and this operation achieves the lowest 95th percentile value. Other operations reporting targeting iron achieve less than 1 mg/L, which represents a larger data set than the single model effluent treatment system self-identifying as targeting.
- The iron concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment systems (based on 95th percentile values) is estimated to be <1.2 mg/L.

6.2.5.4.10 Selenium

Table 6-38 summarizes the selenium concentration statistics for subsets of the precious metal subsector final discharge effluent quality data; observations on these statistics and conclusions for the precious metal subsector are summarized below.

Table 6-38: Selenium Concentration Statistics for the Precious Metal Subsector

Data Set	Minimum (mg-N/L)	Average (mg-N/L)	95th Percentile (mg-N/L)	Maximum (mg-N/L)	# of Final Discharge Points
All Data	0.000095	0.0063	0.021	0.11	57
Model(s)	0.0005	0.0073	0.0165	0.0169	3
Model(s) and Model Equivalent(s)	0.0004	0.016	0.099	0.11	8
Self-Identified as Targeting	0.0002	0.0013	0.0023	0.0024	2
Model(s) that Self-Identify as Targeting	No Data				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	No Data				0

- No operations classified as model or model equivalents self-identified as targeting selenium for removal.
- The differences in concentration statistics between these data subsets are moderately significant for the average and 95th percentile values.
- As no effluent treatment systems classified as model or model equivalent self-identified as targeting selenium for removal, no achievable selenium concentration by these systems can be established. To be conservative, the 95th percentile of the whole precious metal subsector will be applied as the estimated concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (<0.05 mg/L).

6.2.5.4.11 Total Ammonia (as Nitrogen)

Table 6-39 summarizes the total ammonia (as nitrogen) concentration statistics for subsets of the precious metal subsector final discharge effluent quality data; observations on these statistics and conclusions for the precious metal subsector are summarized below.

Table 6-39: Total Ammonia Concentration Statistics for the Precious Metal Subsector

Data Set	Minimum (mg-N/L)	Average (mg-N/L)	95th Percentile (mg-N/L)	Maximum (mg-N/L)	# of Final Discharge Points
All Data	0.0016	3.09	12	36	67
Model(s)	0.03	4.76	11	12.5	3
Model(s) and Model Equivalent(s)	0.0025	5.91	23	33	11
Self-Identified as Targeting	0.01	7.63	17	36	4
Model(s) that Self-Identify as Targeting	5.63	10.26	12	12.5	1
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	5.63	10.37	12	12.5	2

- Total ammonia is not actively removed by the model effluent treatment system nor its equivalents, although some reduction in total ammonia concentrations may be achieved through volatilization during high pH process step(s) and natural degradation in ponds. It is assumed that those operations that self-identified as targeting ammonia that use model effluent treatment systems or equivalents employ water management practices to encourage the passive degradation of ammonia.
- The differences in concentration statistics between these data subsets are significant for the average and 95th percentile values. The systems that reported targeting ammonia have the higher average and 95th percentile values than the total cohort data set.
- The total ammonia concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system that target ammonia (based on 95th percentile values) is estimated to be <12 mg-N/L.

6.2.5.4.12 Model Effluent Treatment System Effluent Concentration Summary

The 95th percentile concentrations achieved effluent treatment systems similar and equivalent to the model effluent treatment system are summarized in Table 6-40. These will be used as representative of the concentrations produced by the model effluent treatment system for augmentative BAT cost estimate and BATEA selection.

Table 6-40: Concentrations Achieved by the Model Effluent Treatment System in the Precious Metal Subsector

Parameter	Concentration
Arsenic	<0.3 mg/L
Copper	<0.11 mg/L
Lead	<0.006 mg/L
Nickel	<0.1mg/L
Zinc	<0.03 mg/L
Cyanide	<0.1 mg/L
TSS	<12 mg/L
Aluminum	<0.05 mg/L
Iron	<1.2 mg/L
Radium-226	<0.05 Bq/L
Selenium	<0.05 mg/L
Total Ammonia (as nitrogen)	<12 mg-N/L

6.3 Metals Sector: Iron Ore

Effluent discharges from the iron ore subsector are subject to the *Metal Mining Effluent Regulations*, and per Environment Canada's 10-Year Review of *Metal Mining Effluent Regulations*, would be subject to the proposed changes to *MMER* for metal mines. One iron ore operation subject to *MMER* has been identified by Environment Canada as being potentially impacted by the changes in discharge limits proposed for the parameters that are currently regulated (arsenic, copper, cyanide, lead, nickel and zinc); however, analysis concerning the potential impact of the additional parameters (ammonia, iron, selenium) proposed by Environment Canada is not available (2). The current Canadian iron ore operations are listed in Table 6-41. Of these, the review of the Canadian iron ore subsector included all 6 operating iron ore operations, one of which submitted a completed questionnaire and one of which submitted an incomplete questionnaire during the data collection portion of this study. Information for the other 4 operations was collected from independent research efforts and from in-house information.

Table 6-41: Canadian Iron Ore Operations

Operation	Owner/Operator	Location	Status
Fire Lake	ArcelorMittal Mines Canada	Mont-Wright, QC	Operating
Mont-Wright	ArcelorMittal Mines Canada	Fermont, QC	Operating
Wabush	Cliffs Natural Resources Ltd.	Wabush, NL	Operating
Bloom Lake	Cliffs Natural Resources Ltd.	Fermont, QC	Operating
Iron Ore Company of Canada (“Carol Project”)	Rio Tinto	Labrador City, NL	Operating
James	Labrador Iron Mines Ltd.	Schefferville, QC	Operating

5 of the 6 iron ore operations reviewed are located in a single cluster (the “Labrador Trough”), near the Quebec-Labrador border, centered around Labrador City, NL. A single operation is further away from the others, around 200 km further north, close to Schefferville, Quebec.

Figure 6-32 illustrates the geographic distribution of the iron ore operations reviewed for this study. No secondary products are produced at any of the operations.

Figure 6-32: Geographic Distribution of Iron Ore Subsector Operations

6.3.1 *Effluent Characteristics*

In general, it is expected that the quality of effluent generated by any mine or mill operation, including iron ore operations, will be variable from operation to operation based on site-specific factors, including, but not limited to what mine, mill and waste management facilities are present on site, the operating status of the site (e.g., closed, producing, etc.), and the mineralogy of the ore and waste rock. However, it is also expected that given the common target element for extraction from these operations, and, in particular for the iron ore subsector, the regional clustering of the operations, effluent at iron ore operations will share some similarities.

To establish what typical contaminants of concern are found in untreated effluent at iron ore operations, the following factors were considered:

- What parameters are included in discharge permits for the iron ore operations reviewed.
- What parameters were reported in untreated effluent data by questionnaire respondents.
- What parameters were reported as targeted by effluent treatment processes by questionnaire respondents.

Of the 2 operations that submitted questionnaires to support this study, only 1 elected to provide untreated effluent quality in its submittal. The only parameters reported by this operation are pH (ranging from 7.14 to 7.18) and total suspended solids (ranging from 228 to 2,659 mg/L). No additional untreated effluent quality data was discovered through independent research.

The sole contaminant that is considered to be typical for iron ore operations based on the information reviewed is total suspended solids. Table 6-42 summarizes some characteristics of the reviewed iron ore operations that may contribute to this typical untreated effluent quality.

Table 6-42: Factors Influencing Iron Ore Subsector Untreated Effluent Quality

Ore and Waste Rock Mineralization	Mine and Mill Operational Status and Facilities	Iron Ore Processing
The ore and waste rock mineralization at iron ore operations is fairly consistent, as the ore bodies are concentrated in a single geographic area. The mineralization found at these locations is generally metamorphic hematite, and mine wastes at these operations are generally non-acid generating and non-metal leaching.	• Mine and mill facilities appear in two configurations at iron ore operations reviewed in this study. Mining is typically from open pits. The mine and mill facility configurations of the operations reviewed are: • Mines with associated waste rock and tailings management facilities but no milling facilities. • Mine and mill/concentrator with associated waste rock and tailings management facilities.	• Ore blasting, crushing, and grinding, resulting in TSS generation. • Mine dewatering and ore washing generates TSS-impacted water from contact with the iron ore.

6.3.2 *Effluent Management and Control Techniques*

In an effort to control the volume and quality of effluent requiring containment and treatment prior to discharge to the environment, and to minimize the risk of potential contaminants being released to the environment, iron ore operations employ a variety of techniques to manage water.

The management techniques employed for effluent volume and quality control at iron ore operations reviewed for this study are summarized in Table 6-43.

Table 6-43: Overview of Effluent Management and Control Techniques at Iron Ore Operations

Volume Control	Quality Control	Minimize Environmental Contact
• Diversion of clean or non-impacted surface and groundwater away from facilities which may degrade water quality upon contact. • Recycle of contact water to minimize the volume of water requiring treatment. • Covers (e.g. soil, vegetation, mine or process waste) on inactive facilities to minimize interaction between precipitation and facilities which may degrade water quality upon contact and to divert precipitation away from impacted percolation/seepage, preventing contamination. • Progressive reclamation of site facilities to minimize footprint requiring water collection.	• Explosives best management plan in force. • Subaqueous disposal of tailings.	• Collection of contact water (run-off and seepage) and isolation from the environment during conveyance to treatment. • Storage of potentially reactive wastes in dedicated storage facilities with environmental controls (e.g., liners, covers, seepage monitoring and collection, etc.)

6.3.2.1 *Mine Facilities and Water Management Techniques*

All of the iron ore operations reviewed in this study extract ore via open pit mining, and one operation also uses strip mining. The 2 operations that submitted operations questionnaires utilize the following techniques to minimize mine-water-environment impact:

- Seepage collection (used at both operations).
- Groundwater interception (used at one operation).
- Surface water diversion (used at one operation).

6.3.2.2 *Explosives Use*

The 2 operations that submitted operations questionnaires utilize bulk ANFO explosives. One operates with an explosives best management plan, while the other does not.

6.3.2.3 *Ore Stockpiles and Water Management Techniques*

Of the 2 operations that submitted operations questionnaires, only 1 has active ore stockpiles on site. This operation employs both surface water diversion and seepage collection to minimize ore stockpile-water-environment interactions.

6.3.2.4 *Waste Rock Disposal Methods and Water Management Techniques*

Only 1 of the 2 operations that submitted operations questionnaires reported waste rock disposal on site, and it reported disposing of waste rock in a stockpile with site environmental controls. This operation utilizes a progressive reclamation system of vegetating waste rock areas no longer in use. In addition, surface water is diverted around waste rock stockpiles. The operation utilizes water sprays for dust suppression at active stockpiles to limit dust emissions.

Only 1 operation classified its waste rock according to potential acid generation and/or metal leaching and reported that all waste rock is non-acid generating (NAG) and non-metal leaching (NML). It is possible that, due to geographic proximity to one another, most of the other iron ore operations that did not submit operations questionnaires would produce waste rock with similar properties.

6.3.2.5 *Tailings Disposal Methods and Water Management Techniques*

Only 2 tailings disposal methods were reported between the 2 operations that submitted questionnaires. The relative frequency of use of these techniques is summarized below:

- Sub-aerial disposal in a dedicated tailings storage facility (2 operations).
- Sub-aqueous disposal in a dedicated tailings storage facility (1 operation).
- Some Canadian iron ore operations have authorizations (via *MMER* Schedule 2 amendments) to deposit tailings in natural water bodies.

Both reporting operations dewater tailings prior to final disposal. Tailings are sent to final disposal at either less than 30% solids or between 30 and 50% solids. Neither operation reported any treatment of the tailings (e.g., neutralization) prior to disposal, as this is not a common practice for the iron ore subsector. Both operations recycle water directly from tailings thickening unit operations to make-up processing water and one operation also recycles tailings decant/run-off water to make-up processing water.

The techniques in place at iron ore operations to minimize tailings-water-environment interactions are:

- Surface water diversion (2 operations).
- Progressive reclamation of tailings storage facilities (1 operation).
- Cap/cover (e.g. soil, vegetation) (1 operation).
- Vegetation (1 operation).
- Sacrificial seeding (1 operation).
- Hydroseeding (1 operation).

Sacrificial seeding is mainly used for dust control and involves the use of vegetation to temporarily cover tailings until more tailings are deposited in the same area. Hydroseeding is hydraulic seeding. It is assumed that this is for permanent vegetative cover, in contrast to sacrificial seeding.

6.3.3 *Effluent Treatment Technologies*

All iron ore operations reviewed employ treatment processes to meet discharge criteria established in their discharge permits, licences or certificates of authorization. All of the treatment processes include TSS removal via settling and polishing ponds. TSS from iron ore operations is colloidal, making it difficult to remove via settling alone. As such, some operations utilize coagulant and flocculant to aid settling. Operations that use ferric sulfate as coagulant may also use pH adjustment, as ferric sulfate depresses effluent pH. However, no parameters other than TSS and pH were specifically mentioned as targeted parameters by operations questionnaire respondents.

The chemical treatment and physical processes utilized in effluent treatment at iron ore operations are summarized in Table 6-44.

Table 6-44: Chemical and Physical Processes for Iron Ore Effluent Treatment

Chemical Processes	Physical Processes
• Solid/Liquid Separation • Coagulant (e.g., ferric sulfate) and flocculant (e.g., polymer) and to aid settling. • Neutralization • Sodium hydroxide addition for pH adjustment to compensate for pH depression effects of ferric sulfate.	• Solid/Liquid Separation • Settling ponds.

A single operation reported the utilization of a containerized treatment system with two static mixers, reagent totes, and dosing pumps to mix effluent with ferric sulfate coagulant and sodium hydroxide for pH adjustment. The containerized treatment system is installed between a primary settling basin and a secondary settling basin. The operation is in the process of replacing the containerized treatment system with a new permanent effluent treatment system including the same chemical treatment scheme and cyclones for TSS removal.

It is important to note that treatment processes occurring in pond-based systems are subject to seasonal temperature and precipitation influx variability, which may interrupt treatment processes or cause variations which may negatively affect removal efficiency. Moreover, sudden increases in flow rate, heavy rainfall events, seasonal turnover, and high winds and wave action can re-suspend precipitates, potentially causing downstream non-compliance.

6.3.4 Effluent Quality

Table 6-45 summarizes treated effluent quality at iron ore operations. The effluent ranges, averages, and 95th percentiles include monthly means of data reported to Environment Canada through *MMER* Schedule 4 and Schedule 5, and additional effluent data gathered through independent research on iron ore operations in Newfoundland and Labrador (3) (4).

For existing *MMER* parameters, monthly mean Schedule 4 data provided by Environment Canada and gathered through independent research were aggregated. These values are denoted with "(AD)" for "Aggregate Data". AD data includes all 6 iron ore operations. Discharge points which are no longer operational were removed from the aggregate data set and values below method detection limits (MDL) were replaced by 50% of the MDL, to ensure consistency with Environment Canada's analysis.

Where available, the table includes Environment Canada's reported range of effluent discharge concentrations included in Appendix 2 to Environment Canada's 10-Year Review of *Metal Mining Effluent Regulations* Discussion Paper, titled Possible Changes to Effluent Discharge Limits for Metal Mining Regulations (Table 3.2 – 3 within Appendix 2) (2). These values are denoted with "(EC)" for "Environment Canada". EC data includes 5 of 6 iron ore operations. These data are from monthly average values.

For new *MMER* parameters, Schedule 5 data provided by Environment Canada and data gathered through independent research were aggregated. These values are denoted with "(AD2)" for "Aggregate Data 2". AD2 data includes all 6 iron ore operations. Discharge points which are no longer operational were removed from the aggregate data set and values below method detection limits (MDL) were replaced by 50% of the MDL, to ensure consistency with Environment Canada's analysis. These data are from grab samples, rather than monthly average values.

Based on the data reviewed, TSS is the primary contaminant of iron ore effluent. Instances of non-compliance with existing *MMER* for metals (arsenic, copper, and zinc) tend to be associated with TSS non-compliance, as a fraction of TSS is comprised of particulate metal. Additional contaminants are aluminum and iron (likely associated with TSS), and ammonia (from explosives).

The summary in Table 6-45 for Schedule 4 parameters (pH, arsenic, copper, lead, nickel, radium-226 zinc and TSS) uses monthly average concentration data generated by Environment Canada from grab data reported by operations. An assessment of the extent that the monthly average data adequately represents the grab data was performed for Revision 1 of this study and it was determined that for the most significant statistics (i.e., the 95th percentile), the difference between the monthly mean data and the grab data was minimal. Therefore, in Revision 1, the monthly mean data are carried forward for analysis. A more detailed assessment of the monthly mean data versus the grab data for each subsector is appended to this report in Appendix D.

Table 6-45: Effluent Summary for the Iron Ore Subsector

Parameters	Unit	Effluent Concentration Basis	Minimum	Average	95th Percentile	Maximum
pH		Monthly Mean	3.8 (AD)	7.2 (AD)	8.2 (AD)	9.2 (AD)
Aluminum	mg/L	Grab	0.005 (AD2)	0.25 (AD2)	0.73 (AD2)	7.4 (AD2)
Ammonia, total	mg-N/L	Grab	0.005 (AD2)	1.54 (AD2)	7.76 (AD2)	38 (AD2)
Arsenic	mg/L	Monthly Mean	0.0003	0.0006	0.001	0.014 (AD) 0.004 (EC)
Copper	mg/L	Monthly Mean	0.0005	0.0016 (AD) 0.0015 (EC)	0.003 (AD) 0.004 (EC)	0.058 (AD) 0.020 (EC)
Cyanide	mg/L	n/a	n/a	n/a	n/a	n/a
Iron	mg/L	Grab	0.025 (AD2)	1.33 (AD2)	5.46 (AD2)	41.5 (AD2)
Lead	mg/L	Monthly Mean	0.00009 (AD) 0.00010 (EC)	0.0008 (AD) 0.0010 (EC)	0.001 (AD) 0.002 (EC)	0.022
Nickel	mg/L	Monthly Mean	0.00039 (AD) 0.00050 (EC)	0.0024 (AD) 0.0031 (EC)	0.013 (AD) 0.020 (EC)	0.029
Radium-226	Bq/L	Monthly Mean	0.0005 (AD)	0.006 (AD)	0.016 (AD)	0.1 (AD)
Selenium[17]	mg/L	Grab	0.0005	0.001	0.005	0.009
Zinc	mg/L	Monthly Mean	0.00075 (AD) 0.00100 (EC)	0.0078 (AD) 0.0100 (EC)	0.024 (AD) 0.028 (EC)	0.071
TSS	mg/L	Monthly Mean	0.32 (AD)	13 (AD)	55 (AD)	315 (AD)

Notes:
Values reported as less than the method detection limit have been incorporated at 50% of the MDL value.
All metal concentrations are total metal concentrations, i.e., the sum of dissolved and suspended fractions.
AD: Aggregate data from *MMER* Schedule 4 reporting and Newfoundland & Labrador provincial reporting. These data are from monthly average values.
EC: Data from Appendix 2 Table 3.2 – 3 of Environment Canada's 10-Year Review of the Metal Mining Effluent Regulations Discussion Paper. These data are from monthly average values.
AD2: Aggregate data from *MMER* Schedule 5 reporting and Newfoundland & Labrador provincial reporting. These data are from grab samples.

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[17] Compiled from grab and composite selenium concentrations reported through Schedule 5 for 2012.

6.3.5 *Model Water Management and Effluent Treatment System*

6.3.5.1 *Model Water Management System*

Based on this review, a model water management plan to represent the typical water management practices employed at iron ore operations has been generated and is presented in Figure 6-33.

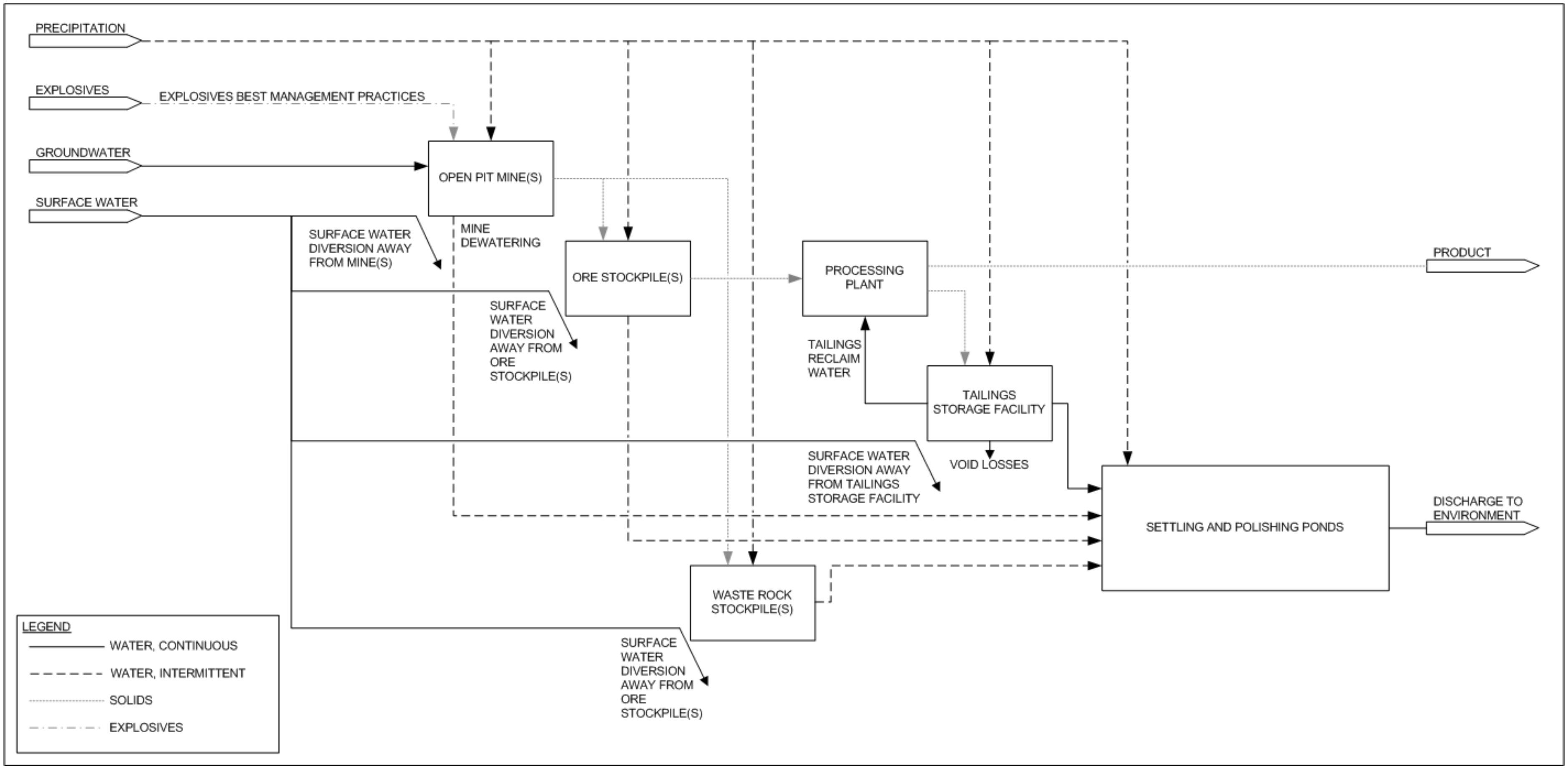

Figure 6-33: Iron Ore Subsector Water Management Model

6.3.5.2 *Model Effluent Treatment System Process Flow Diagram*

To determine a model effluent treatment system for iron ore operations, the parameters targeted by effluent treatment processes and the chemical and physical processes involved in effluent treatment processes were reviewed.

All effluent treatment processes examined include the use of ponds to remove solids. The use of flocculant to aid in the settling of solids is common. The only effluent treatment technique employed that is a variation from the norm is the use of static mixers to mix effluent with ferric sulfate coagulant and sodium hydroxide for subsequent pH adjustment.

As a result of these considerations, the model treatment system illustrated in Figure 6-34 was established. This system closely resembles reviewed effluent treatment systems, but is not identical to any one treatment system.

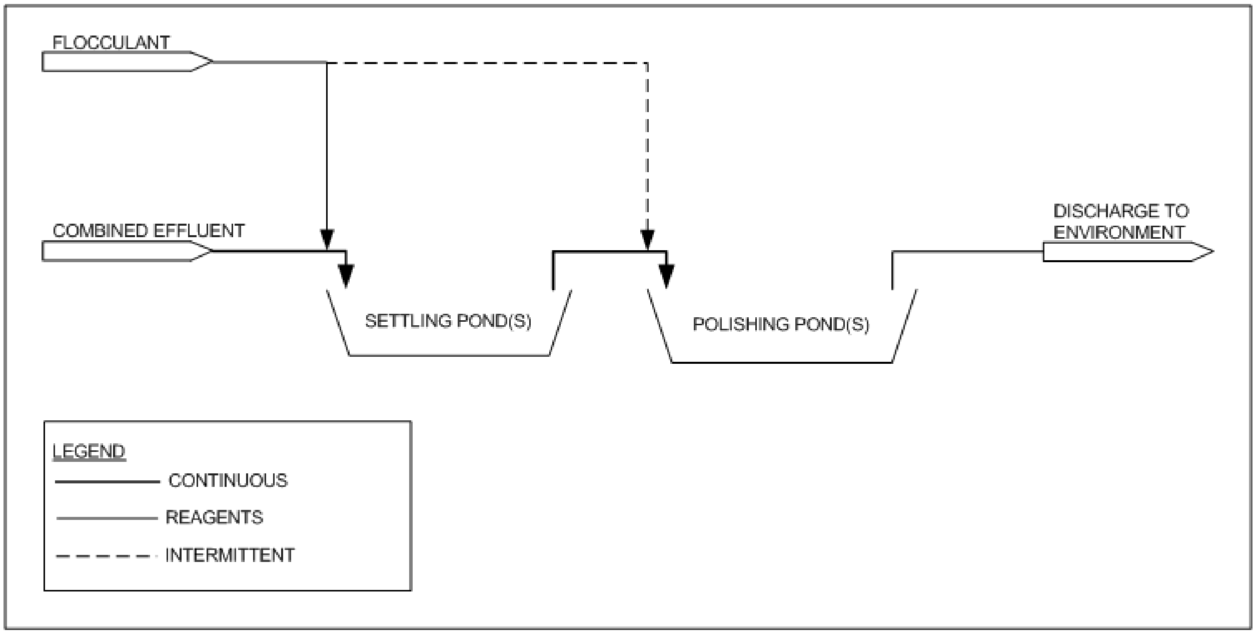

Figure 6-34: Iron Ore Subsector Model Effluent Treatment Process

6.3.5.3 *Model Effluent Treatment System Flow Rate*

1

For Revision 0, to establish a flow rate for the model effluent treatment system, two sources of treatment system flow rate and discharge volume information were used:

- Final discharge point flow rates reported to Environment Canada as part of *MMER* reporting for 2008 – 2010 (the analysis of which generated data set “A” in Table 6-46), and
- Average and design flow rates for effluent treatment systems reported by questionnaire respondents and mini-survey[18] respondents (the analysis of which generated data sets “B” and “C”, respectively in Table 6-46).

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[18] For Revision 1, additional data about effluent treatment systems was also collected from operations that did not provide information for Revision 0. An additional three operations provided information about the treatment systems utilized for effluent prior to discharge and treatment volumes.

The Environment Canada *MMER* reported data set is a complete set of monthly discharge volumes for all mines subject to *MMER* during 2008 – 2010, and thus is a valuable data source as it provides several years of discharge volumes, and additionally, data for those operations that did not participate in the study questionnaire. This data set, however, presents total discharge volumes from operations to the environment at the final discharge point(s) from the site and does not necessarily reflect the volume of water treated prior to discharge, nor the design capacities of effluent treatment systems, which are of significance when considering the costs of modifications/augmentations to effluent treatment systems.

The discharge volumes reported to Environment Canada may differ from the treated volumes as they may include incident precipitation to ponds downstream of effluent treatment systems or streams that do not require treatment. Nonetheless, due to the completeness of this data set compared to the data received via the questionnaire, in terms of time span of data collection and operation participation, it was considered valuable in the selection of a typical design flow rate. This monthly reported data was used to calculate the total annual discharge volume from operations, from which rough average annual hourly flow rates were calculated assuming continuous discharge (24 hours/day, 365 days/year). These values are presented in Table 6-46. This approach may not accurately represent flow rates treated by effluent treatment systems for the following reasons:

- This approach summed the discharge volumes from all final discharge points associated with an operation; for sites with multiple final discharge points, this approach overestimates the total volume requiring treatment by any one treatment system; however, if all final discharge points at an operation were to require augmentation of their effluent treatment systems, this may be representative of the total sum of the capacities of augmentative technologies for a single operation.
- This approach may account for volume that is not actively treated in an effluent treatment system (e.g., accounts for volumes treated only by settling ponds).
- This approach assumes that treatment occurs 365 days a year, for 24 hours a day. This approach could underestimate the treatment system flow rates for those sites that only treat for a portion of the year (e.g., in summer only) or day (e.g., during day shift only).

The second source of data reviewed in the process of establishing the model treatment system was treatment flow rate data provided via the Revision 0 operations questionnaire. As part of the questionnaire, operations were prompted to provide the average, design, maximum and minimum treatment flow rates for their effluent treatment systems. This data set is limited to those operations that provided this information as part of their questionnaire responses, and is thus a less complete data set as compared to the Environment Canada *MMER* reported discharges volumes. However, this data set is a valuable source of information concerning design capacities of treatment technologies, which are not apparent from reported discharge volumes. The average flow rates reported via the questionnaire were used to informally cross-check the questionnaire-reported values against the Environment Canada *MMER* reported values, and the design flow rates are used in the consideration of the typical effluent treatment system design flow rate, or the equipment capacity that would need to be installed for new equipment.

Following the release of Revision 0, two additional sources of treatment system flow rate and discharge volume information were available for review. These sources of treatment system flow rate and discharge volume information and the analysis performed on them are summarized below:

- Environment Canada provided monthly flow rate data reported through *MMER* for 2005 – 2012 for a subset of the iron ore subsector. The methodology undertaken by Environment Canada to analyze this flow rate data was as follows and the approach Hatch took with respect to the iron ore subsector is as follows:
    - To generate approximate average hourly discharge volumes, Environment Canada analyzed the data by calculating the average daily flow rates by month for each discharge point reporting to *MMER*, then assuming that discharge occurs over 24 hours a day. This methodology identifies the average discharge flow rate from each site based on seven years of Schedule 4 data. Hatch re-performed this analysis considering all iron ore final discharge points for 2008 – 2010, except one final discharge point which was considered an extreme outlier (excluded per discussion below). Hatch's analysis generated data set "D" in Table 6-46.
    - To generate approximate maximum hourly discharge volumes for the highest monthly discharge, Environment Canada analyzed the data by first identifying the highest monthly discharge volume for each discharge point reporting to *MMER*, then assuming that discharge occurs continuously over the whole month, for 24 hours a day. This method identifies an approximate hourly discharge flow rate for the highest monthly discharge from each site based on seven years of Schedule 4 data. Hatch re-performed this analysis considering all iron ore final discharge points for 2008 – 2010, except one final discharge point which was considered an extreme outlier (excluded per discussion below). Hatch's analysis generated data set "E" in Table 6-46.

  - ◆ The approaches described above may not accurately represent flow rates treated by effluent treatment systems as they assume that treatment occurs over the entire month, for 24 hours a day. This approach could underestimate the treatment system flow rates for those sites that only treat for a portion of the year (e.g., in summer only) or day (e.g., during day shift only).

- The MEND Report 3.43.1, Review of Mine Drainage and Sludge Management Operations, contains all data collected by the survey associated with the report, including operation subsector classifications and maximum, average and minimum treatment flow rates (1). However, no iron ore operation data are included in this database so this treatment system flow rate source was not used in the revision of flow rates.

In Revision 0, the average treatment flow rate applied for the model effluent treatment system was 6,500 m^3/h based on the average of the estimated average annual hourly discharge volume based on all *MMER* reported final discharge volumes for each operation (data set “A”), and the design treatment flow rate was 27,000 m^3/h based on the median of the estimated average annual hourly discharge volume based on all *MMER* reported final discharge volumes for each operation (data set “A”).

Commentary on Revision A / Revision 0 raised concerns about the use of average and median flow rates of the total cohort of discharge data from iron ore subsector as representative of treatment system flow rates for the iron ore subsector, as this analysis includes several final discharge points that are exit points from lakes used as tailings impoundment areas (TIAs). In one instance, it was confirmed that the TIA/lake receives the total volume of run-off from the lake’s watershed, which contributes to the volume reported at the final discharge point. This discharge volume therefore could represent a larger volume of water than what run-off and precipitation reporting to the operation’s site would generate. It is important to note that the tailings stored in such TIAs/lakes may impact the water reporting to these lakes. As the outflow from these lakes is the regulated final discharge point and thus, is the point of compliance for the quality of the discharge, if the effluent quality at these discharge points was non-compliant with *MMER*, the effluent quality would require management either with upstream water management practices or by treatment of some or all of the discharge volume.

As part of the Revision 1 scope, the iron ore model effluent treatment system flow rate volume has been revised based on this concern and additional data received as part of the Revision 1 effort.

The iron ore subsector has a large variation in discharge volumes reported to *MMER*, due in part to the use of lakes as TIAs. To investigate the extent of this variability, the total annual discharge volumes reported by iron ore operations to Environment Canada for 2008 – 2010 have been graphed and are presented in Figure 6-35.

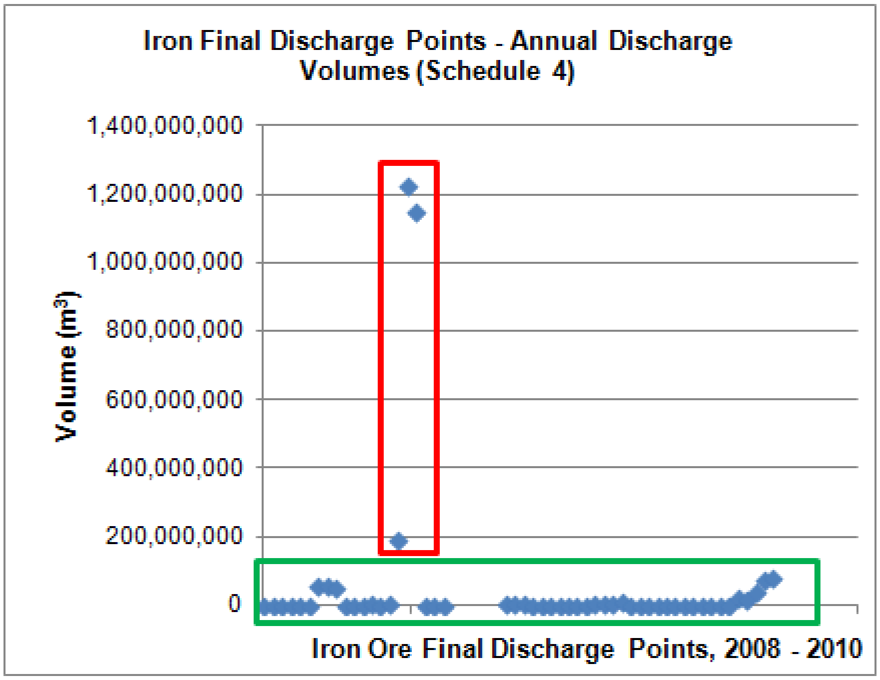

Figure 6-35: Total Annual Discharge Volume from Iron Ore Final Discharge Points

Figure 6-35 illustrates the extraordinary variability in the total annual discharge volumes released from iron ore operations. For Revision 1, the final discharge point represented by the data in the red square box that discharges between 200 million cubic metres of effluent (reflecting only 3 months of discharge) and 1.2 billion cubic metres (reflecting 12 months of discharge from this final discharge point) each year has been excluded from the flow rate analysis as this final discharge point is an extreme outlier. Were this effluent to not comply with *MMER* discharge limits, it is expected that none of the augmentative technologies investigated in this report would be economically feasible to install or operate at the treatment flow rate required to manage the effluent reporting to this final discharge point.

The final discharge points represented by the data within the green square box (final discharge points discharging less than 100 million cubic metres per year) have been considered going forward with this analysis to determine a representative model effluent treatment system flow rate.

Table 6-46: Summary of Reviewed Discharge and Treatment Flow Rates for the Iron Ore Subsector

	Data Set	Methodology	Range (m^3/h)	Average (m^3/h)	Median (m^3/h)
Data Sets Informing Selection of Nominal Model Effluent Treatment System Flow Rates					
A	**Estimated Average Annual Hourly Discharge Volume: Sum of All Final Discharge Points per Site**[19]	Annual discharge volumes for each final discharge point and each site were calculated utilizing Schedule 4 monthly discharge volumes as reported by operations to Environment Canada. The maximum, minimum, average and median annual site discharge volumes were then calculated. These annual site discharge volumes were assumed to occur continuously over 365 days a year and 24 hours a day to generate hourly max, min, average and median flow rates.	31 – 140,600	6,400	26,800
B	**Questionnaire Reported Average Treatment System Flow Rate/Capacity**	The average treatment flow rate volumes provided by operations via the Revision 0 operations questionnaire and the Revision 1 mini-survey were used to calculated maximum, minimum, average and median values.	100 – 20,000	5,670	1,590
D	**Estimated Average Hourly Flows per Final Discharge Point (Hatch Analysis per EC Methodology)**	Schedule 4 monthly flow volume data reported to Environment Canada from 2008 – 2010 was used in this analysis. The average daily discharge volume was identified for each final discharge point. It was assumed that treatment and discharge occurred continuously to generate hourly volumes. Maximum, minimum, average and median values were then calculated for the hourly flow rates determined in this fashion.	0.2 – 21,800	2,000	490
Data Sets Informing Selection of Design Model Effluent Treatment System Flow Rates					
C	**Questionnaire Reported Design/Maximum Treatment System Flow Rate/Capacity**	Operations were prompted for their design and maximum treatment flow rates as part of the Revision 0 operations questionnaire and the Revision 1 mini-survey. The maximum of these two numbers were used to generate a data set for the maximum/design treatment values for the subsector. Maximum, minimum, average and median values were calculated for this data set.	2,271 – 30,000	14,200	10,400
E	**Estimated Average Maximum Hourly Flows per Final Discharge Point**	Schedule 4 monthly flow volume data reported to Environment Canada from 2008 – 2010 was used in this analysis. The maximum monthly discharge volume was identified for each final discharge point. It was assumed that treatment and discharge occurred continuously over the entire month to generate hourly volumes. Maximum, minimum, average and median values were then calculated for the hourly flow rates determined in this fashion.	12 – 21,782	3,700	500

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[19] Based on sum of annual discharge volumes at all final discharge points reported to Environment Canada through *MMER* Schedule 4 from 2008 – 2010. Assumes 365 days/year, 24 hours/day discharge.

In Revision 1, data set “D” was also considered in addition to data sets “A”, “B”, to review the nominal model effluent treatment system flow rates utilized in Revision 0. 1

Based on the data sets and analysis presented in Table 6-46, the average nominal treatment flow rate for the iron ore subsector is between 2,000 m^3/h and 5,670 m^3/h.

The lower value is based on data set “D” which calculates the average daily discharge volume, then assuming continuous discharge of 24 hours/day calculates an approximate hourly discharge volume. This methodology may overestimate the period of discharge (numbers of hours per day that discharge occurs and/or the plant is operated). These numbers may therefore be skewed somewhat low.

The highest value is generated by the data set “B”, which is based on treatment system flow rates and capacity reported via operations questionnaire. This data set is incomplete (e.g., not all sites reporting to Environment Canada in Schedule 4 have provided treatment system flow rates via questionnaire), and may be skewed by sites with higher treatment system flow rates reporting while systems with lower treatment system flow rates have not reported design treatment system flow rate.

To reconcile the difference between these values, recognizing that neither data set or methodology is a completely accurate reflection of the average nominal treatment system flow rates in the iron ore subsector, a median between the two values has been taken to establish the average treatment system flow rate for the model effluent treatment system of 3,900 m^3/h. This value will be used to generate operating costs for augmentative BAT.

In Revision 1, data set “E” was also considered in addition to data set “C”, to review the design model effluent treatment system flow rates utilized in Revision 0.

Based on the data sets and analysis presented in Table 6-46, the average design treatment flow rate for the iron ore subsector is between 3,700 m^3/h and 14,200 m^3/h.

The lower value is generated by data set “E”. In this methodology, the maximum monthly discharge volume in 2008 – 2010 has been generated assuming treatment of that volume occurs over all days of the month for 24 hours/day. This methodology may overestimate the number of hours that discharge occurs, which could underestimate the treatment system flow rate for operations that do not operate their treatment systems over the entire month or for 24 hours/day.

The highest value is generated by the data set “C”, which is based on treatment system flow rates and capacity reported via operations questionnaire. This data set is incomplete (e.g., not all sites reporting to Environment Canada in Schedule 4 have provided treatment system flow rates via questionnaire), and it is possible this value could be skewed by sites with higher treatment system flow rates reporting while systems with lower treatment system flow rates have not reported design treatment system flow rate. Furthermore, the highest design capacity reported within this data set is based on the capacity of a treatment system which is somewhat oversized for the application, as a result of the treatment system not being tailored to the operations effluent flow rates; however, the extent of oversizing is unknown. When the value is removed from analysis, the average design treatment system flow rate is 6,400 m^3/h.

To reconcile the difference between these values, recognizing that no data set or methodology is a completely accurate reflection of the average design treatment system flow rates in the iron ore subsector, the following values were considered:

- 3,700 m^3/h (Maximum monthly discharge volume assuming discharge every day for 24 hours/day, data set “E”).
- 6,400 m^3/h (Average design capacity of questionnaire respondents excluding the highest reported design flow rate).
- 14,200 m^3/h (Average design capacity of all questionnaire respondents, data set “D”).
- A value of 7,000 m^3/h has been selected as the design flow rate for the iron ore model effluent treatment system, as a midrange value of all three of the averages of the flow rate data sets considered above, with a slight correction to account for the apparent skew in the averages of the flow date sets, which are high when compared to the median values in data sets “B”, “C”, “D” and “E”. This value will be used to generate capital equipment and installed costs for augmentative BAT.

6.3.5.4 *Model Effluent Treatment System Effluent Quality*

In Revision 0 of this report, the 95th percentile of the effluent quality summary for the entire iron ore subsector (as summarized in Table 6-45) for each parameter was used to represent the effluent quality that was produced by the model effluent treatment system. It was assumed that for each parameter, the 95th percentile would reflect the concentration in the effluent at the majority of sites and that the 95th percentile value associated with the complete data set would be weighted to reflect the most common effluent treatment technologies (and therefore the model effluent treatment system), as the most common effluent treatment systems would contribute a larger fraction of the concentration values than other systems.

Feedback received from industry indicated two main concerns with the use of 95th percentile values as representative of the model effluent treatment system, as follows:

1. The total cohort of final discharge effluent quality data for the subsector originates from a variety of effluent treatment systems, and not just systems very similar or equivalent to the model effluent treatment system. This could skew the 95th percentile values, as other types of effluent treatment systems may achieve higher or lower concentrations than the model. Thus, using the total cohort of final discharge effluent quality data for the subsector may not be representative of the concentrations specifically achieved by the model effluent treatment system.
2. Using the total cohort of final discharge effluent quality data for the subsector may result in average and 95th percentile values that are skewed low by the inclusion of concentration data from effluent treatment systems that do not target or remove a given parameter (i.e., where the concentration of a given parameter in untreated effluent is compliant with existing *MMER* without treatment). Using the total cohort of final discharge effluent quality data does not consider which concentration values reflect concentrations achievable by treatment, and thus, may not be representative of the concentration achieved by any given treatment system.

To better reflect the concentrations achieved by subsector effluent treatment systems very similar to or equivalent to the model effluent treatment system for systems that target the removal of the parameters in question, Hatch compared concentration statistics for subsets of Schedule 4 and Schedule 5 data. The subsets were organized according to type of effluent treatment system and targeted parameters. Effluent treatment system information was collected during Revision 0 work via questionnaire and independent research, and augmented with additional data collected during Revision 1 work. The purpose of this effort was to narrow the total cohort of final discharge effluent quality data down to the concentration values that are more representative of concentrations achieved by systems similar to the model effluent treatment system.

Two types of effluent treatment systems utilized by iron ore subsector operations were of interest for this analysis: systems similar to the model effluent treatment system (referred to as “model effluent treatment systems”) and systems that are not exactly like the model effluent treatment system but utilize a process that can achieve similar effluent quality to model effluent treatment systems. For the iron ore subsector, these types of treatment systems are defined as follows:

- **Model Effluent Treatment Systems:** Operations utilizing pond settling for TSS, with flocculant addition to aggregate suspended solids and increase settling.

In other subsectors, another type of effluent treatment system examined in this work was those systems considered “model equivalents”, however as there is essentially only one type of treatment system for the iron ore subsector (pond-based settling – the main differentiator between systems is whether a flocculant is used or not), no model equivalent exists for this subsector. However, statistics for final discharge points whose effluent undergoes sedimentation in pond but no flocculant have been provided in this analysis for comparison.

For the iron ore sector, the critical parameters for which concentration statistics were developed were total suspended solids, arsenic, copper, nickel, lead, zinc, aluminum, selenium, total ammonia (as nitrogen), and iron. The majority of sites target only TSS and removal of specific parameters (e.g., iron) is typically achieved through this TSS reduction.

For each of the critical parameters, effluent concentration statistics have been developed for the subsets of the iron ore subsector effluent data generated by:

1. Model effluent treatment systems.
2. Model effluent treatment systems and model equivalent effluent treatment systems.
3. Effluent treatment systems that target the parameter.
4. Model effluent treatment systems that target the parameter.
5. Model effluent treatment systems and model equivalent effluent treatment systems that target the parameter.

Effluent treatment systems targeting parameters were identified per self-reporting by operations via the Revision 0 questionnaire and the Revision 1 mini-survey; this self-reported information was confirmed to the extent possible using paired untreated effluent and treated effluent quality data provided by operations where available. Where information provided in the Revision 0 questionnaire differed from the information provided in the Revision 1 questionnaire, the operation was contacted to ensure a correct understanding of the information.

A comparison between the concentration statistics for each subset of data was performed to assess the extent to which the utilization of the total cohort of the iron ore subsector effluent quality data may skew the concentration statistics in comparison to data associated with model or model equivalent effluent treatment systems that target the parameter. The number of final discharge points associated with each data set is also provided. As the 95th percentile values are used in augmentative BAT cost estimation and BATEA selection later in this report, the agreement between the data subsets for this statistic (95th percentile) is considered more heavily than the other concentration statistics (minimum, average and maximum). For each parameter, a final model effluent treatment system effluent concentration is estimated based on this assessment.

6.3.5.4.1 Arsenic

Table 6-47 summarizes the arsenic concentration statistics for subsets of the iron ore final discharge effluent quality data; observations on these statistics and conclusions for the iron ore subsector are summarized below.

Table 6-47: Arsenic Concentration Statistics for the Iron Ore Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00033	0.00070	0.0010	0.010	22
Model(s)	0.00041	0.00060	0.0010	0.0010	2
Model(s) and Model Equivalent(s)	0.00033	0.00060	0.0010	0.0026	9
Self-Identified as Targeting	No data.				0
Model(s) that Self-Identify as Targeting	No data.				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	No data.				0

- Arsenic is not reported as targeted by any iron ore operation.
- There is little to no difference between the average and 95th percentile concentration values for all data subsets.
- Any removal of arsenic by sedimentation ponds (with or without addition of flocculant) would occur primarily though the removal of TSS. As the concentrations of arsenic are very low in the effluent, it is assumed that arsenic is not typically present in untreated effluent at iron ore sites in any significant concentration.
- As no effluent treatment systems target arsenic and thus the concentrations achieved by the model effluent treatment systems site are not necessarily attributable to the treatment process, to be conservative the 95th percentile value will be utilized to represent the concentration in the final effluent of the model effluent treatment system. The 95th percentile value for arsenic is <0.001 mg/L.

6.3.5.4.2 Copper

Table 6-48 summarizes the copper concentration statistics for subsets of the iron ore final discharge effluent quality data; observations on these statistics and conclusions for the iron ore subsector are summarized below.

Table 6-48: Copper Concentration Statistics for the Iron Ore Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.0005	0.0019	0.0050	0.020	22
Model(s)	0.0005	0.0012	0.0030	0.005	2
Model(s) and Model Equivalent(s)	0.0005	0.0016	0.0034	0.020	9
Self-Identified as Targeting	No data.				0
Model(s) that Self-Identify as Targeting	No data.				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	No data.				0

- Copper is not reported as targeted by any iron ore operation.
- There is minimal difference between the average and 95th percentile concentration values for all data subsets.
- Any removal of copper by sedimentation ponds (with or without addition of flocculant) would occur primarily though the removal of TSS. As the concentrations of copper are very low in the effluent, it is assumed that copper is not typically present in untreated effluent at iron ore sites in any significant concentration.
- As no effluent treatment systems target copper and thus the concentrations achieved by the model effluent treatment systems site are not necessarily attributable to the treatment process, to be conservative the 95th percentile value will be utilized to represent the concentration in the final effluent of the model effluent treatment system. The 95th percentile value for copper is <0.005 mg/L.

6.3.5.4.3 Lead

Table 6-49 summarizes the lead concentration statistics for subsets of the iron ore final discharge effluent quality data; observations on these statistics and conclusions for the iron ore subsector are summarized below.

Table 6-49: Lead Concentration Statistics for the Iron Ore Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00009	0.0010	0.0020	0.020	22
Model(s)	0.00010	0.00087	0.0025	0.0068	2
Model(s) and Model Equivalent(s)	0.00010	0.00096	0.0014	0.022	9
Self-Identified as Targeting	No data.				0
Model(s) that Self-Identify as Targeting	No data.				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	No data.				0

- Lead is not reported as targeted by any iron ore operation.
- There is minimal difference between the average and 95th percentile concentration values for all data subsets.
- As no effluent treatment systems target lead and thus the concentrations achieved by the model effluent treatment systems site are not necessarily attributable to the treatment process, to be conservative the 95th percentile value will be utilized to represent the concentration in the final effluent of the model effluent treatment system. The 95th percentile value for lead is <0.003 mg/L.

6.3.5.4.4 Nickel

Table 6-33 summarizes the nickel concentration statistics for subsets of the iron ore final discharge effluent quality data; observations on these statistics and conclusions for the iron ore subsector are summarized below.

Table 6-50: Nickel Concentration Statistics for the Iron Ore Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.0005	0.0030	0.017	0.029	22
Model(s)	0.0005	0.0011	0.0025	0.0049	2
Model(s) and Model Equivalent(s)	0.0005	0.0044	0.023	0.029	9
Self-Identified as Targeting	No data.				0
Model(s) that Self-Identify as Targeting	No data.				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	No data.				0

- Nickel is not reported as targeted by any iron ore operation.
- There is minimal difference between the average and 95th percentile concentration values for all data subsets.
- As no effluent treatment systems target nickel and thus the concentrations achieved by the model effluent treatment systems site are not necessarily attributable to the treatment process, to be conservative the 95th percentile value will be utilized to represent the concentration in the final effluent of the model effluent treatment system. The 95th percentile value for nickel is <0.003 mg/L.

6.3.5.4.5 Zinc

Table 6-51 summarizes the zinc concentration statistics for subsets of the iron ore final discharge effluent quality data; observations on these statistics and conclusions for the iron ore subsector are summarized below.

Table 6-51: Zinc Concentration Statistics for the Iron Ore Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00075	0.0097	0.027	0.071	22
Model(s)	0.00075	0.0097	0.033	0.071	2
Model(s) and Model Equivalent(s)	0.0023	0.0095	0.025	0.049	9
Self-Identified as Targeting	No data.				0
Model(s) that Self-Identify as Targeting	No data.				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	No data.				0

- Zinc is not reported as targeted by any iron ore operation.
- There is minimal difference between the average and 95th percentile concentration values for all data subsets.
- As no effluent treatment systems target zinc and thus the concentrations achieved by the model effluent treatment systems site are not necessarily attributable to the treatment process, to be conservative the 95th percentile value will be utilized to represent the concentration in the final effluent of the model effluent treatment system. The 95th percentile value for zinc is <0.04 mg/L.

6.3.5.4.6 Total Suspended Solids

Table 6-52 summarizes the total suspended solids concentration statistics for subsets of the iron ore final discharge effluent quality data; observations on these statistics and conclusions for the iron ore subsector are summarized below.

Table 6-52: Total Suspended Solids Concentration Statistics for the Iron Ore Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.5	14.7	61.6	315.2	22
Model(s)	1	30.4	109.1	315.2	2
Model(s) and Model Equivalent(s)	0.5	12.5	29.4	292.5	9
Self-Identified as Targeting	0.5	16.9	66.2	315.2	11
Model(s) that Self-Identify as Targeting	1	30.4	109.1	315.2	2
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.5	12.5	29.4	292.5	9

- TSS is reported as targeted for removal from effluent prior to discharge at eleven iron ore final discharge points. Two of these operations are classified as model effluent treatment systems (e.g., utilize flocculant to encourage settling) and nine are sedimentation only systems (with no flocculant addition).
- The final TSS average and 95th percentile concentrations achieved by the model effluent treatment systems, that utilize flocculant, are higher than both the overall subsector and sedimentation pond only average and 95th percentiles. The use of flocculant would be expected to improve TSS removal; however, it may also indicate that these sites have suspended matter that is not easily settlable and thus requires the use of a flocculant to encourage settling.
- The 95th percentile associated with the effluent treatment systems similar to the model is 109 mg/L; however this is value is considered to be high for TSS removal by pond-based settling. Thus, the concentration achieved by the entire subsector will be used as the base case moving forward for the TSS achieved by the iron ore subsector model treatment system (e.g., <62 mg/L).

6.3.5.4.7 Aluminum

Table 6-53 summarizes the aluminum concentration statistics for subsets of the iron ore final discharge effluent quality data; observations on these statistics and conclusions for the iron ore subsector are summarized below.

Table 6-53: Aluminum Concentration Statistics for the Iron Ore Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.01	0.25	0.73	9.20	20
Model(s)	0.01	0.10	0.27	0.49	2
Model(s) and Model Equivalent(s)	0.01	0.23	0.73	3.32	7
Self-Identified as Targeting	No data.				0
Model(s) that Self-Identify as Targeting	No data.				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	No data.				0

- Aluminum is not reported as targeted by any iron ore operation.
- The model effluent treatment system operations have lower aluminum concentrations in their final effluent than other operations, however as these sites do not specifically target aluminum for removal, and these sites have higher TSS concentrations, it is assumed this is the result of lower influent concentrations rather than targeted removal.
- To be conservative, as no sites target aluminum for removal and thus the concentrations achieved by the model effluent treatment systems site are not necessarily attributable to the treatment process, the 95th percentile for the entire subsector will be used to represent the aluminum concentration achieved by the iron ore subsector model effluent treatment system (<0.8 mg/L).

6.3.5.4.8 Iron

Table 6-54 summarizes the iron concentration statistics for subsets of the iron ore final discharge effluent quality data; observations on these statistics and conclusions for the iron ore subsector are summarized below.

Table 6-54: Iron Concentration Statistics for the Iron Ore Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.03	1.32	5.46	41.5	20
Model(s)	0.05	3.86	17.00	41.5	2
Model(s) and Model Equivalent(s)	0.03	0.86	3.64	10.4	7
Self-Identified as Targeting	0.06	0.76	3.60	6.9	3
Model(s) that Self-Identify as Targeting	No data.				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.06	0.76	3.60	6.9	3

- Iron is reported as targeted for removal prior to discharge at three final discharge points in the iron ore subsector. All three of these systems are sedimentation-only systems; none represent the model effluent treatment system.
- Concentrations achieved at operations similar to the model effluent treatment system have higher average and 95th percentile concentrations of iron in their final effluent than the sedimentation-only operations. However, the operations similar to the model effluent treatment system do report targeting iron for removal. Operations reporting targeting iron have concentrations <3.6 mg/L.
- In absence of sufficient information explaining the discrepancy between the model and sedimentation-only systems, the 95th percentile for the entire subsector will be used to represent the concentration achieved by the iron ore subsector model effluent treatment system (<5.5 mg/L).

6.3.5.4.9 Selenium

Table 6-38 summarizes the selenium concentration statistics for subsets of the iron ore final discharge effluent quality data; observations on these statistics and conclusions for the iron ore subsector are summarized below.

Table 6-55: Selenium Concentration Statistics for the Iron Ore Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.0005	0.001	0.005	0.009	20
Model(s)	0.0005	0.0005	0.0005	0.0005	2
Model(s) and Model Equivalent(s)	0.0005	0.0008	0.001	0.009	7
Self-Identified as Targeting	No data.				0
Model(s) that Self-Identify as Targeting	No data.				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	No data.				0

- Selenium is not reported as targeted by any iron ore operation.
- There is minimal difference between the average and 95th percentile concentration values for all data subsets.
- To be conservative, as no sites target selenium for removal and thus the concentrations achieved by the model effluent treatment systems site are not necessarily attributable to the treatment process, the 95th percentile for the entire subsector will be used to represent the concentration achieved by the iron ore subsector model effluent treatment system (<0.005 mg/L).

6.3.5.4.10 Total Ammonia (as Nitrogen)

Table 6-56 summarizes the total ammonia (as nitrogen) concentration statistics for subsets of the iron ore final discharge effluent quality data; observations on these statistics and conclusions for the iron ore subsector are summarized below.

Table 6-56: Total Ammonia Concentration Statistics for the Iron Ore Subsector

Data Set	Minimum (mg-N/L)	Average (mg-N/L)	95th Percentile (mg-N/L)	Maximum (mg-N/L)	# of Final Discharge Points
All Data	0.01	1.60	7.76	38.0	20
Model(s)	0.03	0.57	1.90	3.40	2
Model(s) and Model Equivalent(s)	0.01	2.89	9.90	38.00	7
Self-Identified as Targeting	No data.				0
Model(s) that Self-Identify as Targeting	No data.				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	No data.				0

- Total ammonia is not reported as targeted by any iron ore operation.
- The model effluent treatment system-like operations have lower total ammonia concentrations in their final discharge. However, total ammonia is not actively removed by the model effluent treatment system. Some ammonia may be removed by natural degradation in sedimentation ponds.
- To be conservative, as no sites target total ammonia for removal and thus the concentrations achieved by the model effluent treatment systems site are not necessarily attributable to the treatment process, the 95th percentile for the entire subsector will be used to represent the concentration achieved by the iron ore subsector model effluent treatment system (<7.76 mg/L).

6.3.5.4.11 Model Effluent Treatment System Effluent Concentration Summary

The 95th percentile concentrations achieved by model and model equivalent effluent treatment systems are summarized in Table 6-57. These will be used as representative of the concentrations produced by the model effluent treatment system for augmentative technology costing and BATEA selection.

Table 6-57: Concentrations Achieved by the Model Treatment System in the Iron Ore Subsector

Parameter	Concentration
Arsenic	<0.001 mg/L
Copper	<0.005 mg/L
Lead	<0.003 mg/L
Nickel	<0.003 mg/L
Zinc	<0.04 mg/L
TSS	<62 mg/L
Aluminum	<0.8 mg/L
Iron	<5.5 mg/L
Selenium	<0.005 mg/L
Total Ammonia (as nitrogen)	<7.76 mg-N/L

6.4 Metals Sector: Uranium

Effluent discharges from active operations or operations in development within this review are subject to the current *Metal Mining Effluent Regulations,* and per Environment Canada's 10-Year Review of *Metal Mining Effluent Regulations*, would be subject to the proposed changes to *MMER* for metal mines. None of the uranium operations subject to *MMER* have been identified by Environment Canada as being potentially impacted by the changes in discharge limits proposed for the parameters that are currently regulated (arsenic, copper, cyanide, lead, nickel and zinc), however analysis concerning the potential impact of the additional parameters (ammonia, iron, selenium) proposed by Environment Canada is not available.

Canadian uranium operations are listed in Table 6-58. Of these, the review of the Canadian uranium subsector included a total of 12 operations, 7 of which submitted complete operations questionnaires as part of the data collection portion of the study. Information for the other 5 operations was collected from independent research efforts and from in-house information.

Table 6-58: Canadian Uranium Operations

Operation	Owner/Operator	Location	Status
McClean Lake	AREVA Resources Canada Inc.	Wollaston Lake, SK	Care and Maintenance
Key Lake	Cameco Corporation	Cree Lake, SK	Operating
McArthur River	Cameco Corporation	Cree Lake, SK	Operating
Rabbit Lake	Cameco Corporation	Wollaston Lake, SK	Operating
Cigar Lake	Cameco Corporation	Wollaston Lake, SK	Development
Buckles	BHP Billiton/Rio Algom Ltd.	Elliot Lake, ON	Closed
Lacnor	BHP Billiton/Rio Algom Ltd.	Elliot Lake, ON	Closed
Milliken	BHP Billiton/Rio Algom Ltd.	Elliot Lake, ON	Closed
Nordic	BHP Billiton/Rio Algom Ltd.	Elliot Lake, ON	Closed
Panel	BHP Billiton/Rio Algom Ltd.	Elliot Lake, ON	Closed
Pronto	BHP Billiton/Rio Algom Ltd.	Elliot Lake, ON	Closed
Quirke	BHP Billiton/Rio Algom Ltd.	Elliot Lake, ON	Closed
Spanish American	BHP Billiton/Rio Algom Ltd.	Elliot Lake, ON	Closed
Stanleigh	BHP Billiton/Rio Algom Ltd.	Elliot Lake, ON	Closed
Denison	Denison Mines Corp.	Elliot Lake, ON	Closed
Stanrock	Denison Mines Corp.	Elliot Lake, ON	Closed

Effluent discharges from 5 of the 12 operations reviewed are subject to the *Metal Mining Effluent Regulations*. Discharges not subject to *MMER* are those from closed or decommissioned sites and subject to licensure by provincial Ministries of the Environment, the Canadian Nuclear Safety Commission (CNSC), or both. Effluent limits in Uranium Mine Decommissioning Licenses issued by the CNSC are typically equivalent to *MMER* limits for the parameters regulated by *MMER*.

The uranium operations are located in two clusters in Canada, in Ontario and Saskatchewan. The 7 operations located in Ontario are found within the Elliott Lake area, and are all closed/decommissioned sites. The 5 operations in northern Saskatchewan are in various states of production including operating, in development, or under care and maintenance awaiting re-commissioning. Figure 6-36 illustrates the status of the uranium operations reviewed in this study. Figure 6-37 illustrates the geographic distribution of the uranium operations reviewed in this study. The primary commodity produced by all operations reviewed is uranium; only one closed operation produced a secondary commodity, copper.

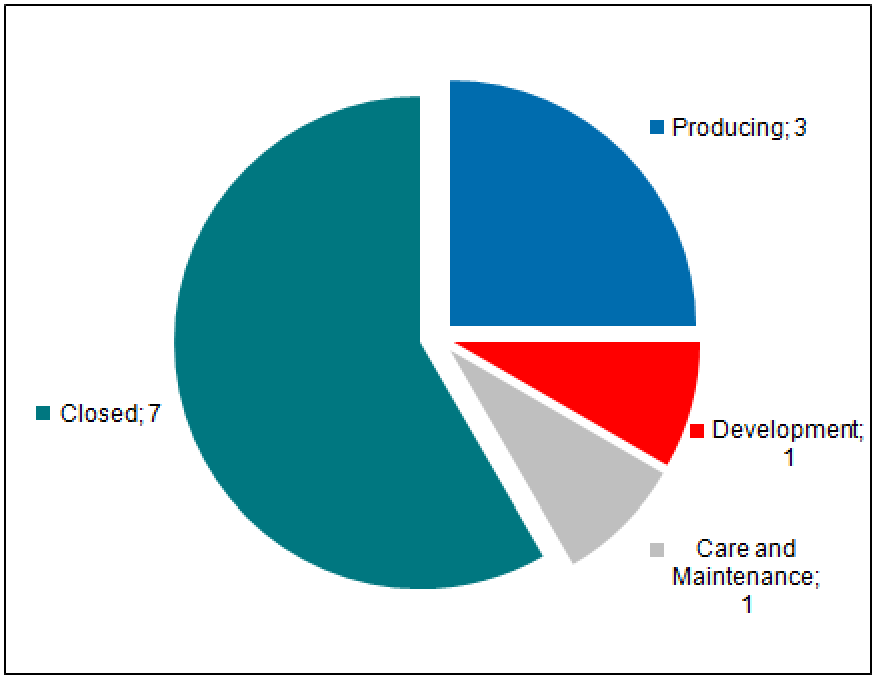

Figure 6-36: Status of Operations Reviewed for the Uranium Subsector

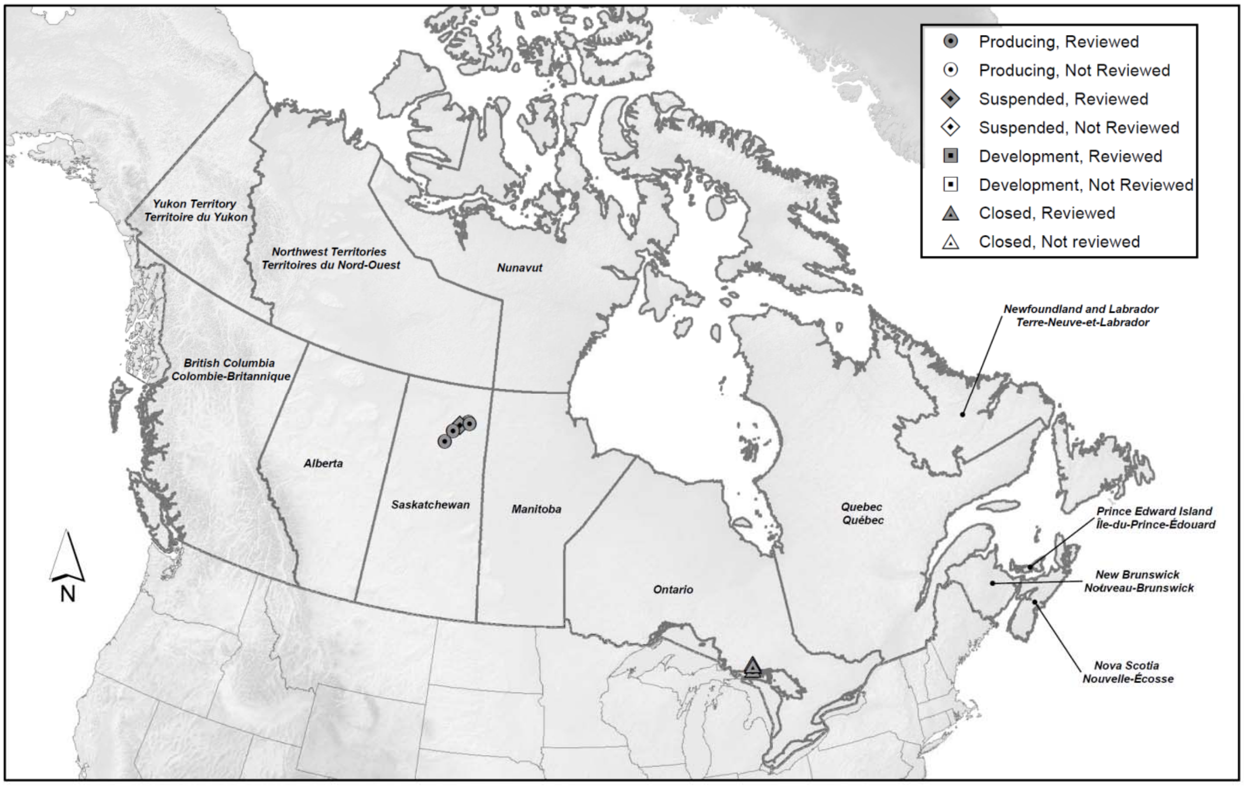

Figure 6-37: Geographic Distribution of Uranium Subsector Operations

6.4.1 *Effluent Characteristics*

In general, it is expected that the quality of effluent generated by any operation, including uranium operations, will be variable based on site-specific factors, including, but not limited to what mine, mill and waste management facilities are present on site, the operating status of the site (e.g., closed, producing, etc.), and the mineralogy of the ore and waste rock. However, it is also expected that given the common target element for extraction from these operations, and, in particular for the uranium subsector, the regional clustering of the operations, effluent at uranium operations will share some similarities.

To establish what contaminants are typically found in untreated effluent at uranium operations parameters included in discharge permits, parameters reported as targeted by effluent treatment processes by questionnaire respondents and parameters reported in untreated effluent data by questionnaire respondents were considered. Figure 6-38 demonstrates the relative frequency of each parameter that appears in effluent discharge permits or is targeted by effluent treatment processes.

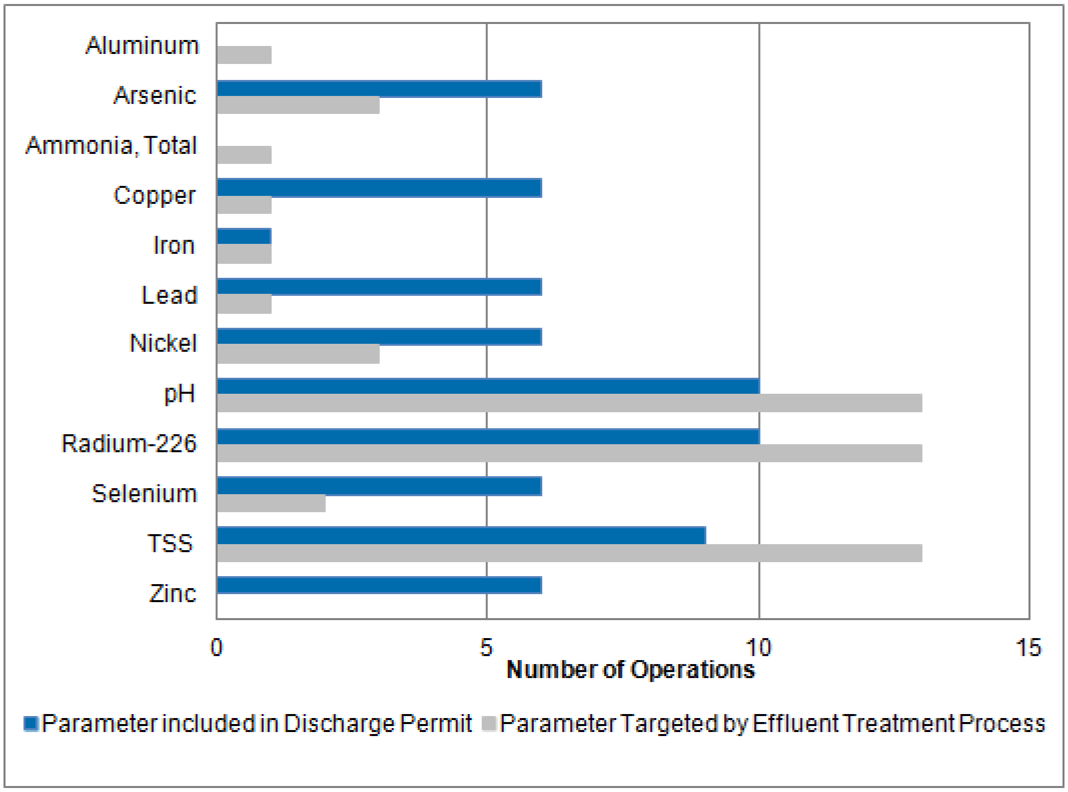

Figure 6-38: Parameters Included in Discharge Permits and Targeted by Effluent Treatment Processes at Reviewed Uranium Operations (10 Operations Discharge Permits / 12 Operations Effluent Treatment Systems)[20]

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[20] Those operations in Saskatchewan are subject to the *Mineral Industry Environmental Protection Regulations* (1996) which include limits for total metals (arsenic, copper, lead, nickel, uranium, and zinc), total radionuclides (radium-226, thorium-230, lead-210), total cyanide, and un-ionized ammonia. However, only existing and proposed *MMER* parameters are included in this figure.

Of the 7 mines that submitted questionnaires to support this study, only 4 elected to provide untreated effluent quality in their submittals. The data are summarized in Table 6-59. Untreated effluent quality for select parameters was publicly available for 5 additional operations; these parameters were limited in most cases to pH and radium-226, and were graphically presented, therefore, these values are estimates from graphs rather than exact figures (5).

Table 6-59: Quarterly Average Concentrations of Parameters in Untreated Effluent at Uranium Operations

Parameter	Unit	Minimum	Average	95th Percentile	Maximum	Number of Operations Reporting Untreated Effluent Concentration
pH		2	6.8	10.6	11.0	8
Aluminum	mg/L	1.5	3.5	6.2	6.7	1
Arsenic	mg/L	0.005	0.6	2.08	2.10	3
Copper	mg/L	0.001	0.002	0.0057	0.0059	1
Iron	mg/L	0.002	0.3	0.7	1.1	4
Lead	mg/L	0.0004	0.002	0.004	0.005	2
Nickel	mg/L	0.002	0.4	1.2	1.3	2
Selenium	mg/L	0.0004	0.004	0.010	0.014	4
Zinc	mg/L	0.004	0.008	0.01	0.02	3
Radium-226	Bq/L	0.02	2.6	7.6	10.4	10
TSS	mg/L	3.3	21	42	55	3
Total Ammonia	mg-N/L	3.3	4.8	7.2	25	3

Notes:
Values reported as less than the method detection limit have been incorporated at the MDL value.
All metal concentrations are total metal concentrations, i.e., the sum of dissolved and suspended fractions.

The contaminants that are considered to be typical based on the frequency of occurrence in untreated effluent at uranium operations are pH (pH that falls outside of the acceptable range of 6.5 – 9.5, per *MMER*), radium-226, and total suspended solids.

These parameters are targeted by most, if not all, of the treatment systems reviewed, and present in concentrations exceeding *MMER* discharge limits in at least two of the reported untreated effluent qualities where concentrations for the parameter was provided. Untreated effluent at uranium operations typically requires treatment for these parameters to meet discharge limits.

Additional contaminants which may be present in untreated uranium effluent include metals (aluminum, arsenic, copper, iron, lead, molybdenum, nickel and uranium), ammonia, and selenium. Other radionuclides such as thorium-230 and lead-210 are included in several permits and may be present, but the data provided by questionnaire respondents indicates that these are not found at levels requiring targeted treatment to meet the discharge limits. The parameters listed in this paragraph may be present in untreated effluent at some operations; however it is important to note that untreated effluent at some operations do not contain nor require dedicated treatment for these parameters. Table 6-60 summarizes some characteristics of the reviewed uranium operations that may contribute to this typical untreated effluent quality as previously described.

Table 6-60: Factors Influencing Uranium Subsector Untreated Effluent Quality

Ore and Waste Rock Mineralization	Mine and Mill Operational Status and Facilities	Uranium Processing
The ore and waste rock mineralization at uranium operations is variable. The ore bodies at many of the operations reviewed are associated with sulfidic and metallic mineralizations, and mine wastes at these operations exhibit some degree of acid generation and metal leaching tendencies.	• Mine and mill facilities appear in a various configurations at uranium operations reviewed in this study. Operational status of facilities is also variable. Mining is typically from open pit or underground. The mine and mill facility configurations and operational statuses of the operations reviewed include: • Operating mines with associated waste rock management facilities but no milling or tailings management facilities. • Operating and suspended mine and mill/concentrator sites with waste rock and tailings management facilities. • Operating mill sites with tailings management facilities but no mining operations or waste rock management facilities. • Closed mine sites with no active mining or processing, but continued tailings management activities.	• Ore grinding, resulting in TSS generation and uranium liberation (grinding also liberates and may contribute to the generation radium-226 as a decay product of uranium). • Acid leaching using sulfuric acid. • Acid neutralization by lime addition and gypsum precipitation. • Organic solvent extraction. • Yellowcake precipitation using ammonia or hydrogen peroxide.

6.4.2 *Effluent Management and Control Techniques*

In an effort to control the volume and quality of effluent requiring containment and treatment prior to discharge to the environment, and to minimize the risk of potential contaminants being released to the environment, uranium operations employ a variety of techniques to manage water. These techniques and their relative frequency of employment are presented in this section.

The management techniques employed for effluent volume and quality control at uranium operations reviewed for this study are summarized in Table 6-61.

Table 6-61: Overview of Effluent Management and Control Techniques Used at Uranium Operations

Volume Control	Quality Control	Minimize Environmental Contact
• Diversion of clean or non-impacted surface and groundwater away from site features which may degrade water quality upon contact. • Recycle of contact water to reduce the volume of water requiring treatment. • Co-disposal or in-pit disposal of waste streams to minimize the total waste storage footprint and thereby minimize contact water run-off volumes generated by precipitation. • Segregation of benign and potentially PAG/PML wastes. • Vegetative cover of closed facilities to separate clean run-off from impacted percolation/seepage.	• Water cover of closed facilities. • Explosives best management plan in force. • Mine waste employed in mine backfill applications.	• Storage of potentially PAG/PML wastes in dedicated storage facilities with environmental controls (e.g., liners, covers, seepage monitoring and collection, etc.). • Collection of contact water (run-off and seepage) and isolation from the environment during conveyance to treatment. • Mill facilities are centralized, with two or more mines providing ore for processing to one mill. This arrangement isolates processing activities, which can reduce the potential for deleterious substances that are used for processing or generated by processing to contaminate contact water or to be released to the environment.

The following sections present a more detailed summary of the mining and waste management disposal methods on site at uranium operations and their associated effluent management and control techniques. It should be noted that in the figures, each operation can employ more than one technique and thus the sum of the number of operations presented in this figure may exceed the number of operations reviewed in this study.

6.4.2.1 *Mine Facilities and Water Management Techniques*

Uranium operations employ a combination of open pit and underground mine facilities; frequently both types of mine facilities are present at a single operation. Both active and inactive mine facilities are found at uranium operations; in fact, the uranium subsector has a large number of closed sites relative to operating sites. For this reason, the water management summary graphs for this subsector demonstrate the number of operations that are closed and open, rather than the total number of operations. Figure 6-39 illustrates the mine types found in the uranium subsector and their relative frequency. The operation that responded they have no mining facilities is an operation that has only ore processing but no mining; this operation receives ore from satellite mining operations.

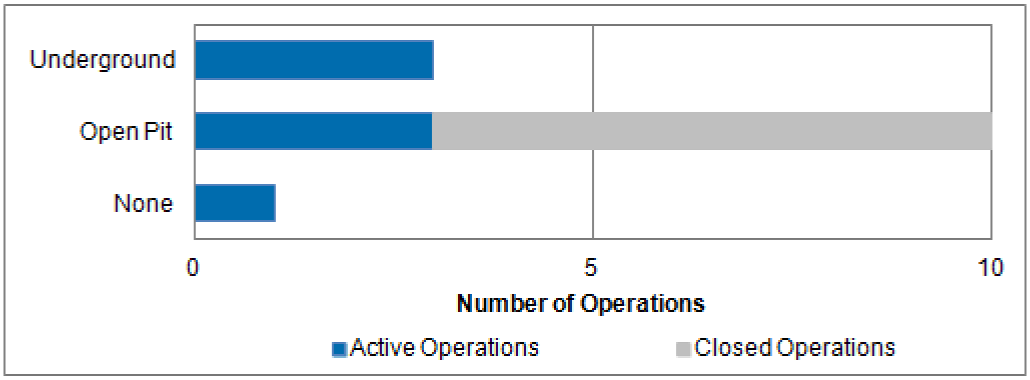

Figure 6-39: Uranium Subsector Mine Facilities (5 Active Operations / 7 Closed Operations)

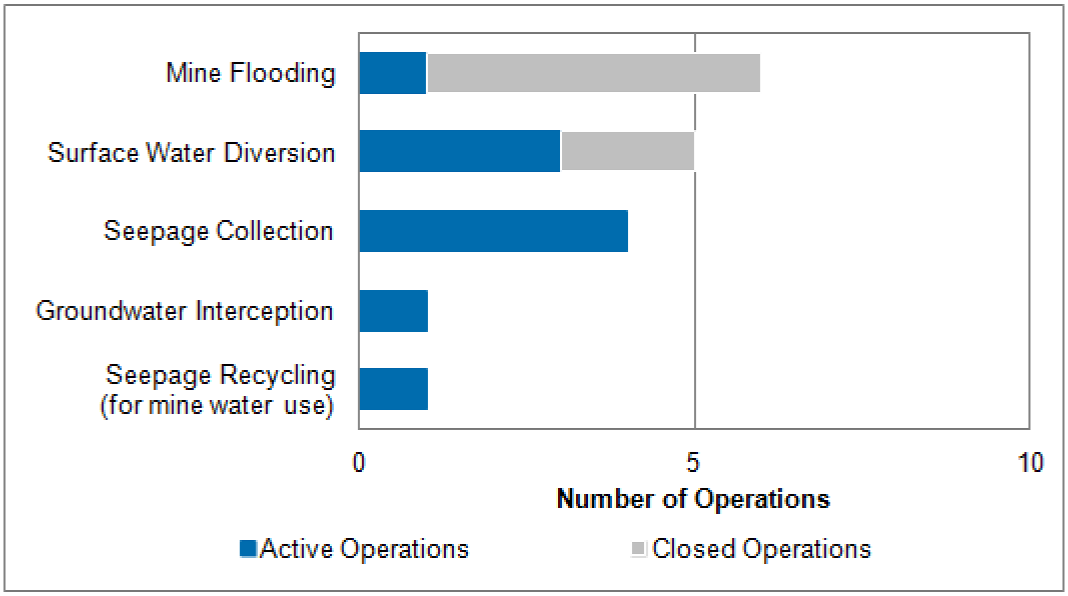

Figure 6-40: Uranium Subsector Mine-Water-Environment Interaction Minimization Techniques (5 Active Operations / 7 Closed Operations)

Figure 6-40 summarizes the mine-water-environment interaction minimization techniques utilized by operations and the frequency of each technique's use for those operations reporting mine facilities present on site.

As with other subsectors, the most common reported water management and effluent control techniques are seepage collection, wherein groundwater reporting to underground mine works is captured in sumps and either recycled or sent to treatment and surface water diversion, wherein surface water is diverted away from mine portals to prevent ingress into underground mine.

At mine facilities that are no longer operational, mine works are flooded to slow mineral oxidation reactions that promote acid generation and metal leaching. Surface water is also diverted around non-operational mines in several instances.

6.4.2.2 *Explosives Use*

All operations with active mining operations use some combination of bulk ammonium nitrate fuel oil (ANFO), packaged ANFO, water-resistant ANFO and packaged emulsions.
Figure 6-41 illustrates the relative frequency of used explosive types as reported by the 4 operations that have active mining operations on site.

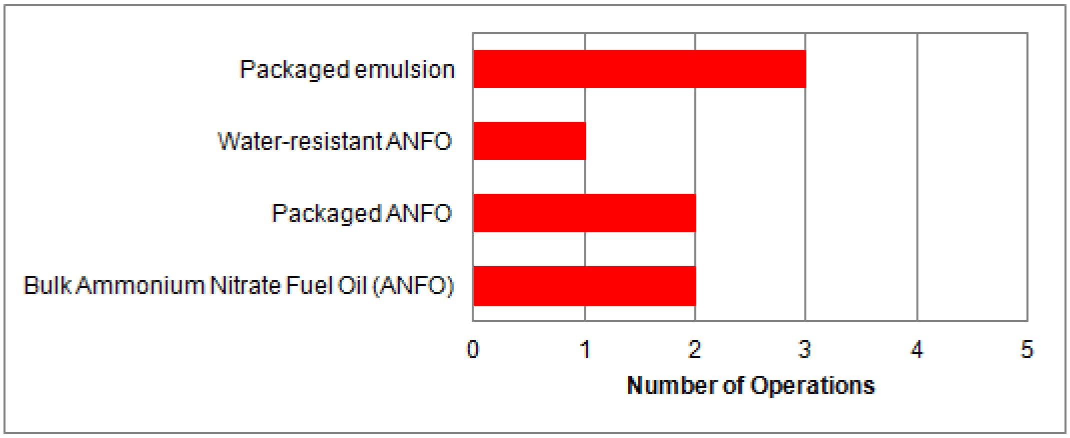

Figure 6-41: Relative Use of Types of Explosives at Uranium Operations (4 Operations)

6.4.2.3 *Ore Stockpiles and Water Management Techniques*

Of the 11 operations reviewed, only 4 have ore stockpiles on site. All operations employ impervious liners (HDPE and/or bentonite) under ore stockpiles, and collect run-off and any seepage/leaks in sumps and convey these water streams to treatment via ditching.
Figure 6-42 shows the techniques employed and their frequency of use to minimize ore stockpile-water-environment interactions. Most active operations employ multiple techniques to ensure isolation of the ore stockpiles from environmental interaction.

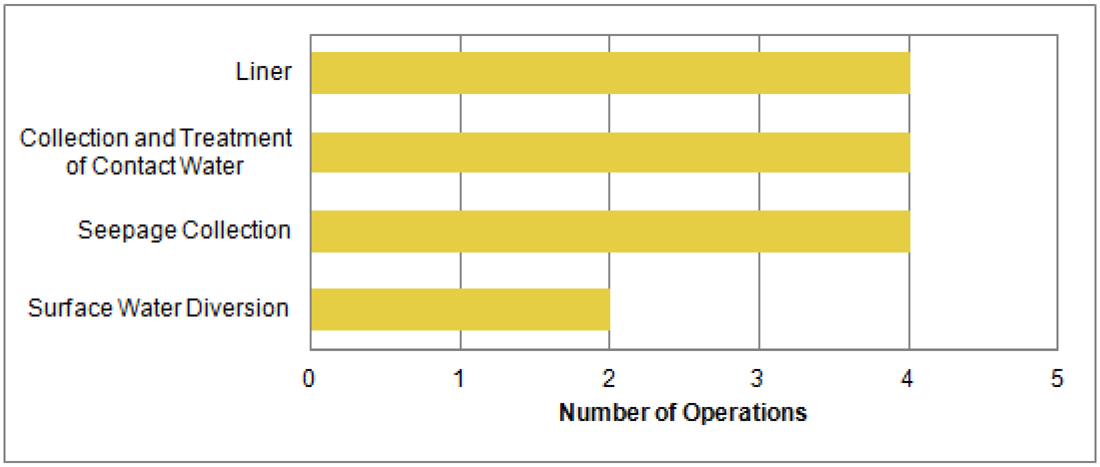

Figure 6-42: Uranium Subsector Ore Stockpile(s)-Water-Environment Interaction Minimization Techniques (4 Operations)

6.4.2.4 *Waste Rock Disposal Methods and Water Management Techniques*

Figure 6-43 summarizes the variety and relative frequency of waste rock disposal methods employed at uranium operations. Waste rock is most frequently segregated and disposed in dedicated storage facilities or used as backfill for underground mines.

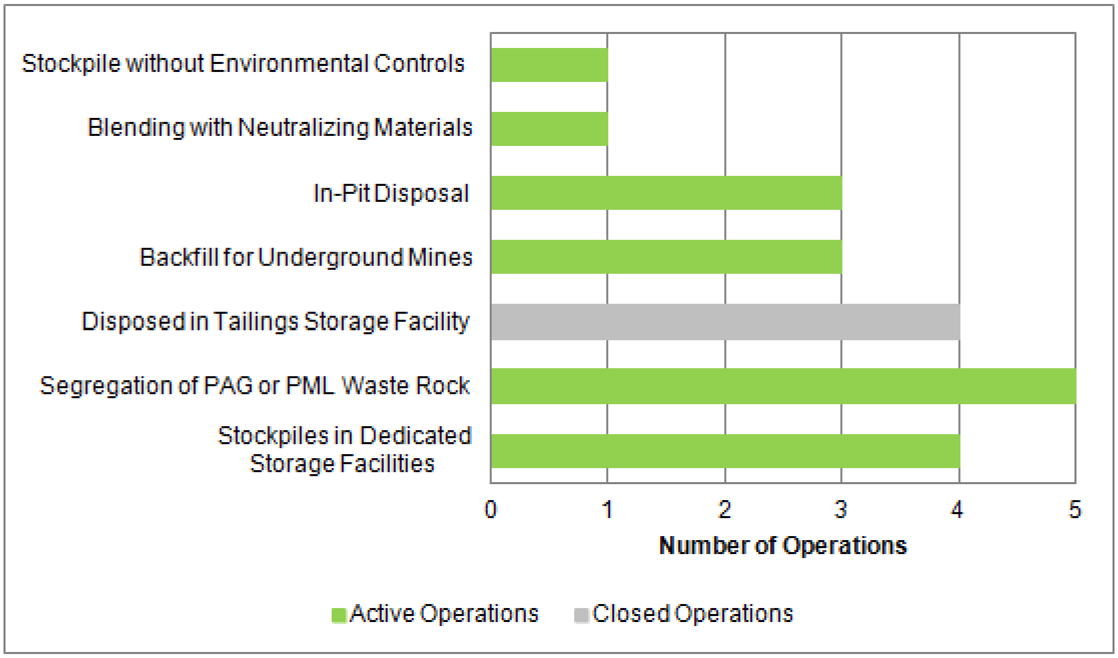

Figure 6-43: Uranium Subsector Current and Historical Waste Rock Disposal Techniques (5 Active Operations / 4 Closed Operations)

Every active operation employs some combination of seepage collection, surface water diversion, progressive reclamation, water cover, cap/cover and liners to minimize waste rock-water-environment interactions. The relative frequency of the use of these techniques is summarized in Figure 6-44.

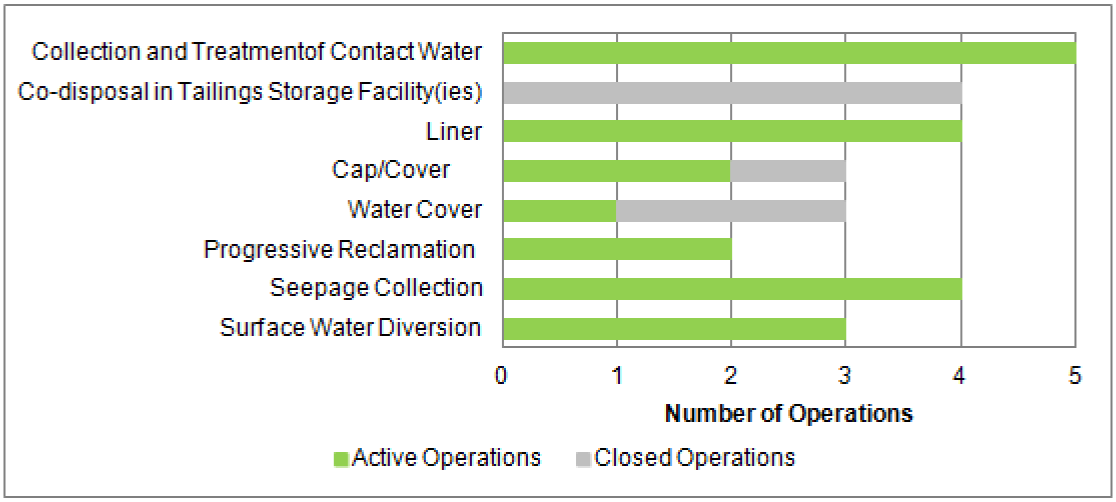

Figure 6-44: Uranium Subsector Waste Rock-Water-Environment Interaction Minimization Techniques (5 Active Operations / 6 Closed Operations)

All active operations segregate waste rock by its potential for being either acid generating or metal leaching. Table 6-62 summarizes the disposal methods employed for the types of waste rock present on site.

Table 6-62: Waste Rock Disposal Methods at Uranium Operations

Waste Rock Classification	Disposal Method or Use
• PML and/or PAG	• In-pit disposal. • Aggregate in concrete for backfill. • PAG co-disposal with tailings. • Stored in both lined and unlined (with seepage collection) stockpiles.
• NML and NAG	• Construction and in-fill use. • Unlined surface stockpiles. • Unlined surface stockpiles undergoing long term decommissioning. • Underground backfill.
• Radioactive	• Underground backfill. • Co-disposal with tailings.

At closed operations, waste rock is primarily co-disposed with tailings in tailings storage facilities under a water cover to minimize mineral oxidation reactions.

6.4.2.5 Tailings Disposal Methods and Water Management Techniques

Tailings disposal methods employed by the 3 active uranium operations that manage, store or dispose of tailings on site and 7 closed uranium operations that manage tailings on site are summarized in Figure 6-45. This figure also illustrates the relative frequency of the type of disposal methods employed by active and closed operations.

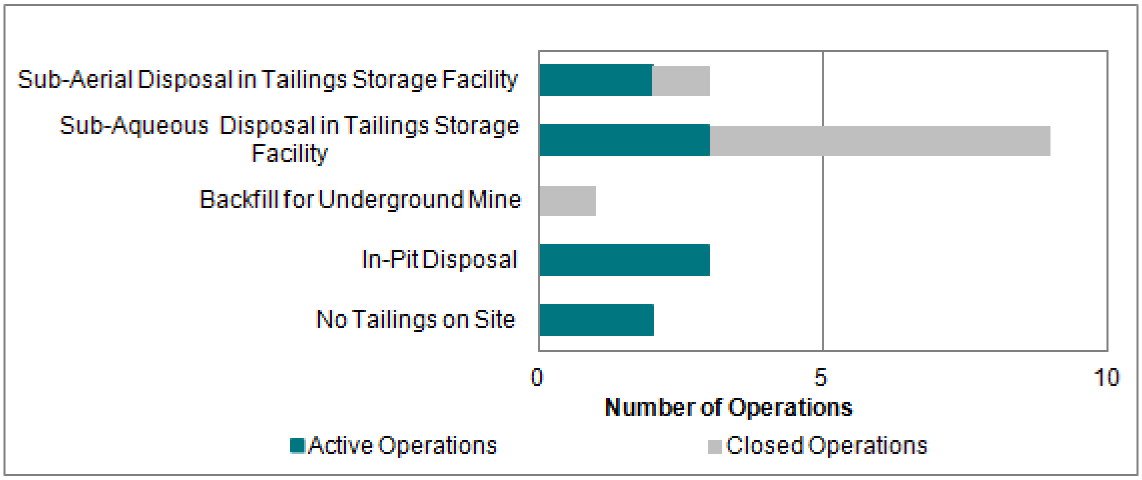

Figure 6-45: Uranium Subsector Current and Historical Tailings Disposal Methods (3 Active Operations / 7 Closed Operations)

Uranium operations frequently employ sub-aqueous disposal in pit or in dedicated storage facilities to slow the rate of oxidation of the tailings, which in turn slows the rate of acid generation. This has been applied at both closed operations as well as active operations. Other techniques applied to minimize the interaction of tailings, the environment and water and the relative frequency of application are summarized in Figure 6-46.

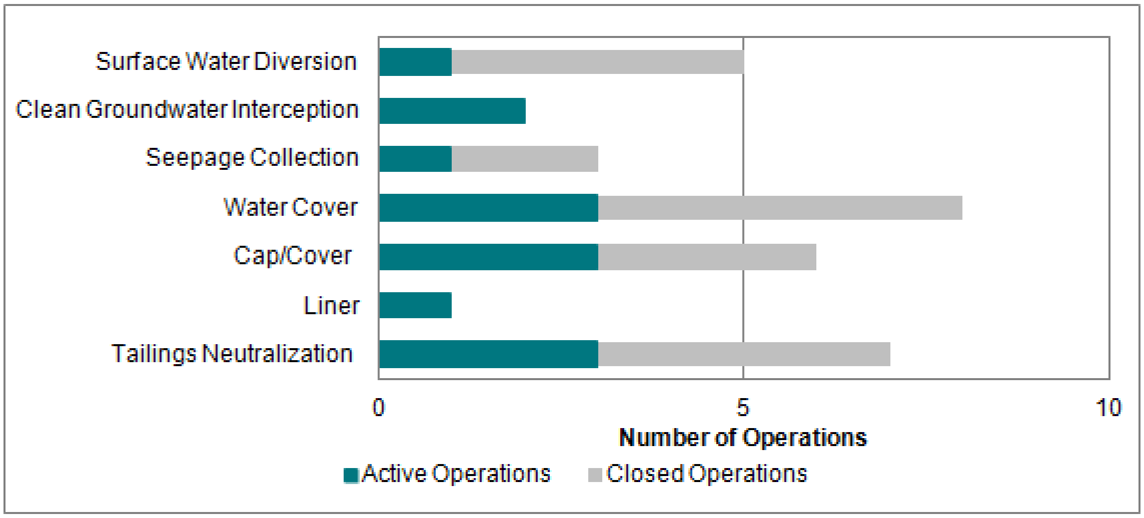

Figure 6-46: Uranium Subsector Tailings-Water-Environment Interaction Minimization Techniques (3 Active Operations / 7 Closed Operations)

The facilities actively producing tailings all employ tailings dewatering or thickening prior to disposal; tailings are sent to the final disposal location at 30 – 50% solids. Tailings dewatering allows the direct recycle of tailings water to the process. Additionally, at all operations tailings are neutralized prior to final disposal to neutralize acidity and, in some cases, to precipitate metals and radium.

All closed operations employ tailings disposal methods that isolate the tailings from the atmospheric environment. With the exception of one operation, tailings isolation at closed operations is achieved by a water cover. The remaining tailings facility has been capped and covered by soil and revegetated. During operations, one operation utilized tailings in underground backfill operations. These isolation methods limit the transfer of oxygen to the tailings and thereby minimize mineral oxidation resulting in acid generation, and subsequent metal leaching. In addition, they also limit the amount of water coming into direct contact with tailings material as water more readily run-offs of vegetated tailings surfaces than percolates into them.

6.4.3 *Effluent Treatment Technologies*

All operations reviewed employ treatment processes to meet discharge criteria established in their discharge permits, licences or certificates of authorization, all of which include radium-226 and TSS removal and pH adjustment. In addition to radium-226, pH, and TSS, some operations specifically include one or more metals removal step(s) as part of the effluent treatment process, including molybdenum, uranium, nickel removal and others. Selenium is also reported to be targeted by several effluent treatment plants processes found at uranium operations.

The chemical and physical processes employed in effluent treatment at uranium operations are summarized in Table 6-63. In addition to these processes, all operations have equalization capacity in ponds upstream of the effluent treatment process.

Table 6-63: Physical and Chemical Processes for Uranium Subsector Effluent Treatment

Chemical Processes	Physical Processes
Co-precipitation/Coagulation • Radium-226 removal by barium sulfate co-precipitation (through addition of barium chloride and if required ferric sulfate). • Molybdenum removal by ferric hydroxide adsorption/co-precipitation (through pH adjustment and ferric sulfate). • Selenium removal by ferric hydroxide adsorption/co-precipitation. • Uranium removal by ferric hydroxide adsorption/co-precipitation (and co-precipitation with other metal hydroxides when present). • Solid/Liquid Separation • Flocculant and coagulant-aided settling. • Hydroxide Precipitation • Metals removal (Ni, Al, Cu, Pb) by lime precipitation (pond-based and reactor-based).	• Solid/Liquid Separation • Conventional clarifiers/thickeners. • Lamella clarifiers. • Settling ponds. • Media filtration. • Filters (unspecified type). **Membrane Separation** • Reverse osmosis.

Two types of effluent treatment systems are used at uranium operations, pond-based and reactor-based systems. Pond-based systems are typical of effluent treatment systems employed at closed operations, while reactor-based systems are typical of effluent treatment systems employed at active operations. In reactor-based treatment systems, the main treatment processes occur in tanks or other dedicated vessels, with ponds only employed prior to the process for equalization and homogenization, and after the process for monitoring and settling (with one exception where both ponds and reactors are employed for chemical processes). In pond-based systems, the effluent treatment processes occur primarily in ponds or mix cells and are open to the environment.

A result of this difference is that the operations that utilize reactor effluent treatment systems have a higher degree of control over their treatment processes, as the quality and volume being treated is more consistent than pond-based systems, and factors affecting the efficiency of the separation processes, such as retention time and dosing can be more accurately controlled. Treatment processes occurring in pond-based systems are subject to seasonal temperature and precipitation influx variability, which may interrupt treatment processes or cause variations which may negatively affect removal efficiency. Moreover, sudden increases in flow rate, heavy rainfall events, and high winds and wave action can re-suspend precipitates, potentially causing downstream non-compliance.

6.4.4 *Effluent Quality*

△1

Table 6-64 summarizes the effluent quality (maximum, minimum, average monthly mean and 95th percentile concentrations) at the final point of discharge for all uranium mines subject to *MMER* in 2008 – 2010. These effluent quality ranges utilize the same data set as employed by Environment Canada for the 10-Year Review of *Metal Mining Effluent Regulations*. The data was employed to generate the summary of treated effluent quality as it is a more complete data set than that generated by the questionnaire submittal, as operations are legally obliged to provide this information to Environment Canada.

This summary in Table 6-64 for Schedule 4 parameters (pH, arsenic, copper, lead, nickel, radium-226 zinc and TSS) uses monthly average concentration data generated by Environment Canada from grab data reported by operations. An assessment of the extent that the monthly average data adequately represents the grab data was performed for Revision 1 of this study and it was determined that for the most significant statistics (i.e., the 95th percentile), the difference between the monthly mean data and the grab data was minimal. Therefore, in Revision 1, the monthly mean data are carried forward for analysis. A more detailed assessment of the monthly mean data versus the grab data for each subsector is appended to this report in Appendix D.

Table 6-64: Treated Effluent Summary for Uranium Metal Subsector

Parameters	Unit	Effluent Concentration Basis	Minimum	Average	95th Percentile	Maximum
pH		Monthly Mean	6.0	7.1	7.6	8.8
Aluminum	mg/L	Grab/Composite	0.00025	0.07	0.35	0.96
Ammonia, total	mg-N/L	Grab/Composite	0.005	3.85	20	24
Arsenic	mg/L	Monthly Mean	0.00005	0.01	0.06	0.25
Copper	mg/L	Monthly Mean	0.0001	0.003	0.008	0.045
Cyanide	mg/L	Monthly Mean	n/a	n/a	n/a	n/a
Iron	mg/L	Grab/Composite	0.0022	0.16	0.46	1.11
Lead	mg/L	Monthly Mean	0.00005	0.0003	0.001	0.005
Nickel	mg/L	Monthly Mean	0.0004	0.04	0.13	0.34
Radium-226	Bq/L	Monthly Mean	0.0025	0.02	0.09	0.17
Selenium[21]	mg/L	Grab/Composite	0.00005	0.003	0.016	0.02
Zinc	mg/L	Monthly Mean	0.0004	0.009	0.03	0.13
TSS	mg/L	Monthly Mean	0.1	1.6	4.1	9.1

Notes:
Values reported as less than the method detection limit have been incorporated at 50% of the MDL value.
All metal concentrations are total metal concentrations, i.e., the sum of dissolved and suspended fractions.
Values in this table are based on effluent quality data reported to Environment Canada as part of *MMER* Schedule 4 and Schedule 5 reporting.

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[21] Compiled from grab and composite selenium concentrations reported through Schedule 5 for 2012.

6.4.5 Model Water Management and Effluent Treatment Systems

6.4.5.1 Model Water Management System

Based on this review of water management techniques employed by uranium operations, a model water management plan to represent the typical water management practices employed at these operations has been generated. This model is presented in Figure 6-47.

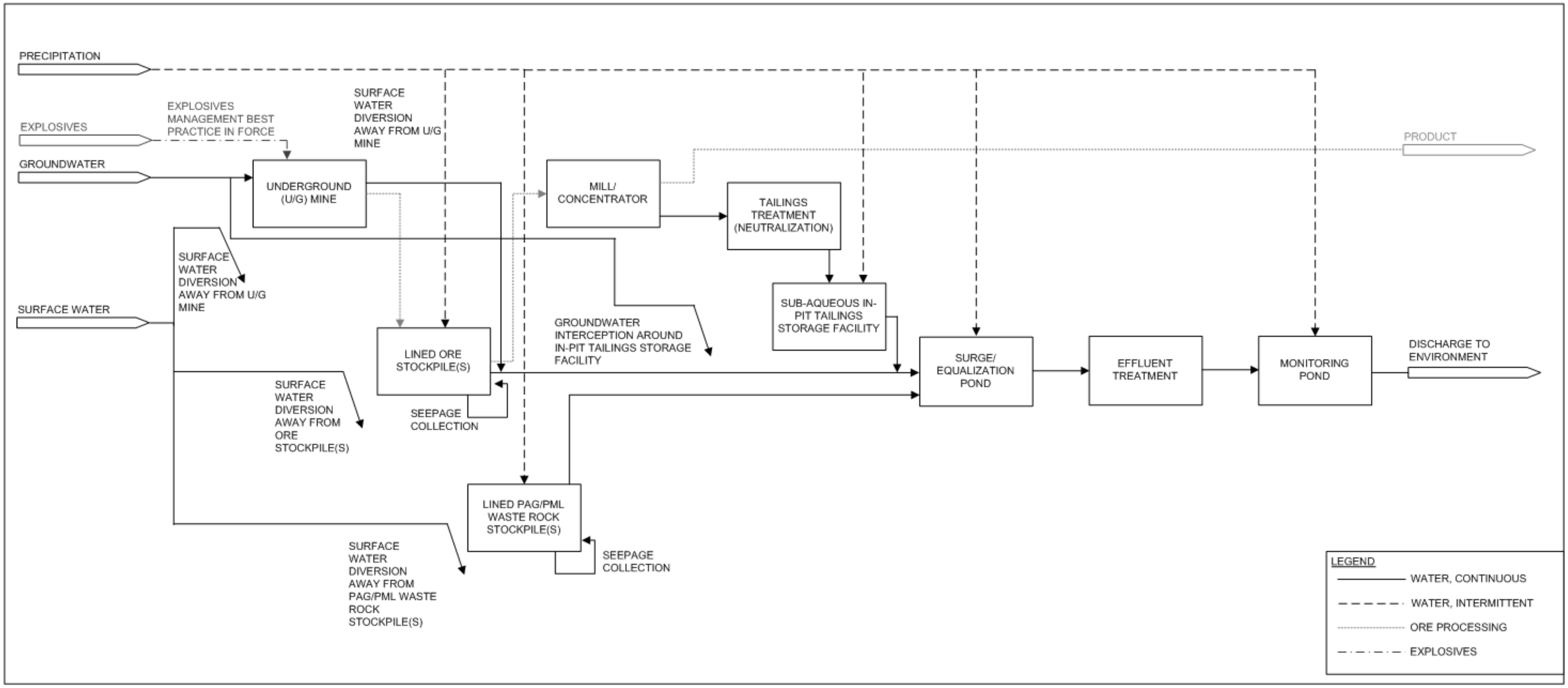

Figure 6-47: Uranium Subsector Water Management Model

6.4.5.2 *Model Treatment System Process Flow Diagram*

To establish a model treatment system, the following aspects of the effluent treatment system(s) reviewed and their associated discharge points were considered:

- Whether the discharge point associated with the effluent treatment process is subject to *MMER.*
- What parameters are most frequently targeted by effluent treatment processes.
- How many chemical reaction stages are used in the effluent treatment processes.
- How many vessels are employed per stage to allow sufficient reaction time.
- What physical processes are used between stages to contribute to removal of targeted parameters.

Operations where discharge is not subject to *MMER* were excluded from consideration as the model effluent treatment system. This applies to closed mine operations, which are subject only to provincial limits or CNSC uranium decommissioning site licences, or both. Though these operations may be indirectly impacted by *MMER* regulations, as many of the discharge limits established by the regulatory bodies are equivalent to *MMER* discharge limits, these operations are not directly impacted by the proposed *MMER* changes and thus are considered to be less of a priority for examination in this study.

Further, the proposed changes to *MMER* do not include changes to radium-226, the main parameter which could impact the non-*MMER* subject operations in the event non-*MMER* regulatory bodies follow Environment Canada's lead in adjusting discharge limits. However, it is acknowledged that in excluding these operations, the model effluent treatment system is not representative of the effluent treatment systems employed at closed uranium operations.

The group of operations subject to *MMER* under consideration in the establishment of the model effluent treatment system are all active operations with fairly similar effluent treatment processes. All effluent treatment process examined for active operations include at least 2 stages of treatment, to target parameters that are removed at significantly different pH values. The highest number of effluent treatment stages is 4, each stage with a different target pH, however the majority of operations have 2 stage effluent treatment processes; one high pH stage for precipitation of metals which precipitate in basic conditions (i.e., nickel) and one low pH stage for metals and other parameters that precipitate or co-precipitate in acidic conditions (i.e., molybdenum, selenium, radium co-precipitation with barium sulfate).

The order of the precipitation stages varies. The first stage of effluent treatment processes that receive high pH/alkaline feed (as a result of upstream process or tailings neutralization steps) is a high pH precipitation stage, followed by a lower pH precipitation stage. The converse is true for those effluent treatment processes that receive low pH/acidic feed; these processes typically begin with the low pH precipitation stage, followed by a high pH precipitation stage. In some instances, at operations where the low pH step precedes the high pH step, the order of pH stages capitalizes on the presence of iron in untreated effluent to control molybdenum and selenium concentrations via rather than add iron as a coagulation/co-precipitation reagent (in the form of ferric sulfate). Systems that utilize iron in untreated effluent reportedly produce less sludge than those systems that add an iron reagent in low pH steps that follow the high pH step (where iron is removed via precipitation).

Between the chemical reaction stages, all operations have a clarification step to separate precipitates from the treated water. Only one operation employs a lamella clarifier. Several, though not all, operations employ filtration between phases for additional suspended solids removal. Almost all operations employ ponds for pre-treatment equalization and for post-treatment monitoring and/or settling.

As a result of these considerations, the model system illustrated in Figure 6-48 was established. This system closely resembles two of the existing effluent treatment systems reviewed, however is not identical to any one operation's effluent treatment system. This process will be carried forward into BATEA selection in subsequent sections of this report.

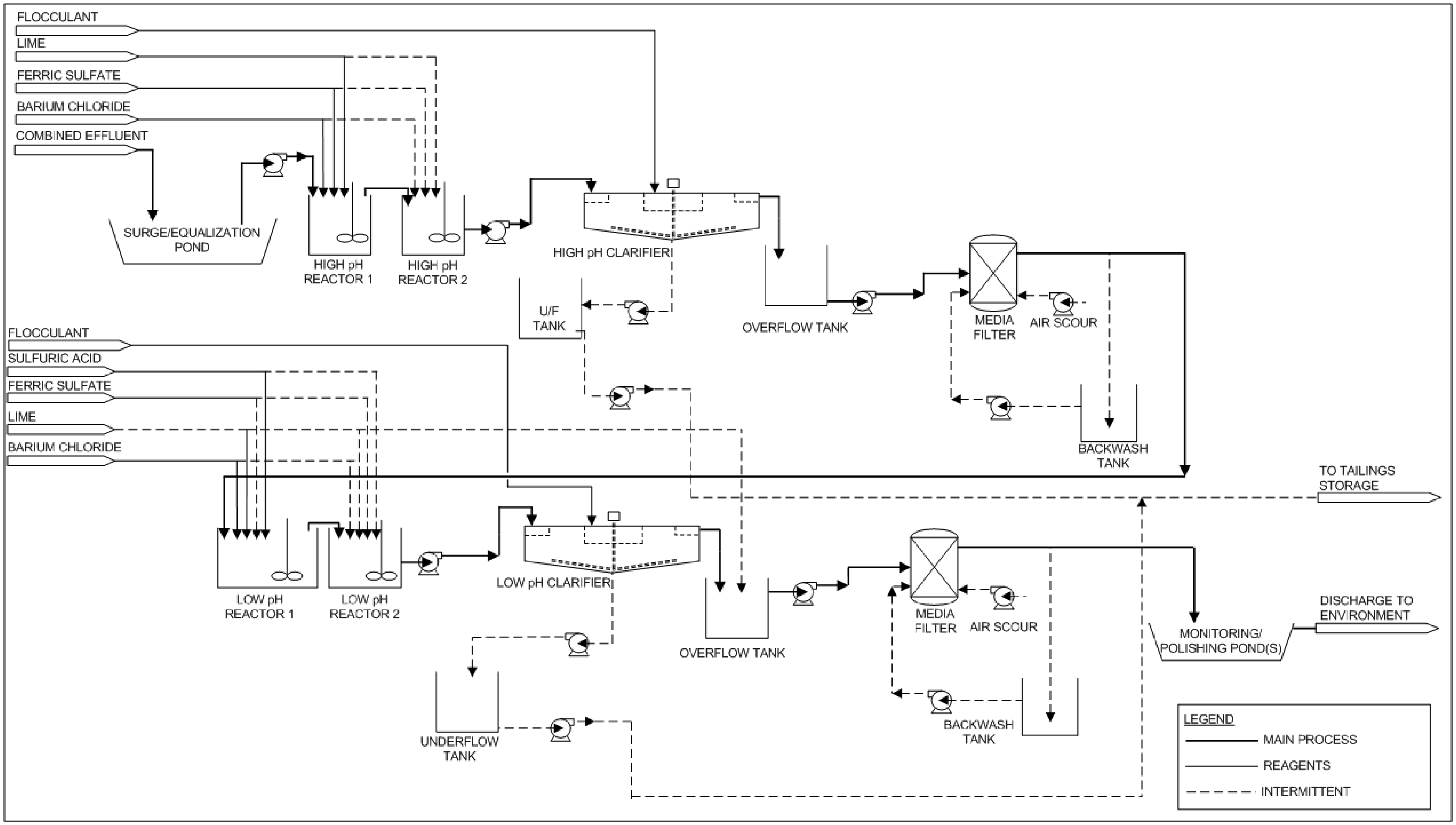

Figure 6-48: Uranium Subsector Model Effluent Treatment Process

6.4.5.3 Model Effluent Treatment System Flow Rate

For Revision 0, to establish a flow rate for the model effluent treatment system, two sources of treatment system flow rate and discharge volume information were used:

- Final discharge point flow rates reported to Environment Canada as part of *MMER* reporting for 2008 – 2010 (the analysis of which generated data set “A” in Table 6-65), and
- Average and design flow rates for effluent treatment systems reported by questionnaire respondents (the analysis of which generated data sets “B” and “C”, respectively in Table 6-65).

The Environment Canada *MMER* reported data set is a complete set of monthly discharge volumes for all mines subject to *MMER* during 2008 – 2010, and thus is a valuable data source as it provides several years of discharge volumes, and additionally, data for those operations that did not participate in the study questionnaire. This data set, however, presents total discharge volumes from operations to the environment at the final discharge point(s) from the site and does not necessarily reflect the volume of water treated prior to discharge, nor the design capacities of effluent treatment systems, which are of significance when considering the costs of modifications/augmentations to effluent treatment systems.

The discharge volumes reported to Environment Canada may differ from the treated volumes as they may include incident precipitation to ponds downstream of effluent treatment systems or streams that do not require treatment. Nonetheless, due to the completeness of this data set compared to the data received via the questionnaire, in terms of time span of data collection and operation participation, it was considered valuable in the selection of a typical design flow rate. This monthly reported data was used to calculate the total annual discharge volume from operations, from which rough average annual hourly flow rates were calculated assuming continuous discharge (24 hours/day, 365 days/year). These values are presented in Table 6-65. This approach may not accurately represent flow rates treated by effluent treatment systems for the following reasons:

- This approach summed the discharge volumes from all final discharge points associated with an operation; for sites with multiple final discharge points, this approach overestimates the total volume requiring treatment by any one treatment system; however, if all final discharge points at an operation were to require augmentation of their effluent treatment systems, this may be representative of the total sum of the capacities of augmentative technologies for a single operation.
- This approach may account for volume that is not actively treated in an effluent treatment system (e.g., accounts for volumes treated only by settling ponds).
- This approach assumes that treatment occurs 365 days a year, for 24 hours a day. This approach could underestimate the treatment system flow rates for those sites that only treat for a portion of the year (e.g., in summer only) or day (e.g., during day shift only).

- The second source of data reviewed in the process of establishing the model treatment system was treatment flow rate data provided via the Revision 0 operations questionnaire. As part of the questionnaire, operations were prompted to provide the average, design, maximum and minimum treatment flow rates for their effluent treatment systems. This data set is limited to those operations that provided this information as part of their questionnaire responses, and is thus a less complete data set as compared to the Environment Canada *MMER* reported discharges volumes. However, this data set is a valuable source of information concerning design capacities of treatment technologies, which are not apparent from reported discharge volumes. The average flow rates reported via the questionnaire were used to informally cross-check the questionnaire-reported values against the Environment Canada *MMER* reported values, and the design flow rates are used in the consideration of the typical effluent treatment system design flow rate, or the equipment capacity that would need to be installed for new equipment.

Following the release of Revision 0, two additional sources of treatment system flow rate and discharge volume information were available for review. These sources of treatment system flow rate and discharge volume information and the analysis performed on them are summarized below:

- Environment Canada provided monthly flow rate data reported through *MMER* for 2005 – 2012. The methodology undertaken by Environment Canada to analyze this flow rate data was as follows:
    - To generate approximate average hourly discharge volumes, Environment Canada analyzed the data by calculating the average daily flow rates by month for each discharge point reporting to *MMER*, then assuming that discharge occurs over 24 hours a day. This method identifies the average discharge flow rate from each site based on seven years of Schedule 4 data (this analysis generated data set “D” in Table 6-65).
    - To generate approximate maximum hourly discharge volumes for the highest monthly discharge, Environment Canada analyzed the data by first identifying the highest monthly discharge volume for each discharge point reporting to *MMER*, then assuming that discharge occurs continuously over the whole month, for 24 hours a day. This method identifies an approximate hourly discharge flow rate for the highest monthly discharge from each site based on seven years of Schedule 4 data (this analysis generated data set “E” in Table 6-65).
    - The approaches described above may not accurately represent flow rates treated by effluent treatment systems as they assume that treatment occurs over the entire month, for 24 hours a day. This approach could underestimate the treatment system flow rates for those sites that only treat for a portion of the year (e.g., in summer only) or day (e.g., during day shift only).

- The MEND Report 3.43.1, Review of Mine Drainage and Sludge Management Operations, contains all data collected by the survey associated with the report, including operation subsector classifications and maximum, average and minimum treatment flow rates (1). However, the size of this data set is substantially smaller than the other data sets available. Flow rate information from this report is only available for two uranium mines located in Canada. Therefore, for the uranium subsector, this data set was not considered in the flow rate evaluation for Revision 1.

The range, average and median values for the data sets described above are presented in Table 6-65. In selecting a flow rate for the typical model effluent treatment system based on the flow rate statistics in Table 6-65, greater consideration was given to the reported design flow rates, as opposed to average flow rates, as design values reflect the installed capacity required to accommodate design events (e.g., years with higher precipitation or extreme precipitation events) to avoid uncontrolled discharge and bypassing or short-circuiting of effluent treatment systems. These values are expected to be more representative of the installed capacities required of additional technology installed to augment existing systems.

Table 6-65: Summary of Reviewed Discharge and Treatment Flow Rates for the Uranium Subsector

	Data Set	Methodology	Range (m^3/h)	Average (m^3/h)	Median (m^3/h)
Data Sets Informing Selection of Nominal Model Effluent Treatment System Flow Rates					
A	**Estimated Average Annual Hourly Discharge Volume: Sum of All Final Discharge Points per Site**	Annual discharge volumes for each final discharge point and each site were calculated (based on the sum of annual discharge volumes at all final discharge points) utilizing Schedule 4 reported monthly discharge volumes as reported by operations to Environment Canada. The maximum, minimum, average and median annual site discharge volumes were then calculated, assuming discharge continuously over 365 days a year and 24 hours a day to generate hourly maximum, minimum, average and median flow rates.	18 – 800	350	300
B	**Questionnaire Reported Average Treatment System Flow Rate**	The average treatment flow rate volumes provided by operations via the operations questionnaire were used to calculated maximum, minimum, average and median values.	100 – 570	270	270
D	**EC Analysis: Estimated Average Hourly Flows per Final Discharge Point**	Schedule 4 monthly flow volume data reported to Environment Canada from 2005 – 2012 was used to calculate an average daily discharge volume for each final discharge point. It was assumed that treatment and discharge occurred continuously over 24 hours per day. Maximum, minimum, average and median values were then calculated for the approximate hourly flow rates determined in this fashion.	38 – 476	211	159
Data Sets Informing Selection of Design Model Effluent Treatment System Flow Rates					
C	**Questionnaire Reported Design/Maximum Treatment System Flow Rate**	Operations were prompted for their design and maximum treatment flow rates as part of the operations questionnaire. The maximum of these two numbers was used to generate a data set for the maximum/design treatment values for the subsector. Maximum, minimum, average and median values were then calculated for the subsector data set.	250 – 750	510	420
E	**EC Analysis: Estimated Average Max Hourly Flows per Final Discharge Point**	Schedule 4 monthly flow volume data reported to Environment Canada from 2005 – 2012 was used to calculate a maximum monthly discharge volume for each final discharge point. It was assumed that treatment and discharge occurred continuously over the entire month to generate approximate maximum hourly discharge volumes. Maximum, minimum, average and median values were then calculated for the hourly flow rates determined in this fashion.	74 – 765	333	282

In Revision 0, data sets “A”, “B”, and “C” in Table 6-65 were considered in determining the average and design flow rates for the model effluent treatment system. The average of the reported average treatment system rates (270 m^3/h, data set “B”) was roughly in accordance with the *MMER* reported data (350 m^3/h, data set “A”). To be conservative, the selected value for the nominal flow rate of the uranium subsector model effluent treatment system was 350 m^3/h; this value was be utilized for operating cost estimating for system augmentation. The selected value for the design capacity of the uranium subsector model effluent treatment system was 500 m^3/h; this value was utilized for capital cost estimating for system augmentation.

In Revision 1, data set “D” was also considered in addition to data sets “A”, “B”, to review the nominal model effluent treatment system flow rates utilized in Revision 0.

Data set “D”, based on Environment Canada’s analysis of Schedule 4 flow rate data from 2005 – 2012 provides an alternate approach to selecting a nominal treatment flow rate for the model effluent treatment system, as it identifies the average daily discharge for each final discharge point and from this generates an average hourly flow rate volume. The average volume calculated by this method (211 m^3/h) is lower than the nominal value used in Revision 0 (350 m^3/h) and the average of the reported nominal flow rates in the operations questionnaire (270 m^3/h, data set “B”). Any reasonable change to this treatment system flow rate (e.g., to 270 m^3/h), would not be expected to impact BATEA selection, therefore the nominal flow rate selected for the uranium subsector remains 350 m^3/h and is used for estimating operating costs for augmentative BAT.

In Revision 1, data set “E” was also considered in addition to data set “C”, to review the design model effluent treatment system flow rates utilized in Revision 0.

Data set “E”, based on Environment Canada’s analysis of Schedule 4 flow rate data from 2005 – 2012, provides an alternate approach to selecting a design treatment flow rate for the model effluent treatment system, as it identifies the maximum volume discharged from each final discharge point over seven years of data and generates an approximate maximum hourly discharge volume from the data. The average of this data set is lower than the average of the reported design flow rates via the operations questionnaire (333 m^3/h vs. 510 m^3/h, respectively).

This could be due to the possibility that the operations questionnaire data reflects sites with larger effluent treatment system capacities; however, given that all operations that are currently producing, or in care and maintenance (with planned production in near future) completed questionnaires and provided design flow rate information, it is assumed this is not the case. The large design values as compared to historical discharge record are more likely a result of effluent treatment systems being designed and installed with a capacity capable of handling extreme precipitation events that are not reflected in Schedule 4 data (e.g., probable maximum precipitation events or extreme wet years). It is ultimately unknown whether the seven years of Schedule 4 data accurately reflect treatment flow rates required for extreme precipitation events or wet years for uranium operations. The design flow rate of 510 m^3/h, based on questionnaire data for the active portion of the uranium subsector remains the design flow rate for the model effluent treatment system. This treatment flow rate is used to estimate capital equipment and total installed costs for the augmentative BAT.

6.4.5.4 Model Effluent Treatment System Effluent Quality

1

In Revision 0 of this report, the 95th percentile of the final discharge effluent quality for the entire uranium subsector for each parameter (as summarized in Table 6-64) was used to represent the effluent quality that was produced by the model effluent treatment system. It was assumed that for each parameter, the 95th percentile generated from the total cohort of uranium effluent quality data would reflect the concentration present in effluent at the final discharge point at the majority of sites and would be inherently weighted to reflect the most common effluent treatment technologies (and therefore the model effluent treatment system), as the most common effluent treatment systems would contribute a larger fraction of the concentration values than other systems.

Feedback received from industry indicated two main concerns with the use of 95th percentile values as representative of the model effluent treatment system, as follows:

1. The total cohort of final discharge effluent quality data for the subsector originates from a variety of effluent treatment systems, and not just systems very similar or equivalent to the model effluent treatment system. This could skew the 95th percentile values, as other types of effluent treatment systems may achieve higher or lower concentrations than the model. Thus, using the total cohort of final discharge effluent quality data for the subsector may not be representative of the concentrations specifically achieved by the model effluent treatment system.
2. Using the total cohort of final discharge effluent quality data for the subsector may result in average and 95th percentile values that are skewed low by the inclusion of concentration data from effluent treatment systems that do not target or remove a given parameter (i.e., where the concentration of a given parameter in untreated effluent is compliant with existing *MMER* without treatment). Using the total cohort of final discharge effluent quality data does not consider which concentration values reflect concentrations achievable by treatment, and thus, may not be representative of the concentration achieved by any given treatment system.

To better reflect the concentrations achieved by subsector effluent treatment systems very similar to or equivalent to the model effluent treatment system for systems that target for removal the parameters in question, Hatch compared concentration statistics for subsets of Schedule 4 and Schedule 5 data. The subsets were organized according to type of effluent treatment system and targeted parameters. Effluent treatment system information was collected during Revision 0 work via questionnaire and independent research, and augmented with additional data collected during Revision 1 work. The purpose of this effort was to narrow the total cohort of final discharge effluent quality data down to the concentration values that are more representative of concentrations achieved by systems similar to the model effluent treatment system.

Two types of effluent treatment systems utilized by uranium subsector operations were of interest for this analysis: systems very similar to the model effluent treatment system (referred to as “model effluent treatment systems”) and systems that are not exactly like the model effluent treatment system but utilize a process that can achieve similar effluent quality to model effluent treatment systems (referred to “model equivalent effluent treatment systems”). For the uranium subsector, these types of treatment systems are defined as follows:

- **Model Effluent Treatment Systems**: Reactor-based lime hydroxide precipitation system with a minimum of two pH-stages, where the high pH step precedes the low pH step, and solid/liquid separation occurs in a reactor clarifier followed by filtration.
- **Model Equivalent Effluent Treatment Systems:** Reactor-based lime hydroxide precipitation system with a minimum of two pH-stages, where the low pH step precedes the high pH step, and solid/liquid separation occurs in a reactor clarifier followed by filtration.

For the uranium subsector, the critical parameters for which concentration statistics were developed were arsenic, copper, lead, nickel, zinc, radium-226, total suspended solids (TSS), aluminum, iron, selenium and total ammonia. Cyanide was not reviewed as this parameter is typically not a concern in effluent at uranium operations. For each of these parameters, final discharge effluent quality statistics have been developed for the subsets of the total cohort, organized into the following classifications:

1. Model effluent treatment systems.
2. Model effluent treatment systems and model equivalent effluent treatment systems.
3. Effluent treatment systems that target the parameter.
4. Model effluent treatment systems that target the parameter.
5. Model effluent treatment systems and model equivalent effluent treatment systems that target the parameter.

Effluent treatment systems targeting parameters were identified per self-reporting by operations via the Revision 0 questionnaire and Revision 1 mini-survey; this self-reported information was confirmed to the extent possible using paired untreated effluent and treated effluent quality data provided by operations where available.

A comparison between the concentration statistics for each subset of data was performed to assess the extent to which the utilization of the total cohort of uranium subsector final discharge effluent quality data may skew the concentration statistics in comparison to data associated with model or model equivalent effluent treatment systems that target the parameter. The number of final discharge points associated with each data set is also provided. As 95th percentile values are used in augmentative BAT cost estimation and BATEA selection later in this report, the agreement between the data subsets for this statistic (95th percentile) is considered more heavily than the other concentration statistics (minimum, average, and maximum). For each parameter, a final model effluent treatment system effluent concentration is estimated based on this assessment.

6.4.5.4.1 Arsenic

Table 6-66 summarizes the arsenic concentration statistics for subsets of the uranium subsector final discharge effluent quality data; observations on these statistics and conclusions for the uranium subsector are summarized below.

Table 6-66: Arsenic Concentration Statistics for the Uranium Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00005	0.014	0.055	0.25	10
Model(s)	0.0002	0.016	0.057	0.061	3
Model(s) and Model Equivalent(s)	0.0002	0.013	0.055	0.061	5
Self-Identified as Targeting	0.0002	0.023	0.058	0.21	4
Model(s) that Self-Identify as Targeting	0.0002	0.023	0.057	0.061	2
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.0002	0.019	0.057	0.061	3

- The differences in concentration statistics between these data subsets are minor for the average values and essentially negligible for the 95th percentile values.
- One effluent treatment system targeting arsenic for removal is associated with the maximum treated effluent arsenic concentration of 0.2 mg/L; however this appears to be an exception, as all other concentration values at this final discharge point are <0.08 mg/L.
- The arsenic concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on 95th percentile values) is estimated to be <0.06 mg/L.

6.4.5.4.2 Copper

Table 6-67 summarizes the copper concentration statistics for subsets of the uranium subsector final discharge effluent quality data; observations on these statistics and conclusions for the uranium subsector are summarized below.

Table 6-67: Copper Concentration Statistics for the Uranium Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.0001	0.0031	0.0081	0.045	10
Model(s)	0.00053	0.0027	0.0072	0.014	3
Model(s) and Model Equivalent(s)	0.00053	0.0041	0.012	0.045	5
Self-Identified as Targeting	0.0022	0.010	0.034	0.045	1
Model(s) that Self-Identify as Targeting	No Data.				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.0022	0.010	0.034	0.045	1

- No operations with treatment systems classified as model effluent treatment systems self-identified as targeting copper.
- The differences in concentration statistics between these data subsets is significant, especially with respect to the average and 95th percentiles for the total cohort versus the effluent treatment system targeting copper. It is noted that the 95th percentile value for effluent treatment system targeting copper is based on only one operation.
- The copper concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on 95th percentile values) is estimated to be <0.04 mg/L.

6.4.5.4.3 Lead

Table 6-68 summarizes the lead concentration statistics for subsets of the uranium subsector final discharge effluent quality data; observations on these statistics and conclusions for the uranium subsector are summarized below.

Table 6-68: Lead Concentration Statistics for the Uranium Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00005	0.00034	0.0010	0.0050	10
Model(s)	0.00005	0.00031	0.00063	0.0016	3
Model(s) and Model Equivalent(s)	0.00005	0.00036	0.0012	0.005	5
Self-Identified as Targeting	0.00013	0.00072	0.0012	0.005	1
Model(s) that Self-Identify as Targeting	No Data				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.00013	0.00072	0.0018	0.005	1

- No operations with effluent treatment systems classified as model effluent treatment systems self-identified as targeting lead.
- The differences in concentration statistics between these data subsets are minor for the average and 95th percentile values.
- The lead concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on 95th percentile values) is estimated to be <0.002 mg/L.

6.4.5.4.4 Nickel

Table 6-69 summarizes the nickel concentration statistics for subsets of the uranium subsector final discharge effluent quality data; observations on these statistics and conclusions for the uranium subsector are summarized below.

Table 6-69: Nickel Concentration Statistics for the Uranium Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.0004	0.036	0.133	0.34	10
Model(s)	0.0004	0.022	0.080	0.1714	3
Model(s) and Model Equivalent(s)	0.0004	0.039	0.144	0.26425	5
Self-Identified as Targeting	0.0004	0.036	0.133	0.34	3
Model(s) that Self-Identify as Targeting	0.025	0.060	0.100	0.1714	1
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.025	0.088	0.211	0.26425	2

- The differences in concentration statistics between these data subsets are minor for the 95th percentile values and moderate for the average values (statistical concentration values for model and equivalent effluent treatment systems that target nickel are higher than statistical concentration values for the total cohort).
- The nickel concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment systems (based on 95th percentile values) is estimated to be <0.2 mg/L.

6.4.5.4.5 Zinc

Table 6-70 summarizes the zinc concentration statistics for subsets of the uranium subsector final discharge effluent quality data; observations on these statistics and conclusions for the uranium subsector are summarized below.

Table 6-70: Zinc Concentration Statistics for the Uranium Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00036	0.0088	0.032	0.13	10
Model(s)	0.0010	0.014	0.037	0.13	3
Model(s) and Model Equivalent(s)	0.00036	0.011	0.033	0.13	5
Self-Identified as Targeting	No Data.				0
Model(s) that Self-Identify as Targeting	No Data.				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	No Data.				0

- No operations reported targeting zinc via effluent treatment in the uranium subsector. As no uranium subsector operations reported targeting zinc via effluent treatment, it is not possible to establish the concentrations achieved by effluent treatment systems removing zinc. Influent concentrations of zinc from operations reporting influent data are very low, however some low levels of removal (<50%) are achieved across some systems.
- The differences in concentration statistics between these data subsets are minor for the average and 95th percentile values.
- The 95th percentile of the zinc concentration for the uranium subsector is <0.04 mg/L.

6.4.5.4.6 Radium-226

Table 6-71 summarizes the radium-226 concentration statistics for subsets of the uranium subsector final discharge effluent quality data; observations on these statistics and conclusions for the uranium subsector are summarized below.

Table 6-71: Radium-226 Concentration Statistics for the Uranium Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.0025	0.024	0.092	0.17	10
Model(s)	0.0025	0.030	0.10	0.17	3
Model(s) and Model Equivalent(s)	0.0025	0.024	0.10	0.17	5
Self-Identified as Targeting	0.0025	0.023	0.10	0.17	6
Model(s) that Self-Identify as Targeting	0.0025	0.030	0.11	0.17	3
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.0025	0.024	0.10	0.17	5

- The differences in concentration statistics between these data subsets are negligible for the average and 95th percentile values.
- The radium-226 concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on the 95th percentile) is estimated to be <0.11 mg/L.

6.4.5.4.7 Total Suspended Solids

Table 6-72 summarizes the total suspended solids concentration statistics for subsets of the uranium subsector final discharge effluent quality data; observations on these statistics and conclusions for the uranium subsector are summarized below.

Table 6-72: Total Suspended Solids Concentration Statistics for the Uranium Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.1	1.6	4.14	9.1	10
Model(s)	0.5	1.6	3.5	4.6	3
Model(s) and Model Equivalent(s)	0.5	2.0	5.03	7.18	5
Self-Identified as Targeting	0.5	1.9	4.8	7.18	6
Model(s) that Self-Identify as Targeting	0.5	1.6	3.5	4.6	3
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.5	2.0	5.03	7.18	5

- The differences in concentration statistic values between these data subsets are minor for the average concentrations. The 95th percentile values are moderately different, but within ±1.5 mg/L of each other.
- The TSS concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on 95th percentile values) is estimated to be <5.0 mg/L.

6.4.5.4.8 Aluminum

Table 6-73 summarizes the aluminum concentration statistics for subsets of the uranium subsector final discharge effluent quality data; observations on these statistics and conclusions for the uranium subsector are summarized below.

Table 6-73: Aluminum Concentration Statistics for the Uranium Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00025	0.073	0.35	0.96	8
Model(s)	0.0013	0.059	0.22	0.32	3
Model(s) and Model Equivalent(s)	0.0013	0.10	0.40	0.96	5
Self-Identified as Targeting	0.095	0.32	0.69	0.96	1
Model(s) that Self-Identify as Targeting	No Data.				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.095	0.32	0.69	0.96	1

- The differences in concentration statistics between these data subsets are significant, especially with respect to the differences in average and 95th percentiles between the total cohort and the effluent treatment systems targeting aluminum.
- The aluminum concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on 95th percentile values) is estimated to be <0.7 mg/L.

6.4.5.4.9 Iron

Table 6-74 summarizes the iron concentration statistics for subsets of the uranium subsector final discharge effluent quality data; observations on these statistics and conclusions for the uranium subsector are summarized below.

Table 6-74: Iron Concentration Statistics for the Uranium Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.0022	0.16	0.46	1.11	8
Model(s)	0.024	0.25	0.80	1.11	3
Model(s) and Model Equivalent(s)	0.0062	0.18	0.56	1.11	5
Self-Identified as Targeting	0.058	0.17	0.35	0.42	1
Model(s) that Self-Identify as Targeting	0.058	0.17	0.35	0.42	1
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.058	0.17	0.35	0.42	1

- The differences in concentration statistics between these data subsets are minor for the average and 95th percentile values, with the exception of the 95th percentile of model effluent treatment systems versus the other subsets, where the 95th percentile of model effluent treatment systems is slightly higher than the model effluent treatment systems targeting iron.
- The iron concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on 95th percentile values) is estimated to be <0.5 mg/L.

6.4.5.4.10 Selenium

Table 6-75 summarizes the selenium concentration statistics for subsets of the uranium subsector final discharge effluent quality data; observations on these statistics and conclusions for the uranium subsector are summarized below.

Table 6-75: Selenium Concentration Statistics for the Uranium Subsector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.00005	0.003	0.016	0.02	8
Model(s)	0.0003	0.001	0.0029	0.0034	3
Model(s) and Model Equivalent(s)	0.0003	0.005	0.016	0.02	5
Self-Identified as Targeting	0.0031	0.011	0.019	0.02	2
Model(s) that Self-Identify as Targeting	No Data.				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	0.0031	0.011	0.019	0.02	2

- The differences in concentration statistics between these data subsets are moderately significant for the average values, though are minor for the 95th percentile values, though model effluent treatment systems appear to achieve a 95th percentile value lower than the other subsets.
- The selenium concentration achieved by effluent treatment systems similar or equivalent to the model effluent treatment system (based on 95th percentile values) is estimated to be <0.02 mg/L.

6.4.5.4.11 Total Ammonia (as Nitrogen)

Table 6-76 summarizes the total ammonia (as nitrogen) concentration statistics for subsets of the uranium subsector final discharge effluent quality data; observations on these statistics and conclusions for the uranium subsector are summarized below.

Table 6-76: Total Ammonia Concentration Statistics for the Uranium Subsector

Data Set	Minimum (mg-N/L)	Average (mg-N/L)	95th Percentile (mg-N/L)	Maximum (mg-N/L)	# of Final Discharge Points
All Data	0.005	3.85	20	24	8
Model(s)	0.11	2.26	10	13	3
Model(s) and Model Equivalent(s)	0.11	5.39	20	24	5
Self-Identified as Targeting	15	19.5	22.9	24	1
Model(s) that Self-Identify as Targeting	No Data.				0
Model(s) and Model Equivalent(s) that Self-Identify as Targeting	15	19.5	22.9	24	1

- Total ammonia is not actively removed by the model effluent treatment system nor its equivalents, although some reduction in total ammonia concentrations may be achieved through volatilization during high pH process step(s) and natural degradation in ponds. It is assumed that those operations that self-identified as targeting ammonia that use model effluent treatment systems or equivalents employ water management practices to encourage the passive degradation of ammonia.
- The differences in concentration statistics between these data subsets are significant for the average and 95th percentile values. The effluent treatment systems that target ammonia have the highest average and 95th percentile values, which indicates that the concentration statistics for the total subsector data set may be skewed low by the sites that do not have significant concentrations of ammonia in untreated effluent.
- The total ammonia concentration achieved by the model effluent treatment system or equivalent that target ammonia (based on the 95th percentile) is <23 mg/L. It is assumed that this represents minimal removal (via volatilization and natural degradation) across the effluent treatment system and that the concentrations achieved in the treated effluent are similar to those in the untreated effluent.

6.4.5.4.12 Model Effluent Treatment System Effluent Concentration Summary

The 95th percentile concentrations achieved by model and model equivalent effluent treatment systems are summarized in Table 6-77. These will be used as representative of the concentrations produced by the model effluent treatment system for augmentative BAT cost estimation and BATEA selection.

Table 6-77: Concentrations Achieved by the Model Effluent Treatment System in the Uranium Subsector

Parameter	Concentration
Arsenic	<0.06 mg/L
Copper	<0.04 mg/L
Lead	<0.002 mg/L
Nickel	<0.2 mg/L
Zinc	<0.04 mg/L
Radium-226	<0.11Bq/L
TSS	<5.0 mg/L
Aluminum	<0.7 mg/L
Iron	<0.5 mg/L
Selenium	<0.02 mg/L
Total Ammonia (as nitrogen)	<23 mg-N/L

6.5 Diamond Sector

Canadian diamond operations are not, at present, subject to the current *Metal Mining Effluent Regulations*. Instead, they are subject to Section 36 of the *Fisheries Act* (general prohibition against the deposit of deleterious substances into water frequented by fish) and to site-specific limits based on applicable provincial and territorial regulations and policies. For operations located in the Northwest Territories, the *Northwest Territories Waters Act*, MVLWB Water and Effluent Quality Management Policy, and the CCME Canadian Water Quality Guidelines for the Protection of Aquatic Life are applied in the development of permitted discharge limits. The operation in Ontario is subject to a site-specific Certificate of Approval for Industrial Sewage Works for effluent treatment and discharge. Figure 6-49 illustrates the geographic distribution of Canadian diamond operations.

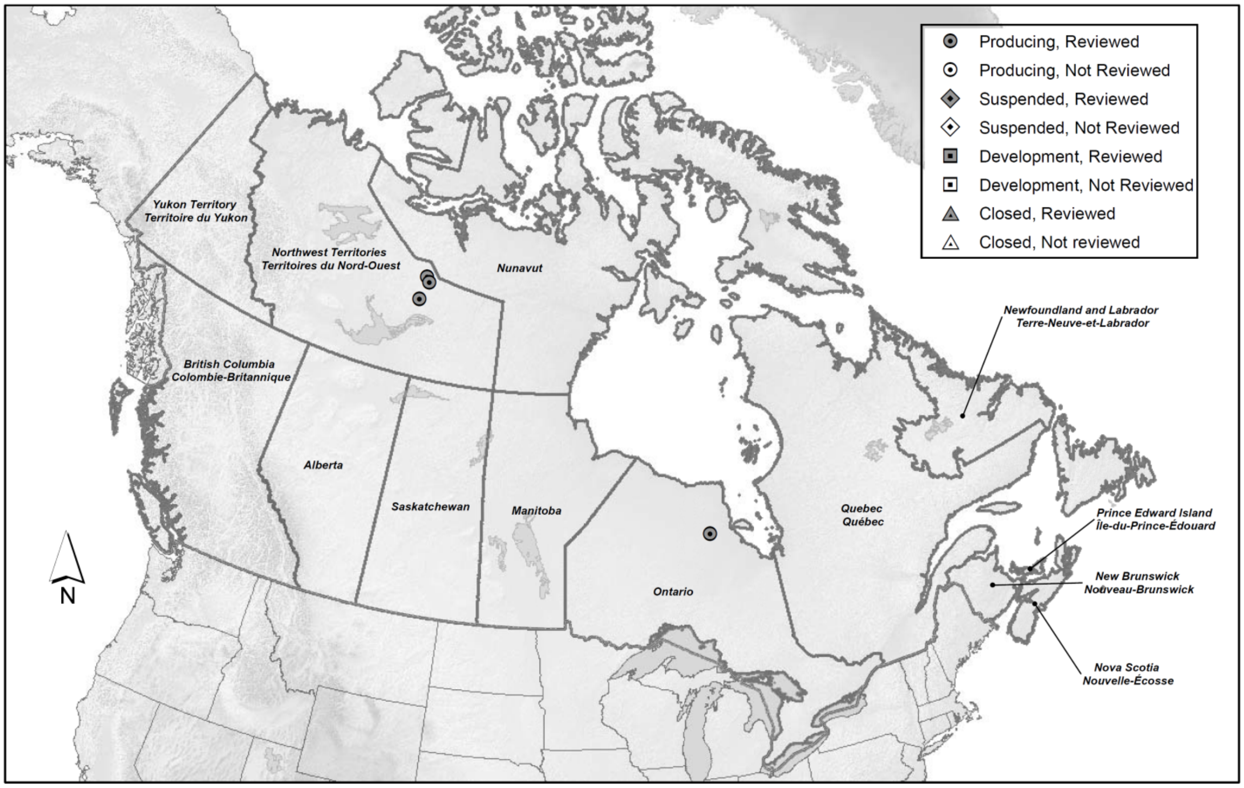

Figure 6-49: Geographic Distribution of Diamond Sector Operations

In 2009, WorleyParsons completed a report for Environment Canada on best available control technologies (BACT) for diamond mining effluent (6). Based in part on this report, Environment Canada has proposed to expand the scope of the *MMER* to include diamond operations in its 10-Year Review of *Metal Mining Effluent Regulations.* Also based on the same report, Environment Canada has posited that no diamond operation would be impacted by this regulatory change as all operations are satisfying jurisdictional regulatory requirements through the use of best available control technologies (7).

The review of the Canadian diamond sector included all 4 producing operations, as listed in Table 6-78, 3 of which submitted questionnaires as part of the data collection portion of the study, and 1 of which was researched independently. Jericho Diamond Mine in Nunavut was not evaluated in this study as it is assumed to be an abandoned operation and is in the care of the federal Contaminated Sites Program (8). Associated with these 4 operations were a total of 5 effluent treatment processes and 6 discharge points. No secondary products are produced at any of the operations.

Table 6-78: Canadian Diamond Operations

Operation	Owner/Operator	Location	Status
Snap Lake	De Beers Canada	Snap Lake, NWT	Operating
Victor	De Beers Canada	James Bay Lowlands, ON	Operating
Ekati	Dominion Diamond Corporation	Lac de Gras, NWT	Operating
Diavik	Dominion Diamond Corporation	Lac de Gras, NWT	Operating

The WorleyParsons's 2009 report "Identification of Best Available Control Technologies Applicable to Canadian Diamond Mining Effluent" prepared for Environment Canada provided a portion of the information summarized in this section (6). However, information provided via operations questionnaires was considered to be most recent and accurate and replaced any contradictory information from the WorleyParsons report.

Additional summary level information was provided by one development for incorporation into Revision 0 of this report. The development project is located in central Saskatchewan. The project has completed the feasibility study phase of engineering work and an Environmental Impact Statement for the project has been submitted to the Canadian Environmental Assessment Agency. As such, the water/effluent management techniques and treatment technologies planned for the project are expected to be fairly well developed.

6.5.1 *Effluent Characteristics*

In general, it is expected that the quality of effluent generated by any mine or mill operation, including diamond operations, will be variable from operation to operation based on site-specific factors, including, but not limited to, mine, mill, and waste management facilities present on site, the operating status of the site (e.g., closed, producing, etc.), local climate, and the mineralogy of the ore and waste rock. However, it is also expected that given the common target element for extraction from these operations, and common milling processes, effluent at diamond operations will share some similarities. A discussion of the similarities and differences between operation characteristics culminating in an establishment of a typical untreated effluent quality for diamond mines is presented in the following sections.

To establish what contaminants of concern are typically found in untreated effluent at diamond operations, parameters included in discharge permits, parameters reported as targeted by effluent treatment processes by questionnaire respondents and parameters reported in untreated effluent data by questionnaire respondents were considered. Figure 6-50 demonstrates the relative frequency of each parameter that appears in effluent discharge permits or is targeted by effluent treatment processes.

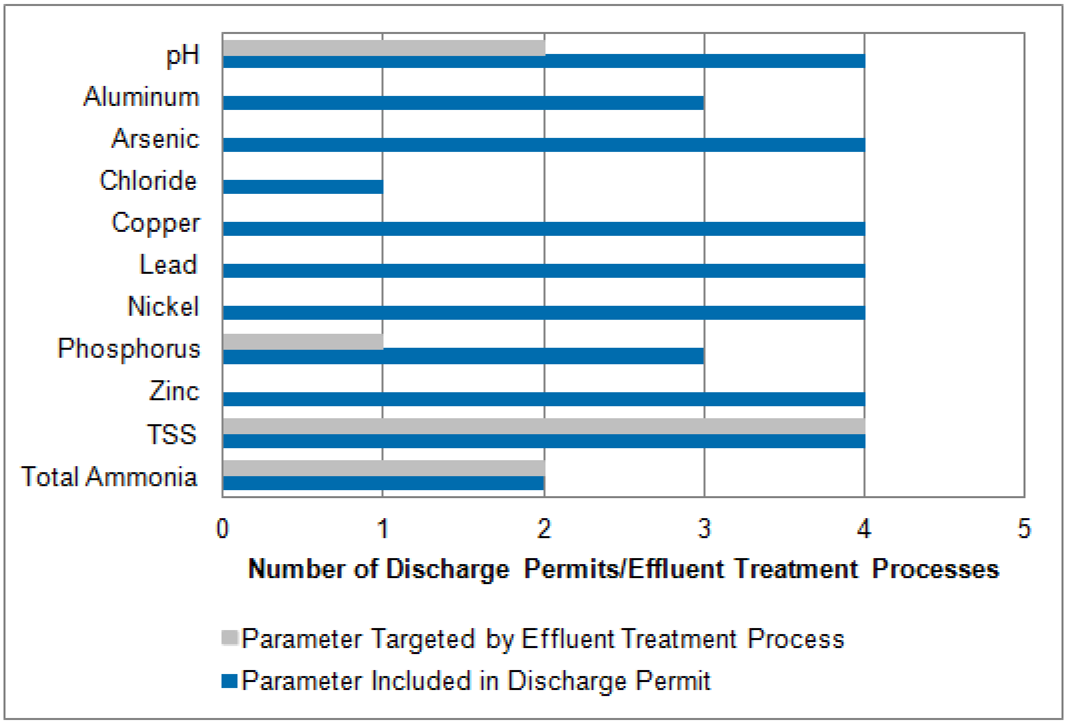

Figure 6-50: Parameters Included in Discharge Permits and Targeted by Effluent Treatment Processes at Reviewed Diamond Operations (4 Operations Discharge Permits / 4 Operations Treatment Processes)

Of the 3 diamond operations that submitted operations questionnaires to support this study, only 2 elected to provide untreated effluent quality as part of their submittals, as summarized in Table 6-79.

Table 6-79: Quarterly Average Concentrations of Parameters in Diamond Operations Untreated Effluent

Parameter	Unit	Minimum	Average	95th Percentile	Max	Number of Operations Reporting Untreated Effluent Concentration
pH		7.60	8.08	8.50	8.65	2
Aluminum	mg/L	0.185	0.254	0.309	0.312	1
Ammonia, total	mg-N/L	0.05	0.17	0.32	0.35	2
Arsenic	mg/L	0.004	0.0048	0.0056	0.0057	1
Chloride	mg/L	19.4	56	77.0	78.8	2
Copper	mg/L	0.0008	0.0017	0.0027	0.0029	2
Iron	mg/L	0.12	0.39	0.76	0.82	2
Lead	mg/L	0.00018	0.00037	0.00046	0.00047	2
Manganese	mg/L	0.019	0.038	0.053	0.055	2
Mercury	mg/L	0.00003	0.00068	0.00177	0.00180	2
Nickel	mg/L	0.0028	0.0069	0.0112	0.0119	2
Phosphorus	mg/L	0.01	0.20	0.44	0.47	2
Selenium	mg/L	0.0004	0.00059	0.00080	0.0008	1
Zinc	mg/L	0.0028	0.0035	0.0053	0.0061	2
TSS	mg/L	4.89	10.7	22.5	22.5	2

Notes:
Values reported as less than the method detection limit have been incorporated at the MDL value.
All metal concentrations are total metal concentrations, i.e., the sum of dissolved and suspended fractions.

The main contaminant that is considered to be typical based on frequency of occurrence in untreated effluent at diamond operations is TSS. In all 4 operations reviewed, total suspended solids are targeted by all the effluent treatment systems.

Additional potential contaminants of concern that may be present in untreated effluent at diamond operations include pH, ammonia, phosphorus, and chloride (9). Ammonia in untreated effluent originates from explosives used for mining. Phosphorus in untreated effluent may originate from site-specific factors such as leaching of phosphorus from geologic materials and groundwater quality. Chloride appears to originate from site-specific factors such as groundwater quality. Two operations have reported exceedences of limits for zinc which may be due to analytical or undisclosed site-specific reasons (6). Table 6-80 summarizes the characteristics of the reviewed diamond operations that may contribute to the typical untreated effluent quality. The central Saskatchewan development project expects to be compliant with currently regulated *MMER* parameters and limits, but to have high chloride concentrations based on water quality modeling which considers glacial overburden geology and the interception of a confined aquifer at depth. The project's effluent treatment processes, as planned, will target TSS only.

Table 6-80: Factors Influencing Diamond Sector Untreated Effluent Quality

Ore and Waste Rock Mineralization	Mine and Mill Operational Status and Facilities	Diamond Processing
All 4 diamond operations in Canada mine kimberlite, which is an alkaline, generally non-sulfidic, non-acid mineral. There is potential for acid generation from host rock and intrusions. Groundwater inflows to mine features may contain dissolved solids of concern (e.g., chloride, phosphorus) at concentrations of concern for site-specific discharge criteria.	All operations reviewed for this sub-sector are in operation. There are 4 mines with a primary activity of ore extraction from open pit and underground mines, with ore stockpiles, mill facilities for kimberlite processing and diamond recovery from ore, tailings facilities and waste rock storage facilities.	The main extractive process for diamonds which may have a detrimental effect on untreated effluent quality is the crushing of ore. Crushing ore generates small particles, which increase levels of total suspended solids in the process water. Grease tables may be used as part of diamond recovery. Grease is managed carefully and should not impact effluent quality. Solvent or acid may be used to clean recovered diamonds. Wash solution is managed carefully and should not impact effluent quality.

6.5.2 *Effluent Management and Control Techniques*

In an effort to control the volume and quality of effluent requiring containment and treatment prior to discharge to the environment, and to minimize the risk of potential contaminants being released to the environment, diamond operations employ a variety of techniques to manage water. It should be noted that many diamond operations are intimately situated with bodies of high quality water and hence must carefully manage and control effluent to meet site-specific objectives. The management techniques employed for effluent volume and quality control at diamond operations reviewed for this study are summarized in Table 6-81.

Table 6-81: Effluent Management and Control Techniques at Diamond Operations

Volume Control	Quality Control	Minimize Environmental Contact
• Diversion of non-impacted surface water and groundwater away from facilities that may negatively impact water quality. • Recycling of impacted water back to processing plant to reduce volume of water requiring treatment. • Segregation of NAG and NML waste from PAG and PML waste. • Goal of zero liquid discharge (ZLD) from "Processed Kimberlite" tailings storage facility, net precipitation permitting.	• Explosives best management plan in force. • Waste rock and cemented tailings used as underground mine backfill. • Goal of zero liquid discharge (ZLD) from "Processed Kimberlite" tailings storage facility, net precipitation permitting.	• Storage of PAG and PML waste in dedicated storage facilities with environmental controls (e.g. caps/covers, liners, water cover). • Collection of impacted water and conveyance to treatment (e.g. seepage collection).

The following sections present a more detailed summary of the mining and waste management methods at diamond operations and associated effluent management and control techniques. It should be noted that in the figures, each operation can employ more than one technique and thus the sum of the number of operations presented in this figure may exceed the number of operations reviewed in this study.

6.5.2.1 Mine Facilities and Water Management Techniques

Based on the questionnaire responses, mine operations are distributed evenly among underground and open pit mines, with one mine operating an underground mine, one mine operating an open pit and one mine operating both. As shown in Figure 6-51, diamond mines use surface water diversion, seepage collection, and groundwater interception to minimize mine-water-environment interactions.

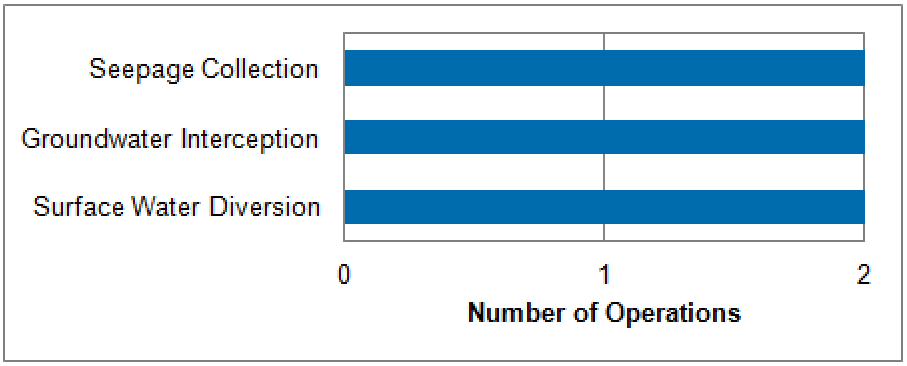

Figure 6-51: Diamond Sector Mine-Water-Environment Interaction Minimization Techniques (3 Operations)

6.5.2.2 *Explosives Use*

Of the operations that submitted operations questionnaires, one operation uses bulk emulsion exclusively, another uses bulk emulsion and packaged ANFO (minor amounts for surface quarrying activities only), and another uses bulk emulsion (for underground mining) as well as bulk ANFO (for open pit mining). Explosives best management plans were reported by all 3 questionnaire respondents. Figure 6-52 illustrates the explosive use at diamond operations.

Source control of explosives via best management plans was has been previously recommended in lieu of selection of BAT effluent treatment technology(ies) for ammonia control at diamond mining operations in the Northwest Territories (10). Moreover, one operation has investigated a wide range of technologies for the removal of ammonia from mine effluent and combined effluent and found that even the most feasible treatment approach to be environmentally and financially prohibitive.

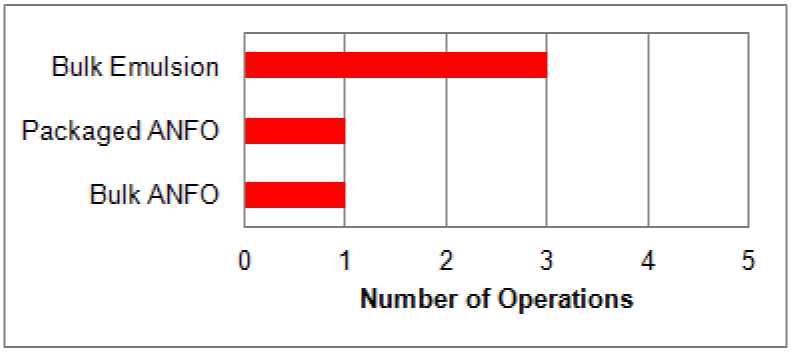

Figure 6-52: Relative Use of Types of Explosives at Diamond Operations (3 Operations)

6.5.2.3 *Ore Stockpiles and Water Management Techniques*

Of the 3 operations that submitted operations questionnaires, 2 have active ore stockpiles on site. One of these operations does not employ any technique to minimize ore stockpile-water-environment interactions, because the ore that is stockpiled (kimberlite) has been assessed to be NAG, NML, and alkaline. As illustrated in Figure 6-53 the other operation minimizes ore stockpile-water-environment interaction through seepage collection and treatment. In Figure 6-53, "Not Minimized" indicates that the operation does not employ Ore Stockpile-Water-Environment minimization techniques to prevent air and water contact with ore stockpiles.

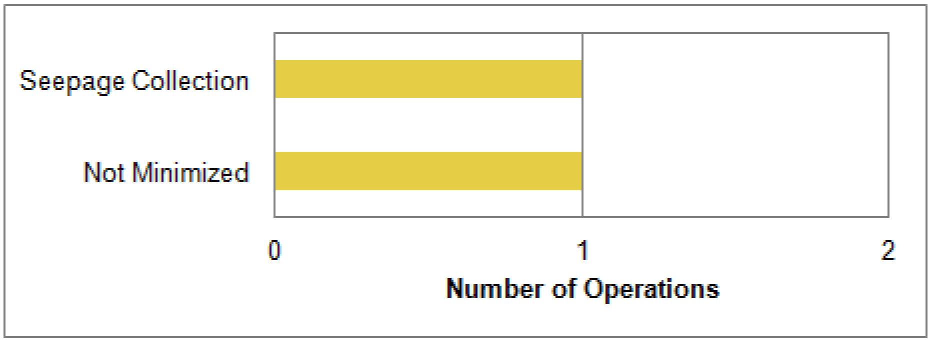

Figure 6-53: Diamond Sector Ore Stockpile(s)-Water-Environment Interaction Minimization Techniques (2 Operations)

6.5.2.4 *Waste Rock Disposal Methods and Water Management Techniques*

Figure 6-54 summarizes the relative frequency of the methods that diamond operations utilize to dispose of waste rock. Of the operations that submitted operations questionnaires, 1 does not employ environmental controls for waste rock stockpiles, while the other 2 operations both segregate waste rock according to potential for acid generation and metal leaching.

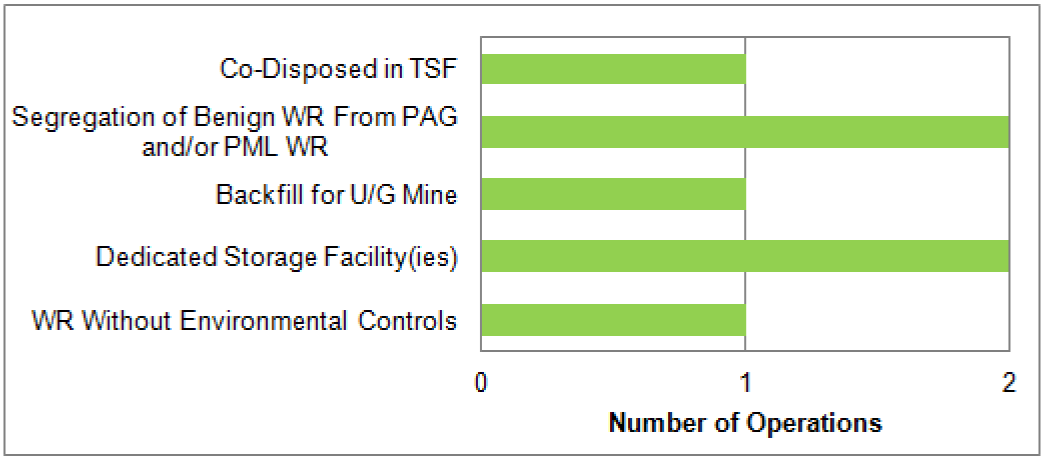

Figure 6-54: Diamond Sector Waste Rock Disposal Techniques (3 Operations)

Table 6-82 summarizes the disposal methods for the different types of waste rock present at these operations.

Table 6-82: Waste Rock Disposal Methods at Diamond Operations

Waste Rock Classification	Disposal Method or Use
PAG and/or PML	• PAG co-disposal within tailings in tailings storage facility. • PML thermal cover (permafrost) barrier at closure.
NML and NAG	• Use in construction. • Sub-aerial waste rock stockpiles.

The 2 operations that reported segregating waste rock both employ seepage collection, liners, and either surface water diversion or a cap/cover (e.g., soil, vegetation). Additionally, progressive reclamation is planned for 2 operations. Figure 6-55 summarizes the relative frequency of the use of these methods. “Not Applicable” in Figure 6-55 refers to operations with waste rock stockpiles without environmental controls.

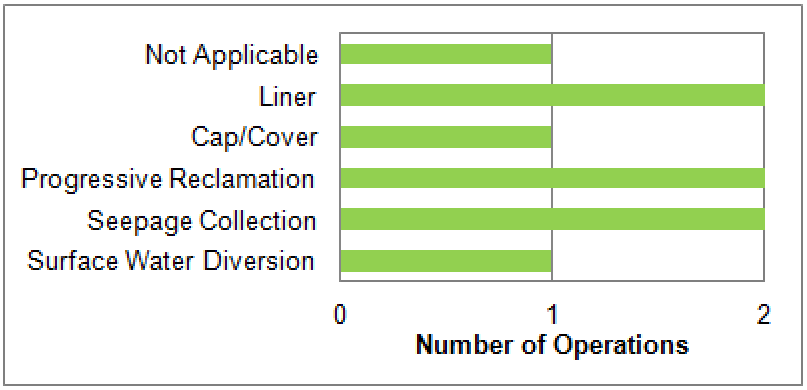

Figure 6-55: Diamond Sector Waste Rock-Water-Environment Interaction Minimization Techniques (3 Operations)

6.5.2.5 *Tailings Disposal Methods and Water Management Techniques*

Diamond operations generally refer to their tailings as “Processed Kimberlite” (PK). All of the operations that submitted questionnaires produce and dispose of PK on site; 2 do so in dedicated sub-aerial tailings storage facilities and the other employs a combination of underground mine backfill and co-disposal of PK with waste rock in a dedicated sub-aerial storage facility. This information is summarized in Figure 6-56.

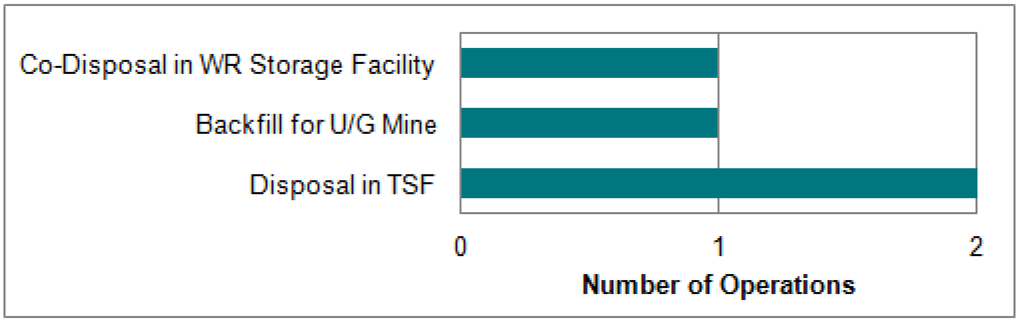

Figure 6-56: Diamond Sector Tailings Disposal Methods (3 Operations)

PK is dewatered prior to disposal at 2 of the operations that submitted questionnaires and at 1 additional operation for which data was gathered from other sources. However, PK does not undergo any other treatment prior to final discharge.

PK-water-environment interactions are minimized through the utilization of seepage collection, progressive reclamation of tailings storage facilities, surface water diversion, liner, and cap/cover. Water cover is planned to be employed at closure. The relative use of these measures is illustrated in Figure 6-57.

At least 2 operations recycle tailings reclaim from their PK tailings storage facilities to their processing plants.

The central Saskatchewan development project plans to recycle tailings reclaim from its PK storage facility to supply up to 100% of processing plant water demand; however, no recycle has been assumed (this would establish a conservative water balance with respect to effluent discharge volumes). For this development, seepage collection is planned as a contingency. Collected seepage may be recycled, detained, or discharged to the environment, as appropriate.

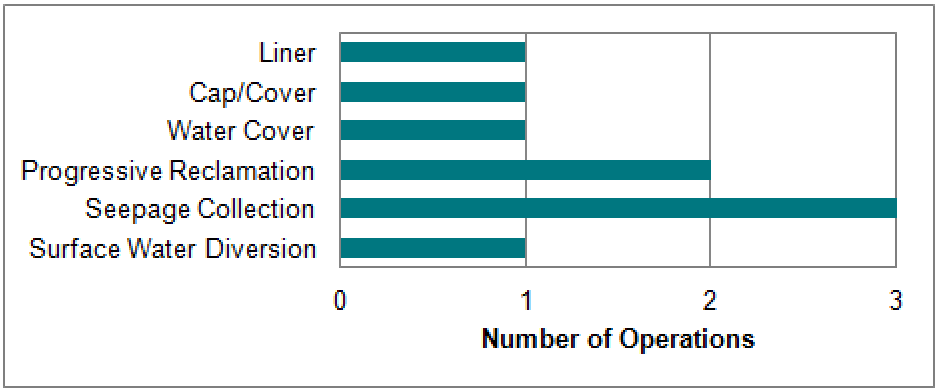

Figure 6-57: Diamond Sector Tailings-Water-Environment Interaction Minimization Techniques (3 Operations)

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6.5.3 *Effluent Treatment Technologies*

All diamond operations use treatment processes to meet discharge criteria established in their discharge permits, certificates of authorization, or water licenses. All 4 operations include TSS removal technologies, while pH and ammonia are targeted at 2 operations, and phosphorus is targeted at 1 operation. The chemical processes and physical processes that are employed in effluent treatment processes at diamond operations and summarized in Table 6-83. One operation is currently investigating membrane size/charge exclusion technologies (i.e., reverse osmosis) to remove dissolved solids from a mine effluent stream under direct influence from groundwater. Following the best practice of prioritizing treatment on lower volume higher concentration effluents, the stream would be isolated from other effluent streams. This would allow for reduction of effluent treatment capital and operating costs, as well as the reduction treatment residuals produced (e.g., reject, brine). Another operation performed a similar investigation to support its environmental assessment and found reverse osmosis to be uneconomical for the removal of chloride from mine dewatering effluent

As previously stated, effluent treatment processes for the central Saskatchewan development project, as planned, will target TSS only through retention and settling ponds.

Table 6-83: Chemical and Physical Processes for Diamond Sector Effluent Treatment

Chemical and Biological Processes	Physical Processes
• Solid/Liquid Separation • Aluminum sulfate/ferric sulfate addition to co-precipitate phosphorus and coagulate TSS. • Flocculant addition to flocculate TSS. • pH Adjustment • Contingency sodium hydroxide or lime-based pH adjustment and alkalinity control for coagulation buffering and precipitation of aluminum or iron from reagent addition • Sulfuric acid addition for pH adjustment and to minimize fraction of ammonia as un-ionized ammonia (NH_3). • Passive Treatment • Passive volatilization and natural degradation of ammonia (bio-physico-chemical process). • Passive natural degradation of phosphorus (bio-chemical process).	• Solid/Liquid Separation • Settling ponds. • Semi-pervious filter dykes. • Floating silt curtain. • Conventional clarifiers. • High rate clarifiers. • Media filters.

Both pond-based settling and clarifiers are used at diamond operations for TSS removal. Polishing ponds and media filtration are used as final polishing steps. It is important to note that treatment processes occurring in pond-based systems are subject to seasonal temperature and precipitation influx variability, which may interrupt treatment processes or cause variations which may negatively affect removal efficiency. Moreover, sudden increases in flow rate, heavy rainfall events, seasonal turnover and high winds and wave action can re-suspend precipitates, potentially causing downstream non-compliance.

6.5.4 *Effluent Quality*

Table 6-84 summarizes the effluent quality reported by diamond operations to Environment Canada, provided to Hatch for the purpose of this study. The values in this table are based on analysis by Environment Canada, except for pH, chloride, phosphorus, TAN and TSS. The concentration statistics for chloride, phosphorus, TAN and TSS were generated by Hatch to support model effluent treatment quality work in Section 6.5.5.4. pH remains the same as in Revision 0.

Table 6-84: Diamond Sector Treated Effluent Summary

Parameters	Unit	Minimum Quarterly Mean Concentration	Average Quarterly Mean Concentration	95th Percentile Quarterly Mean Concentration	Maximum Quarterly Mean Concentration	Number of Operations Reporting Treated Effluent Concentration
pH		7.55	7.74	7.95	8.00	3
Aluminum	mg/L	0.001	0.20	0.51	1.29	4
Ammonia, total	mg-N/L	0.002500	0.60	2.35	8.52	4
Arsenic	mg/L	0.00006	0.00090	0.0023	0.0036	4
Chloride	mg/L	0.54	375.76	1,240	1,950	4
Copper	mg/L	0.0002	0.0041	0.0086	0.19	4
Iron	mg/L	0.003	0.19	0.82	11.7	4
Lead	mg/L	0.00001	0.00028	0.00050	0.0011	4
Manganese	mg/L	0.001	0.038	0.079	1.0	4
Nickel	mg/L	0.0003	0.0065	0.014	0.04	4
Phosphorus	mg/L	0.0005	0.037	0.15	0.16	4
Selenium	mg/L	0.00002	0.00027	0.00088	0.00190	4
Zinc	mg/L	0.00005	0.0021	0.0054	0.0174	4
TSS	mg/L	0.2	2.66	7.54	124	**9**

Notes:
Values reported as less than the method detection limit have been incorporated at half of the MDL value.
All metal concentrations are total metal concentrations, i.e., the sum of dissolved and suspended fractions.

6.5.5 Model Water Management and Effluent Treatment System

6.5.5.1 Model Water Management System

Based on this review of water management techniques employed by diamond operations, a model water management plan to represent the typical water management practices employed at these operations has been generated. This model is presented in Figure 6-58.

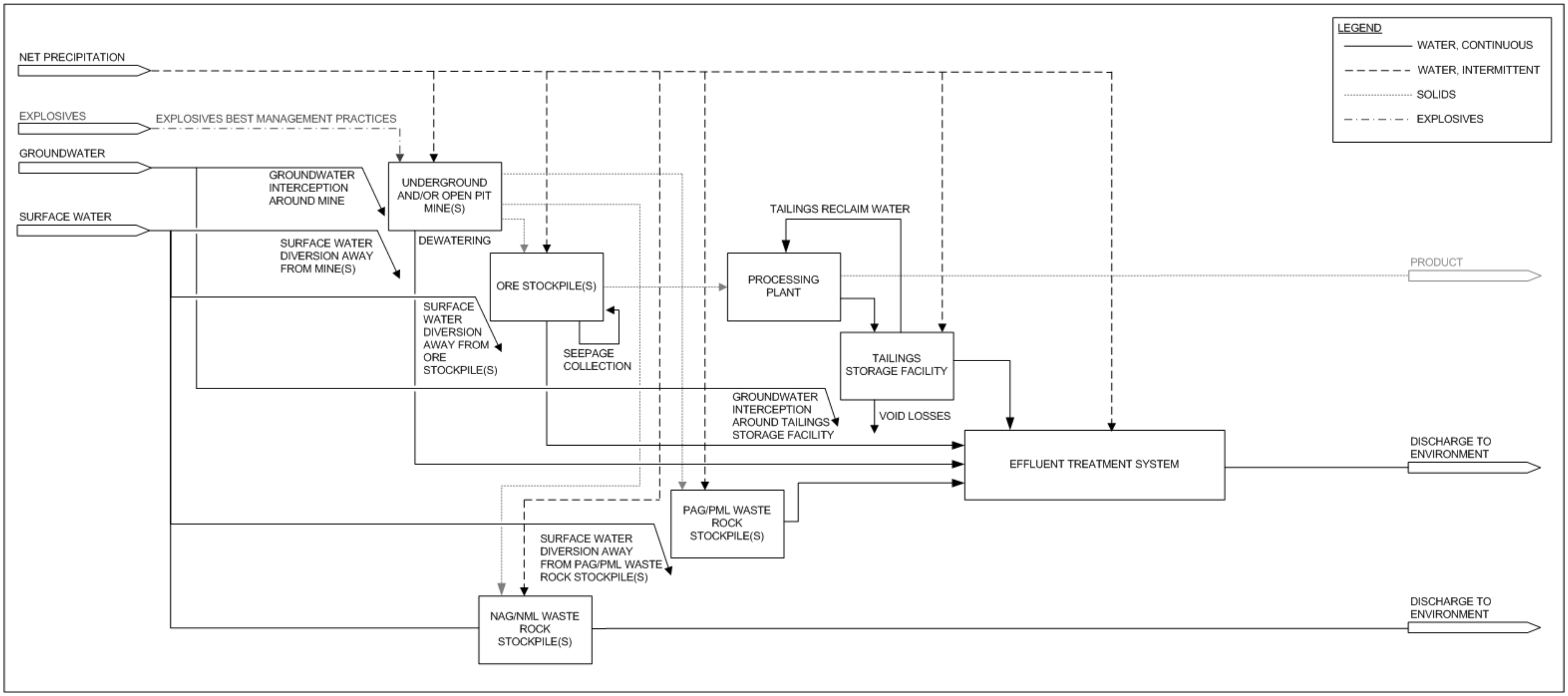

Figure 6-58: Diamond Sector Water Management Model

6.5.5.2 *Model Treatment System Process Flow Diagram*

To determine a model effluent treatment system for diamond operations, the following aspects of the effluent treatment systems were reviewed:

- What parameters are targeted by effluent treatment processes, and which parameters are of the most concern.
- What physical processes are used.
- What chemical treatment processes are used.

The four operations under consideration for the model effluent treatment process are all active, with several common treatment technologies. All four operations considered use settling ponds, for pre-treatment and/or post-treatment of TSS and natural degradation of ammonia and phosphorus, and/or for quality monitoring purposes. One operation utilizes semi-pervious filter dykes and one operation uses a floating silt curtain to improve TSS removal. Two operations use media filtration (sand and sand/anthracite) for the same purpose. Two operations utilize lime on an as needed/contingency basis for pH adjustment and alkalinity control for coagulation buffering and precipitation of aluminum or iron from reagent addition. Several reagents are added throughout the treatment systems to aid in coagulation and flocculation and control pH. These reagents are: flocculant, aluminum sulfate/ferric sulfate, lime, sodium hydroxide, and sulfuric acid.

As a result of these considerations and evaluations, the model system illustrated in Figure 6-59 was established. In this model, effluent is equalized prior to treatment and bulk TSS is removed via pond-based settling. The equalization/settling pond(s) also allow time for passive natural degradation of ammonia and phosphorus. The effluent is coagulated (e.g., with ferric sulfate or aluminum sulfate). If required, to adjust effluent pH, hydroxide reagent (e.g., lime, sodium hydroxide) may be added on a contingency basis. Precipitates are then allowed to settle, aided by flocculant, in a clarifier. Clarifier overflow is then polished by media filtration before being pH adjusted with sulfuric acid to meet un-ionized ammonia/toxicity limits prior to discharge to the environment. Clarifier underflow is co-disposed with tailings.This system closely resembles several existing effluent treatment systems, but is not identical to any one treatment system. This system is consistent with the BAT findings of the Lakefield Research Ltd. and SENES Consultants Ltd report to the Department of Indian and Northern Affairs Canada(10) BACT findings of the WorleyParsons report to Environment Canada (6) and in particular, treatment train Scenario #2.

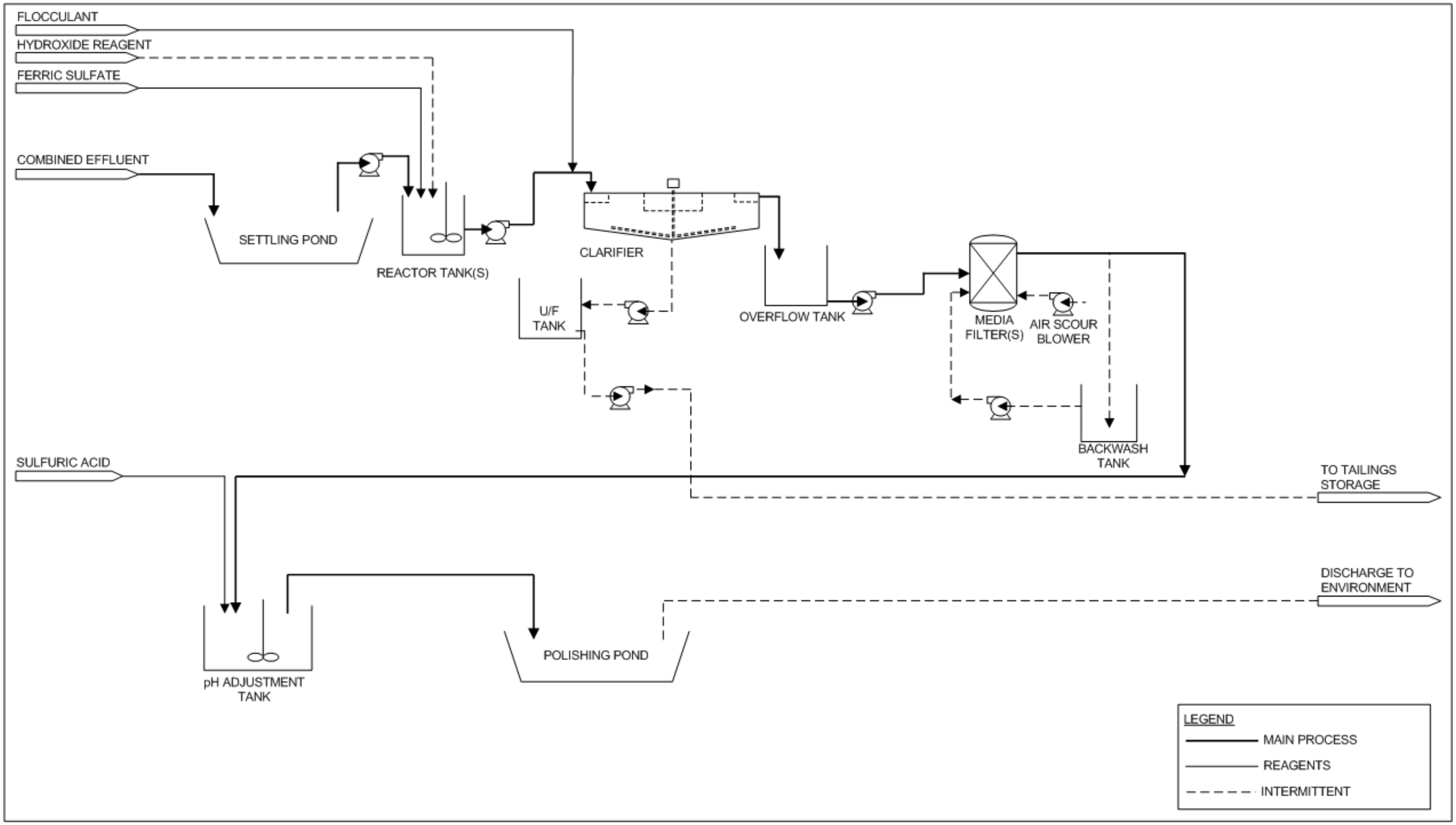

Figure 6-59: Diamond Sector Model Effluent Treatment Process

6.5.5.3 *Model Effluent Treatment System Flow Rate*

While some operations discharge year round, other operations discharge only during non-winter months (e.g., April/September to October). Discharge volume depends on a number of site-specific factors including, but not limited to, precipitation, evaporation, footprints of site features and groundwater inflow to site features. Discharge volumes from diamond operations vary from 3.7 million m^3/year to over 57.4 million m^3/year, as shown in Table 6-85. The higher flow rates tend to be related to high groundwater inflow to site features. For the purposes of this study, the selected value for the design capacity of the diamond sector model effluent treatment system is 3,000 m^3/h. This value will be utilized for capital cost estimating for system augmentation. The selected value for the nominal flow rate of the diamond sector model effluent treatment system is 2,000 m^3/h to compromise between the average estimated hourly discharge volume and the questionnaire reported average treatment system flow rate. This value will be utilized for operating cost estimating for system augmentation.

Table 6-85: Discharge Statistics for the Diamond Sector

	Annual Discharge Volume (m^3/year)[22]	Estimated Hourly Discharge volume (m^3/h)[23]	Questionnaire Reported Average Treatment System Flow Rate	Questionnaire Reported Design/Maximum Treatment System Flow Rate
Range	3,700,000 to 57,400,000	422 to 6,553	50 – 1,700	1,740 – 3,750
Average Flow	20,722,931	2,366	1,060	2,870
Median	10,895,862	1,244	1,420	3,125

6.5.5.4 *Model Effluent Treatment System Effluent Quality*

In Revision 0 of this report, the 95th percentile of the effluent quality summary for the entire diamond sector (as summarized in Table 6-84) for each parameter was used to represent the effluent quality that was produced by the model effluent treatment system. It was assumed that for each parameter, the 95th percentile would reflect the concentration in the effluent at the majority of sites and that the 95th percentile value associated with the complete data set would be weighted to reflect the most common effluent treatment technologies (and therefore the model effluent treatment system), as the most common effluent treatment systems would contribute a larger fraction of the concentration values than other systems.

Feedback received from industry indicated two main concerns with the use of 95th percentile values as representative of the model effluent treatment system, as follows:

1. The total cohort of final discharge effluent quality data for the subsector originates from a variety of effluent treatment systems, and not just systems very similar or equivalent to the model effluent treatment system. This could skew the 95th percentile values, as other types of effluent treatment systems may achieve higher or lower concentrations than the

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[22] Aggregated from WorleyParsons Diamond Mining Effluent BACT report (6) and operations questionnaire responses.
[23] Assumes 365 days/year, 24 hours/day discharge.

model. Thus, using the total cohort of final discharge effluent quality data for the subsector may not be representative of the concentrations specifically achieved by the model effluent treatment system.

2. Using the total cohort of final discharge effluent quality data for the subsector may result in average and 95th percentile values that are skewed low by the inclusion of concentration data from effluent treatment systems that do not target or remove a given parameter (i.e., where the concentration of a given parameter in untreated effluent is compliant with existing *MMER* without treatment). Using the total cohort of final discharge effluent quality data does not consider which concentration values reflect concentrations achievable by treatment, and thus, may not be representative of the concentration achieved by any given treatment system.

To better reflect the concentrations achieved by subsector effluent treatment systems very similar to or equivalent to the model effluent treatment system for systems that target the removal of the parameters in question, Hatch compared concentration statistics for subsets of Schedule 4 and Schedule 5 data. The subsets were organized according to type of effluent treatment system and targeted parameters. Effluent treatment system information was collected during Revision 0 work via questionnaire and independent research, and augmented with additional data collected during Revision 1 work. The purpose of this effort was to narrow the total cohort of final discharge effluent quality data down to the concentration values that are more representative of concentrations achieved by systems similar to the model effluent treatment system.

Two types of effluent treatment systems utilized by diamond subsector operations were of interest for this analysis: systems similar to the model effluent treatment system (referred to as “model effluent treatment systems”) and systems that are not exactly like the model effluent treatment system but utilize a process that can achieve similar effluent quality to model effluent treatment systems (referred to “model equivalent effluent treatment systems”). For the diamond sector, this type of treatment systems is defined as follows:

- **Model Effluent Treatment Systems:** Site utilizing treatment systems similar or identical to Figure 6-59: TSS removal via clarification with addition of flocculant, coagulant and contingent hydroxide addition when necessary).

In other subsectors, another type of effluent treatment system examined in this work was those systems considered “model equivalents”, however as there are essentially only two types of effluent treatment systems for the diamond sector (e.g., reactor-based clarification and pond-based clarification), there is no model equivalent for this sector.

For the diamond sector, the critical parameters for which concentration statistics were developed were phosphorus, chloride, total ammonia, and total suspended solids (TSS), as these are the parameters proposed to be included in *MMER* for the diamond sector. pH has been excluded as a critical parameter as the control over final pH is well understood and practiced. For each of these parameters, effluent quality statistics have been developed for the subsets of the total cohort, according to:

1. Model effluent treatment systems

2. Effluent treatment systems that target the parameter
3. Model effluent treatment systems that target the parameter

Effluent treatment systems targeting parameters were identified per self-reporting by operations via the Revision 0 questionnaire and the Revision 1 mini-survey; this self-reported information was confirmed to the extent possible using paired untreated effluent and treated effluent quality data provided by operations where available. Where information provided in the Revision 0 questionnaire differed from the information provided in the Revision 1 questionnaire, the operation was contacted to ensure a correct understanding of the information.

A comparison between the concentration statistics for each subset of data was performed to assess the extent to which the utilization of the total cohort of diamond subsector effluent quality data may skew the concentration statistics in comparison to data associated with model or model equivalent effluent treatment systems that target the parameter. The number of final discharge points associated with each data set is also provided. As the 95th percentile values are used in augmentative BAT cost estimation and BATEA selection later in this report, the agreement between the data subsets for this statistic (95th percentile) is considered more heavily than the other concentration statistics (minimum, average and maximum). For each parameter, a final model effluent treatment system effluent concentration is estimated based on this assessment

6.5.5.4.1 Phosphorus

Table 6-86 summarizes the phosphorus concentration statistics for subsets of the diamond final discharge effluent quality data; observations on these statistics and conclusions for the diamond sector are summarized below.

Table 6-86: Phosphorus Concentration Statistics for the Diamond Sector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.0005	0.037	0.15	0.16	9
Model(s)	0.00050	0.031	0.09	0.16	3
Self-Identified as Targeting	0.010	0.045	0.098	0.16	1
Model(s) that Self-Identify as Targeting	0.01000	0.045	0.098	0.16	1

- The differences in concentration statistics between these data subsets is minor for the average values, however is somewhat significant for the 95th percentile values. The 95th percentile of the whole sector data set is somewhat higher than the 95th percentile for the operation targeting phosphorus and for all the model effluent treatment systems.
- The phosphorus concentration achieved by effluent treatment systems similar to the model effluent treatment system that target phosphorus is estimated to be <0.1 mg/L.

6.5.5.4.2 Chloride

Table 6-87 summarizes the chloride concentration statistics for subsets of the diamond final discharge effluent quality data; observations on these statistics and conclusions for the diamond sector are summarized below.

Table 6-87: Chloride Concentration Statistics for the Diamond Sector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.54	375.76	1,240	1,950	9
Model(s)	46.00	144.01	270.55	335	3
Self-Identified as Targeting	No data.				0
Model(s) that Self-Identify as Targeting	No data.				0

- No operations self-identified as targeting chloride for removal from effluent prior to discharge.
- The model effluent treatment system does not remove chloride from effluent. Differences between concentration statistics for the model effluent treatment system and the entire sector data are the result of site-specific factors and not the effluent treatment system itself.
- The 95th percentile based on the whole diamond sector data set was carried forward as the chloride concentration achieved by the model effluent treatment system to conservatively represent the sites with higher chloride concentrations, as operations would not achieve additional removal with the use of the model effluent treatment system.
- The 95th percentile of chloride concentration for the diamond sector is 1,240 mg/L.

6.5.5.4.3 Total Ammonia as Nitrogen

Table 6-88 summarizes the total ammonia (as nitrogen) concentration statistics for subsets of the diamond final discharge effluent quality data; observations on these statistics and conclusions for the diamond sector are summarized below.

Table 6-88: Total Ammonia Concentration Statistics for the Diamond Sector

Data Set	Minimum (mg-N/L)	Average (mg-N/L)	95th Percentile (mg-N/L)	Maximum (mg-N/L)	# of Final Discharge Points
All Data	0.0025	0.60	2.35	8.52	9
Model(s)	0.010	0.90	2.74	8.52	3
Self-Identified as Targeting	No data.				0
Model(s) that Self-Identify as Targeting	No data.				0

- No operations self-identified as targeting ammonia for removal from effluent prior to discharge.

- The model effluent treatment system does not actively remove ammonia from effluent; however, some natural degradation could occur in settling and polishing ponds within the effluent treatment system. Some level of ammonia reduction may be achieved by this mechanism. Any differences between concentration statistics for all diamond sector data and the model subset of effluent data are assumed to be due to site-specific factors.
- There are minor differences between the data sets examined for the 95th percentile and average values.
- The 95th percentile based on the whole diamond sector data set was carried forward as the ammonia concentration achieved by the model effluent treatment system, as operations would not necessarily achieve additional removal with the use of the model effluent treatment system.
- The 95th percentile of total ammonia concentration achieved by the model effluent treatment system is <2.35 mg/L.

6.5.5.4.4 Total Suspended Solids

Table 6-89 summarizes the total suspended solids (TSS) concentration statistics for subsets of the diamond final discharge effluent quality data; observations on these statistics and conclusions for the diamond sector are summarized below.

Table 6-89: TSS Concentration Statistics for the Diamond Sector

Data Set	Minimum (mg/L)	Average (mg/L)	95th Percentile (mg/L)	Maximum (mg/L)	# of Final Discharge Points
All Data	0.2	2.66	7.55	124	9
Model(s)	1.34	2.90	7.0	124	3
Self-Identified as Targeting	0.2	2.76	8.11	124	5
Model(s) that Self-Identify as Targeting	1.34	2.90	7.0	124	3

- The differences between concentration statistics for TSS are minor for the average and 95th percentile values.
- The TSS concentration achieved by effluent treatment systems similar to the model effluent treatment system is estimated to be <7.0 mg/L based on 95th percentile values.

6.5.5.4.5 Model Effluent Treatment System Effluent Concentration Summary

The 95th percentile concentrations achieved by model and model equivalent effluent treatment systems for the diamond sector are summarized in Table 6-90.These will be used as representative of the concentrations produced by the model effluent treatment system for augmentative technology costing and BATEA selection.

Table 6-90: Concentrations Achieved by the Model Effluent Treatment Systems in the Diamond Sector

Parameter	Concentration
Phosphorus	<0.1 mg/L
Chloride	<1,240 mg/L
TSS	<7.0 mg/L
Total Ammonia (as nitrogen)	<2.35 mg-N/L

6.6 Coal Sector

Canadian coal operations are not, at present, subject to the *Metal Mining Effluent Regulations*. Instead, they are subject to Section 36 of the *Fisheries Act* (general prohibition against the deposit of deleterious substances into water frequented by fish) and to site-specific limits based on applicable provincial and territorial regulations and policies, such as the *Alberta Coal Mining Wastewater Guidelines*, which establishes effluent release limits for TSS, pH, floating solids and foam, and oil and grease (11).

In 2011, Stantec completed a study report for Environment Canada on Canadian coal mining effluents and effluent pollution control technology (12). Based in part on this report, Environment Canada has proposed to expand the scope of the *MMER* to include coal operations in its 10-Year Review of *Metal Mining Effluent Regulations.*

The two main purposes of this coal sector summary are:

- To summarize the sector's current water management and effluent treatment practices (based on information collected in the questionnaire, independent research, and in-house knowledge/information).
- To establish a model site wide water management plan and model effluent treatment process to carry forward in this study for use in BATEA selection.

Current Canadian Coal operations are listed in Table 6-91. Of these, the review of the Canadian coal sector included a total of 16 operations, 13 of which submitted complete operations questionnaires as part of the data collection portion of the study. An additional 3 operations partially completed questionnaires. Stantec's 2011 report "Study on Canadian Coal Mining Effluents" prepared for Environment Canada was used to fill in any missing information not provided in the questionnaires (12).

Table 6-91: Canadian Coal Operations (13) (12) (14)

Operation	Owner/Operator	Location	Status
Trend	Anglo American Canada/ Peace River Coal	Tumbler Ridge, BC	Operating
Basin	Coalmont Energy Corporation	Coalmont, BC	Suspended / Care and Maintenance
Vista	Coalspur Mines (Operations) Ltd.	Hinton, AB	Development
Dodds Coal Mine	Dodds Coal Mining Company Ltd.	Ryley, AB	Operating
Echo Hill	Hillsborough Resources Ltd.	Tumbler Ridge, BC	Development
Quinsam	Hillsborough Resources Ltd.	Campbell River, BC	Operating
Stellarton	Pioneer Coal Ltd.	Stellarton, NS	Operating
Point Aconi	Pioneer Coal Ltd.	Point Aconi, NS	Suspended / Care and Maintenance
Bienfait	Westmoreland Coal Company	Bienfait, SK	Operating
Boundary Dam	Westmoreland Coal Company	Estevan, SK	Operating
Poplar River	Westmoreland Coal Company	Coronach, SK	Operating
Coal Valley	Westmoreland Coal Company	Edson, AB	Operating
Paintearth	Westmoreland Coal Company	Forestburg, AB	Operating
Sheerness	Westmoreland Coal Company	Hanna, AB	Operating
Genesee	Westmoreland Coal Company	Warburg, AB	Operating
Coleman	Westmoreland Coal Company	Coleman, AB	Suspended/Reclamation
Gregg River	Westmoreland Coal Company	Hinton, AB	Suspended/Reclamation
Obed Mountain	Westmoreland Coal Company	Hinton, AB	Suspended /Care and Maintenance
Cardinal River Operations	Teck Resources Ltd.	Hinton, AB	Operating
Coal Mountain	Teck Resources Ltd.	Sparwood, BC	Operating
Elkview	Teck Resources Ltd.	Sparwood, BC	Operating
Fording River	Teck Resources Ltd.	Elkford, BC	Operating
Greenhills	Teck Resources Ltd.	Elkford, BC	Operating
Line Creek	Teck Resources Ltd.	Sparwood, BC	Operating
Highvale	Transalta Corporation/SunHills Mining Limited Partnership	Seba Beach, AB	Operating
Whitewood	Transalta Corporation	Seba Beach, AB	Closed
Brule	Walter Energy, Inc.	Chetwynd, BC	Operating
Willow Creek	Walter Energy	Chetwynd, BC	Suspended / Care and Maintenance
Wolverine Group (Perry Creek)	Walter Energy	Tumbler Ridge, BC	Operating
Grande Cache	Winsway Coking Coal Holdings Ltd. and Marubeni Corporation (prev. Grande Cache Coal Corporation)	Grande Cache, AB	Operating

Canadian coal operations are found in four regions: Nova Scotia, Southern Saskatchewan, Central Alberta, and British Columbia (mainly near the Alberta border). Of the operations reviewed for this study, Alberta has the largest concentration with 9 operations; British Columbia has 4 operations, and Saskatchewan has 3 operations. Figure 6-60 illustrates the geographic distribution of the coal sector operations.

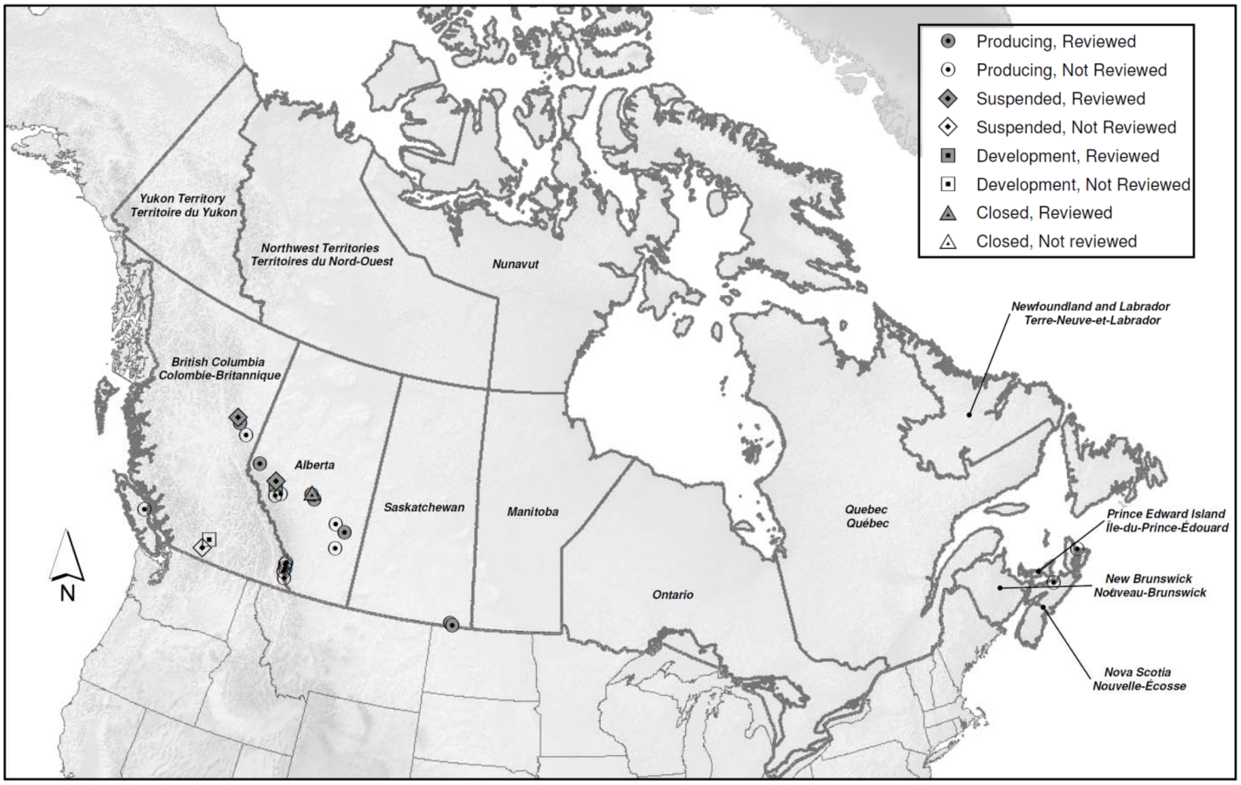

Figure 6-60: Geographic Distribution of Coal Sector Operations

14 of the coal operations reviewed are active, 1 is closed, and 1 is in development. The primary commodity produced at all 16 operations surveyed is coal. Only 1 operation produces a secondary commodity, gravel.

6.6.1 *Effluent Characteristics*

In general, it is expected that the quality of effluent generated by any mine or mill operation, including coal operations, will be variable based on site-specific factors, including, but not limited to, the mine, mill and waste management facilities present on site, the operating status of the site (e.g., closed, producing, etc.), local climate, and the mineralogy of the coal and waste rock. However, it is also expected that given the common target element for extraction from these operations, and common milling processes, untreated effluent at coal mine and mills will share some similarities. A discussion of the similarities and differences between site characteristics culminating in an establishment of a typical untreated effluent quality for coal mines is presented in the following sections.

In establishing what typical contaminants of concern are found in untreated effluent at coal operations, the following factors were considered:

- Which parameters are included in discharge permits for the coal operations reviewed (Figure 6-61).
- Which parameters are targeted by effluent treatment systems (as reported in questionnaires) (Figure 6-61).

- Which parameters were reported in untreated effluent data through operations questionnaires.

Of the 13 coal operations that submitted complete operations questionnaires to support this study, only 2 elected to provide untreated effluent quality as part of their submittals. The sole parameter reported in these two submittals was total suspended solids which ranged from 10 to 15,000 mg/L TSS in the untreated effluent.

Of the 13 operations that submitted complete questionnaires, 11 operations elected to provide discharge permits. These 11 operations provided information on 37 discharge permits, reflecting more than one permit per site. The parameters included in the majority of permits are total suspended solids, settleable solids, and pH. As settleable solids may be treated by the same treatment methods that target total suspended solids, this parameter has not been considered separately. The discharge permits indicate that some operations may require pH adjustment before effluent can be discharged. Figure 6-61 demonstrates the relative frequency of each parameter that appears in effluent discharge permits or is targeted by effluent treatment processes.

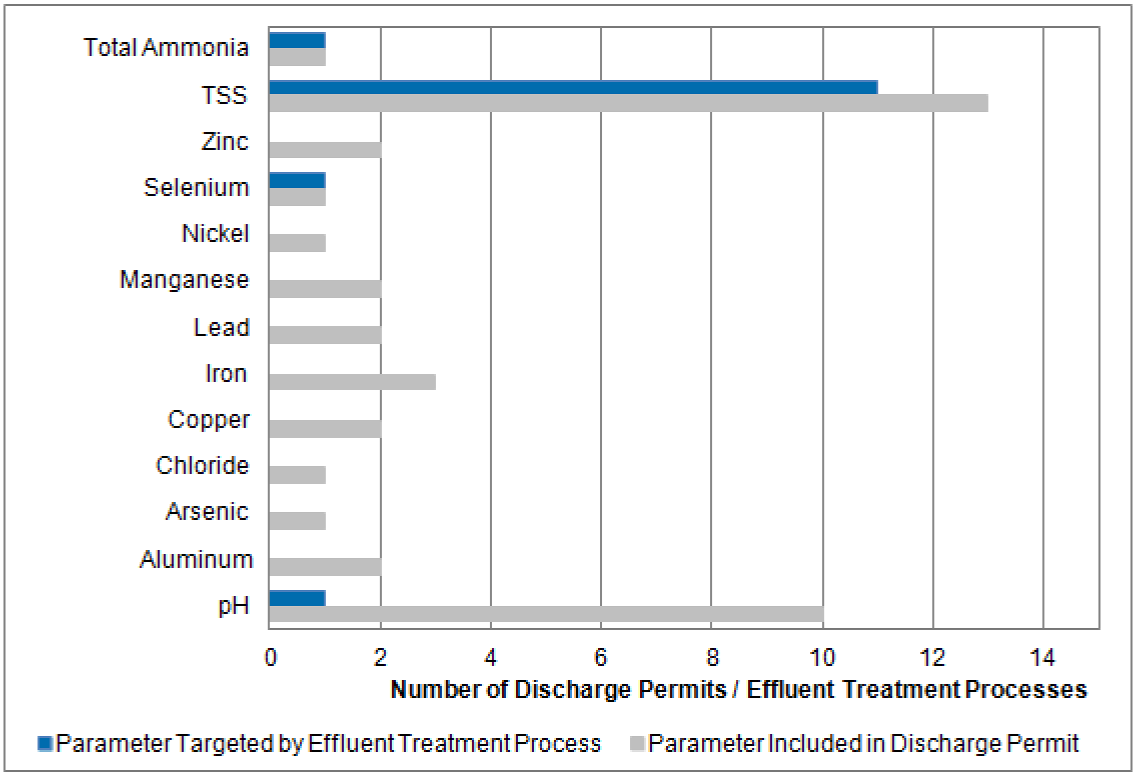

Figure 6-61: Parameters Included in Discharge Permits and Targeted by Effluent Treatment Processes at Reviewed Coal Operations (15 Operations Discharge Permits / 11 Operations Effluent Treatment Processes)

All treatment systems reviewed target total suspended solids, while pH and ammonia are targeted by one treatment system, and selenium is targeted by another treatment system.

Environment Canada has proposed coal effluent limits for aluminum, arsenic, iron, manganese, selenium, TSS, total ammonia, and pH (9).

Table 6-92 summarizes characteristics of the coal operations reviewed that may contribute to the untreated effluent quality.

Table 6-92: Factors Influencing Coal Sector Untreated Effluent Quality

Coal and Waste Rock Mineralization	Mine and Mill Operational Status and Facilities	Coal Processing
Almost all coal deposits are found in sedimentary formations, frequently including shale and sandstone. Coalfield formations can be sulfidic. In addition, acid mine drainage can be an issue at some coal operations (12).	The status of the operations reviewed for this sector is predominantly "in production". However, there are a variety of operations with and without coal processing, and a few operations either in development, under care and maintenance, or closed. The following list characterizes the group of coal operations reviewed by status and facility configurations: • 9 operating sites, where the only activity is mining. • 4 operating sites that engage in both mining and coal processing. • 1 mine site in development, with plans for both mining and coal processing. • 1 mine site under care and maintenance, with both mining and coal processing facilities. • 1 closed site, with no stockpiles, tailings or milling facilities.	The main extractive processes for coal which may have a detrimental effect on untreated effluent quality are: • Removal of vegetation and overburden • Blasting • The use of heavy equipment • Coal blasting, handling and crushing produce small particles, which increase levels of total suspended solids in mine dewatering water and process water. In addition, size reduction creates a larger surface area for leaching and acid generation, when the mineral is exposed to oxygen and water. • Coal washing and cleaning.

6.6.2 *Effluent Management and Control Techniques*

In an effort to control the volume and quality of effluent requiring containment and treatment prior to discharge to the environment, and to minimize the risk of potential contaminants being released to the environment, coal operations employ a variety of techniques to manage water on site.

An overview of the water management techniques employed for effluent volume control, effluent quality control, and the minimization of environment contact for coal operations are summarized below in Table 6-93.

Table 6-93: Overview of Effluent Management and Control Techniques Used at Coal Operations

Volume Control	Quality Control	Minimize Environmental Contact
• Diversion of non-impacted surface and groundwater away from stockpiles and facilities that may negatively impact water quality. • Recycling of impacted water back to processing plant to reduce volume of water requiring treatment. • Segregation of PAG/PML from NAG/NML waste. • Covers (e.g., soil, vegetation) on inactive facilities to minimize interaction between precipitation and facilities which may degrade water quality upon contact. • Progressive reclamation of site facilities. • Stockpiles constructed on high ground to prevent groundwater contact. • Co-disposal or in-pit disposal of waste streams to minimize the total waste storage footprint and thereby minimize contact water run-off volumes generated by precipitation.	• Explosives best management practices. • Water cover on active facilities. • Underground/in-pit disposal of tailings and waste rock. • PAG waste rock blended with NAG/neutralizing waste rock to control acid generation and metal leaching.	• Storage of PAG/PML wastes in dedicated storage facilities with environmental controls (e.g., caps/covers, liners, water cover). • Collection of impacted water and conveyance to treatment (e.g., seepage collection). • Coal managed to prevent long retention time in stockpiles. • Chemical dust suppressants or water applied to tailings and coal stockpiles to minimize dust generation. • Vegetative windbreak in place to minimize dust generation from wind. • Mill facilities are centralized, with two or more mines providing ore for processing to one mill. This arrangement isolates processing activities, which can reduce the potential for deleterious substances that are used for processing or generated by processing to contaminate contact water or to be released to the environment.

6.6.2.1 Mine Facilities and Water Management Techniques

An overview of the relative frequency of different mining facilities found at coal operations is presented in Figure 6-62, while Figure 6-63 captures the mine-water-environment interaction minimization techniques in place at operations (as reported in the operations questionnaire), and the frequency of each technique's use. Coal mines in Canada are predominantly either open pit or strip mines, although there are two underground mines. Many operations employ more than one mining method. The most widely reported water management and effluent control techniques are:

- Surface water diversion (surface water is diverted away from mine facilities through the use of diversion ditches, berms, culverts, and dams).

- Groundwater interception (interception wells collect groundwater and prevent it from contacting mine facilities).
- Seepage collection (collection of seepage from coal and waste rock stockpiles and tailing facilities which is then either recycled or conveyed to treatment systems).

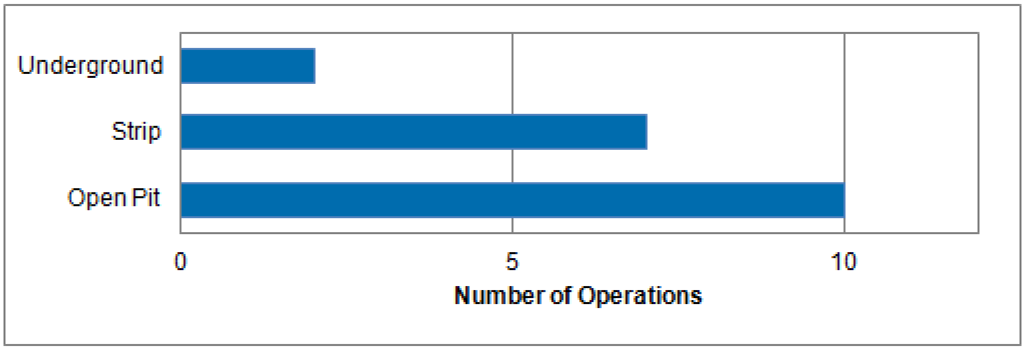

Figure 6-62: Coal Sector Mine Facilities (16 Operations)

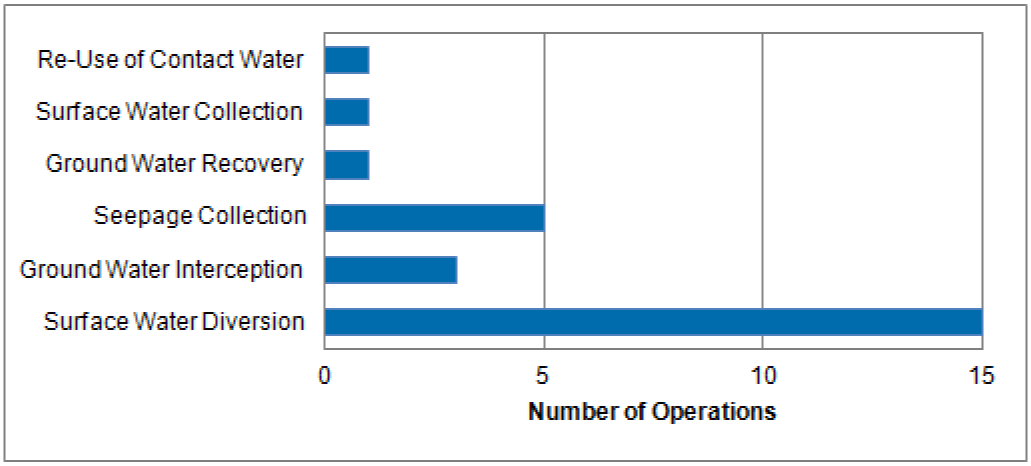

Figure 6-63: Coal Sector Mine-Water-Environment Interaction Minimization Techniques (16 Operations)

6.6.2.2 *Explosives Use*

Many coal operations with active mining operations use some combination of ammonium nitrate fuel oil (ANFO) and emulsion, both bulk and packaged. Most of the operations that use explosives operate under explosives best management plans. However, there are also a significant proportion of coal mines that use no explosives, in part due to the fact that coal is often found in softer rock that may not require blasting for extraction (12). Figure 6-64 illustrates the relative frequency of explosive types used as reported by operations questionnaire respondents.

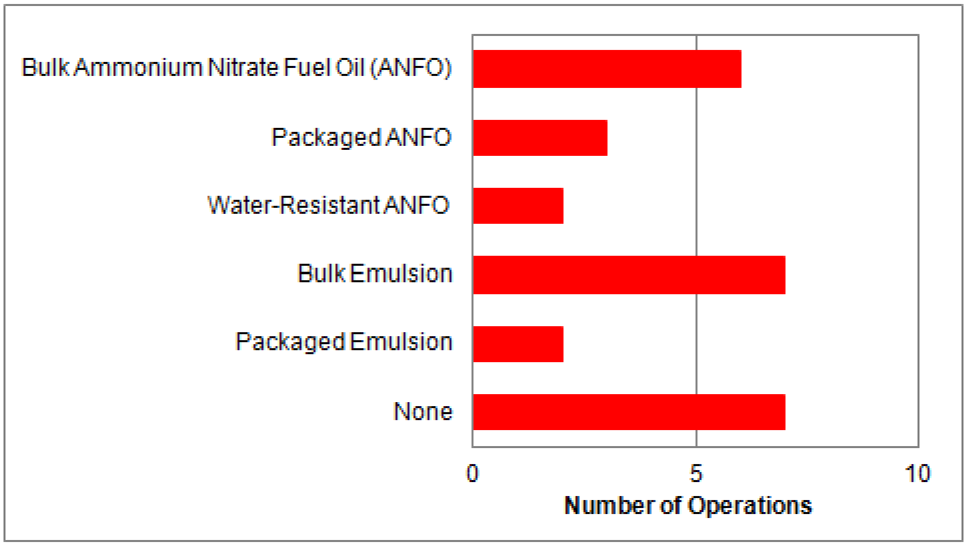

Figure 6-64: Relative Use of Types of Explosives in the Coal Sector (16 Operations)

6.6.2.3 *Coal Stockpiles and Water Management Techniques*

13 operations reported managing coal stockpiles on site. Figure 6-65 provides an overview on the relative frequency of the use of coal stockpile-water-environment interaction minimization techniques. A variety of minimization techniques are used, the most common being surface water diversion and seepage collection. The “Not Applicable” category in Figure 6-65 refers to mines that do not attempt to minimize coal stockpile-water-environment interactions, and does not include operations that do not have coal stockpiles on site.

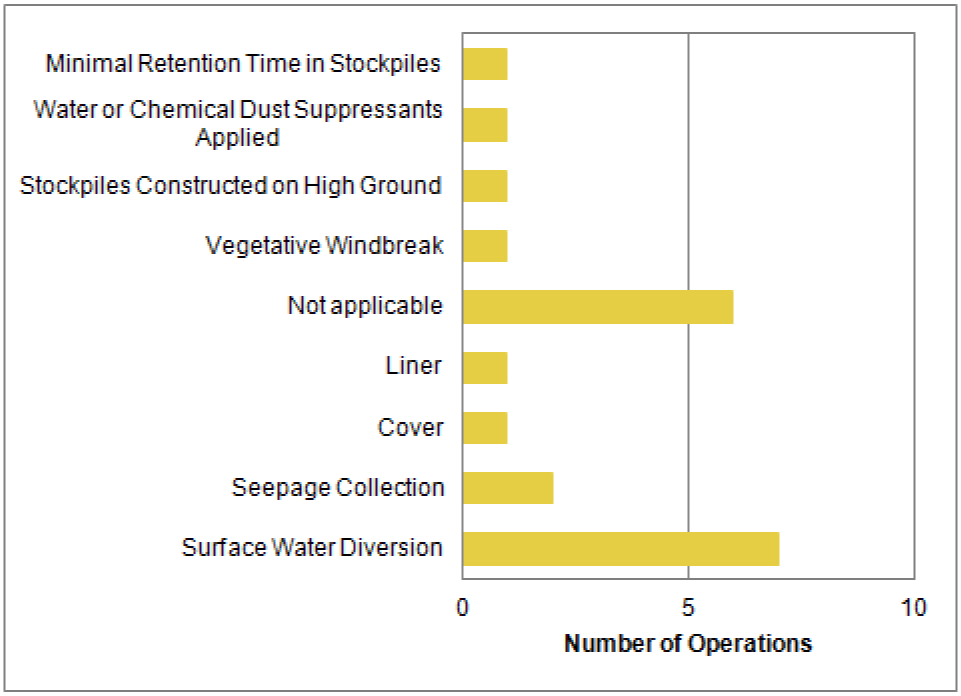

Figure 6-65: Coal Sector Coal Stockpile-Water-Environment Interaction Minimization Techniques (13 Operations)

6.6.2.4 Waste Rock Stockpiles and Water Management Techniques

Figure 6-66 provides an overview of the disposal methods for waste rock, and their relative frequency of use at coal operations. As illustrated, in-pit disposal is used in 8 of the coal operations as the main method for waste rock disposal and represents 100% of the operations that reported disposal of waste rock on site.

Figure 6-67 captures the waste rock stockpile-water-environment interaction minimization techniques in place at operations (as reported in the operations questionnaire), and the frequency of each technique’s use. Assorted techniques are used to minimize potential interactions between waste rock stockpiles, water, and the environment. The most common methods used are surface water diversion, caps/covers, and progressive reclamation of waste rock stockpiles.

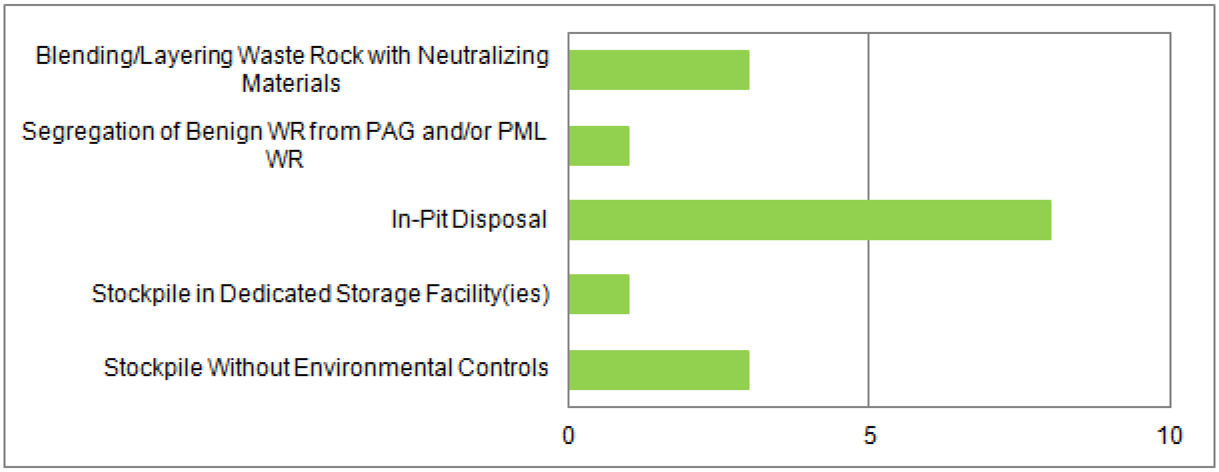

Figure 6-66: Coal Sector Waste Rock Disposal Techniques (8 Operations)

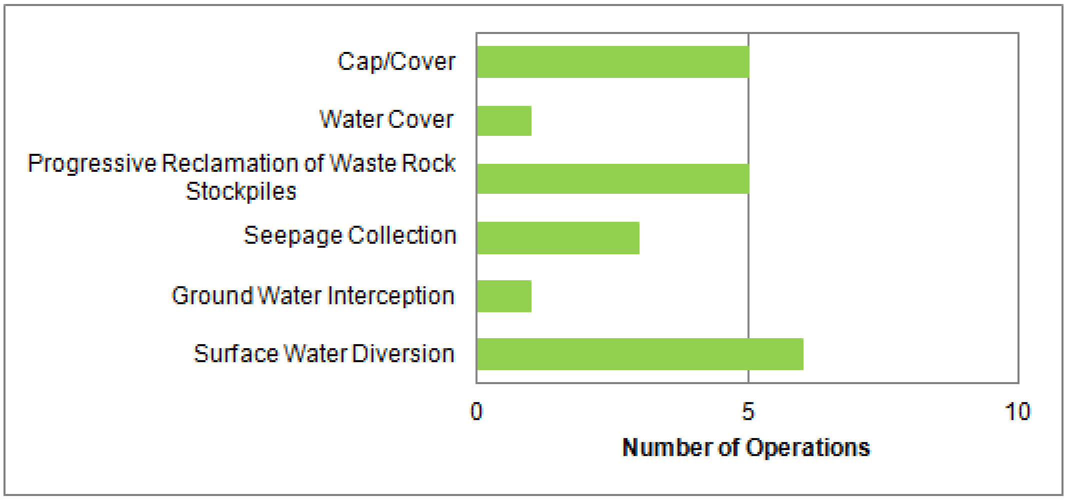

Figure 6-67: Coal Sector Waste Rock-Water-Environment Interaction Minimization Techniques (8 Operations)

Of the 8 operations that reported disposal of waste rock on site, only 1 reported segregating waste rock by characterization as benign or potentially acid generating/potentially metal leaching (PAG/PML). However, several operations reported that they generate no PAG/PML waste rock and, as such, have no need for segregation. Those operations that have PAG/PML waste rock but do not segregate by waste rock type generally blend the PAG/PML rock with the benign waste rock as it is disposed. Table 6-94 summarizes the disposal methods employed based on the type of waste rock present on site.

Table 6-94: Waste Rock Disposal Methods at Coal Operations

Waste Rock Classification	Disposal Method or Use
PAG and/or PML	• Blended together with non-acid generating and non-metal leaching waste rock (NAG and NML) and disposed of in-pit. • Blended together with non-acid generating and non-metal leaching waste rock (NAG and NML) and submerged under water (sub-aqueous disposal). • Blended together with non-acid generating and non-metal leaching waste rock (NAG and NML) and stored in dedicated waste rock storage facility.
NML and NAG	• In-pit disposal. • Waste rock stockpiles without environmental controls.

6.6.2.5 Tailings Disposal Methods and Water Management Techniques

Figure 6-68 provides an overview of the different tailings disposal methods, and the frequency of each method's use. The most widespread tailings disposal methods in use are disposal in dedicated tailings storage facilities (either sub-aqueous or sub-aerial) and in-pit disposal. Three sites reported disposing of their tailing sub-aqueously while two sites reported using sub-aerial techniques. Of the 4 operations that reported tailings disposal on site, 2 also reported dewatering tailings prior to disposal. None of the coal operations that deposit tailings on site reported chemically treating the tailings in any way prior to disposal.

Figure 6-69 summarizes the tailings-water-environment minimization techniques reported in the questionnaire, and the relative frequency of their use. The most frequently reported techniques were surface water diversion, seepage collection, and water cover.

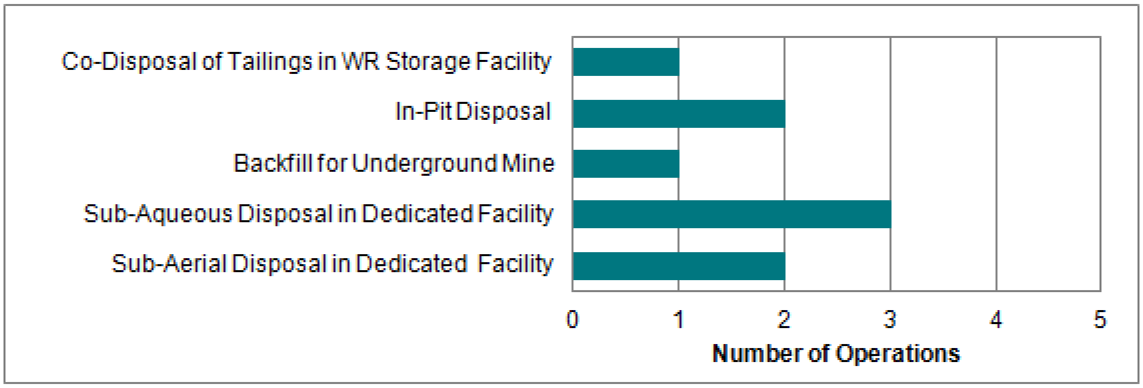

Figure 6-68: Coal Sector Tailings Disposal Methods (4 Operations)

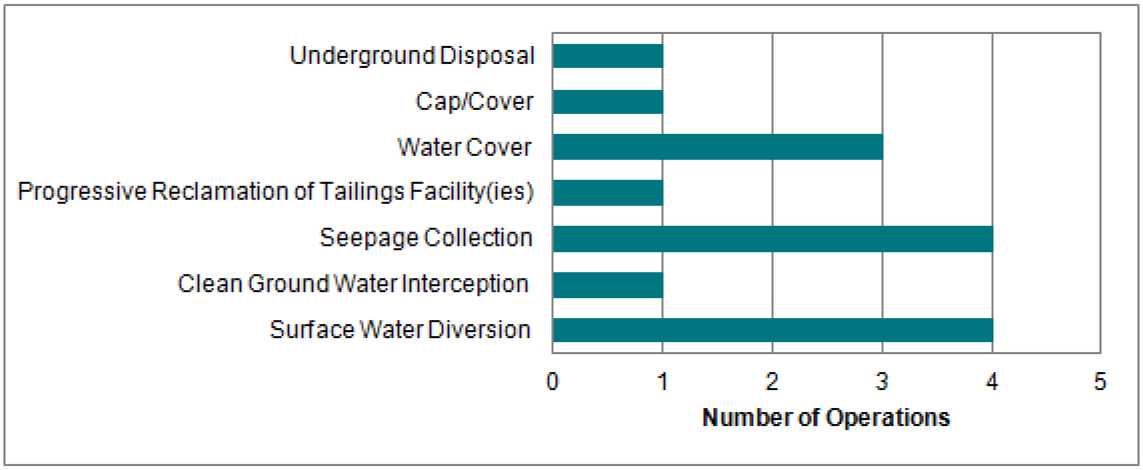

Figure 6-69: Coal Sector Tailings-Water-Environment Interaction Minimization Techniques (4 Operations)

6.6.3 *Effluent Treatment Technologies*

The biological, chemical, and physical processes employed for effluent treatment at coal operations are summarized in Table 6-95.

Table 6-95: Processes for Coal Sector Effluent Treatment

Biological Processes	Chemical Processes	Physical Processes
• Passive Bioreactor for Selenium Treatment.	**Solid/Liquid Separation** • Coagulant and flocculant to aid TSS settling.	**Solid/Liquid Separation** • Settling ponds. • In pond sediment curtains.

The effluent treatment system used at coal operations is predominantly a pond-based system. In pond-based systems, the main treatment objective is the removal of suspended solids, which occurs in a combination of settling/sedimentation and polishing ponds. Reagents such as coagulants and flocculants can be added at various stages to aid in the settling and removal of solids.

A single operation reported two variations to the standard pond-based system. It reported an in-pond sediment curtain to improve pond-based solids removal and also a passive bioreactor system to treat a seep for selenium. No information was provided on the source of the seep or the nature of the passive bioreactor system. As these two technologies are only present at a single operation, they are not considered to be representative of the industry. However, Teck Resources Ltd. is presently constructing an FBR system at its Line Creek Operations in British Columbia. The system is expected to be operational in 2014 (15).

It is important to note that treatment processes occurring in pond-based systems are open to seasonal temperature and precipitation influx variability, which may interrupt treatment processes or cause variations which may negatively affect removal efficiency. Moreover, sudden increases in flow rate, heavy rainfall events, seasonal turnover and high winds and wave action can re-suspend precipitates, potentially causing downstream non-compliance.

6.6.4 *Effluent Quality*

Two sets of treated effluent quality data were available for this study: the treated effluent quality provided by two questionnaire respondents, which was analyzed and summarized in Revision 0 of this study, and treated effluent quality provided by the Coal Association of Canada, which reflects treated effluent quality data from 14 to 18 operations (variable by parameter). The CAC data set is more complete than that collected as part of the questionnaire and is therefore used to generate a summary of the concentration statistics for the entire coal sector. This summary is provided in Table 6-96. The data in this table was collected between 2002 and 2013, with the majority of data collected between 2010 and 2013. The ammonia data set contains only data collected between 2010 and 2013.

Table 6-96: Coal Sector Treated Effluent Summary

Parameters	Unit	Effluent Concentration Basis	Minimum Concentration	Average Concentration	95th Percentile Concentration	Maximum Concentration	Number of Operations Reporting Effluent Quality to CAC
pH		Composite/Grab	5.56	8.21	8.48	8.98	18
Aluminum	mg/L	Grab	0.001	0.79	0.90	1,250	16
Ammonia, total	mg-N/L	Grab	0.0005	0.075	0.37	16.7	14
Arsenic	mg/L	Grab	0.00005	0.00053	0.0013	0.051	16
Iron	mg/L	Grab	0.005	0.45	0.82	387	16
Manganese	mg/L	Grab	0.000005	0.040	0.13	15.6	16
Selenium	mg/L	Grab	0.00005	0.076	0.38	0.81	16
TSS	mg/L	Grab	0.1	62.23	76.33	37,257	18

Notes:
Values reported as less than the method detection limit have been incorporated at half of the MDL value.
All metal concentrations are total metal concentrations, i.e., the sum of dissolved and suspended fractions.

6.6.5 Model Water Management and EffluentTreatment System

6.6.5.1 Model Water Management System

Based on this review of water management techniques employed by coal operations, a model water management plan to represent the typical water management practices employed at these operations has been generated. This model is presented in Figure 6-70.

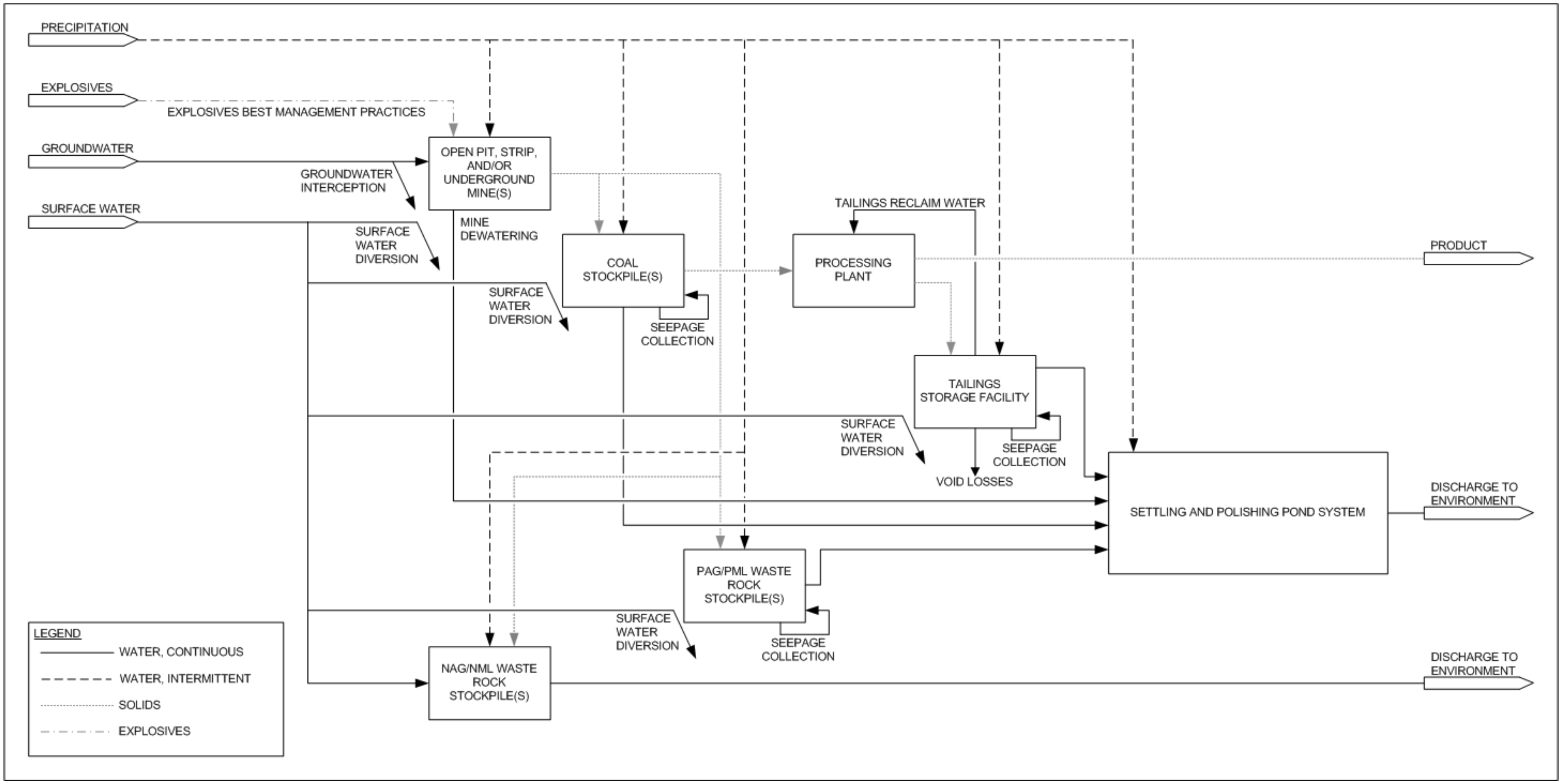

Figure 6-70: Coal Sector Water Management Model

6.6.5.2 *Model Treatment System Process Flow Diagram*

To determine a model effluent treatment system for coal mines, the following aspects of the effluent treatment systems were reviewed:

- Which parameters are targeted by effluent treatment processes, and which parameters are of the most concern.
- What biological, physical, and chemical treatment processes are used to remove targeted parameters.

Of the 13 operations that submitted complete operations questionnaires, 11 were considered for the model effluent treatment process. One of the excluded operations was not considered because it is a closed operation. The other operation was not considered because details about its effluent treatment system were not submitted or found through independent research.

All 11 of the operations use a fairly similar treatment process, pond-based systems, with anywhere from 1 to 4 ponds. Flocculant use is common to aid in the settling of solids, and a few operations also use coagulants. The only technologies employed that stray significantly from this standard is the use of a floating silt curtain within a polishing pond to further remove suspended solids from effluent and the use of a passive bioreactor to remove selenium from an undisclosed seep.

From these observations, the model treatment system illustrated in Figure 6-71 was established. In this model, bulk TSS is removed via pond-based settling and polishing which may be assisted by the addition of flocculant. The settling and polishing pond(s) also allow time for passive natural degradation of ammonia. This system closely resembles several existing effluent treatment systems, but is not identical to any one existing system.

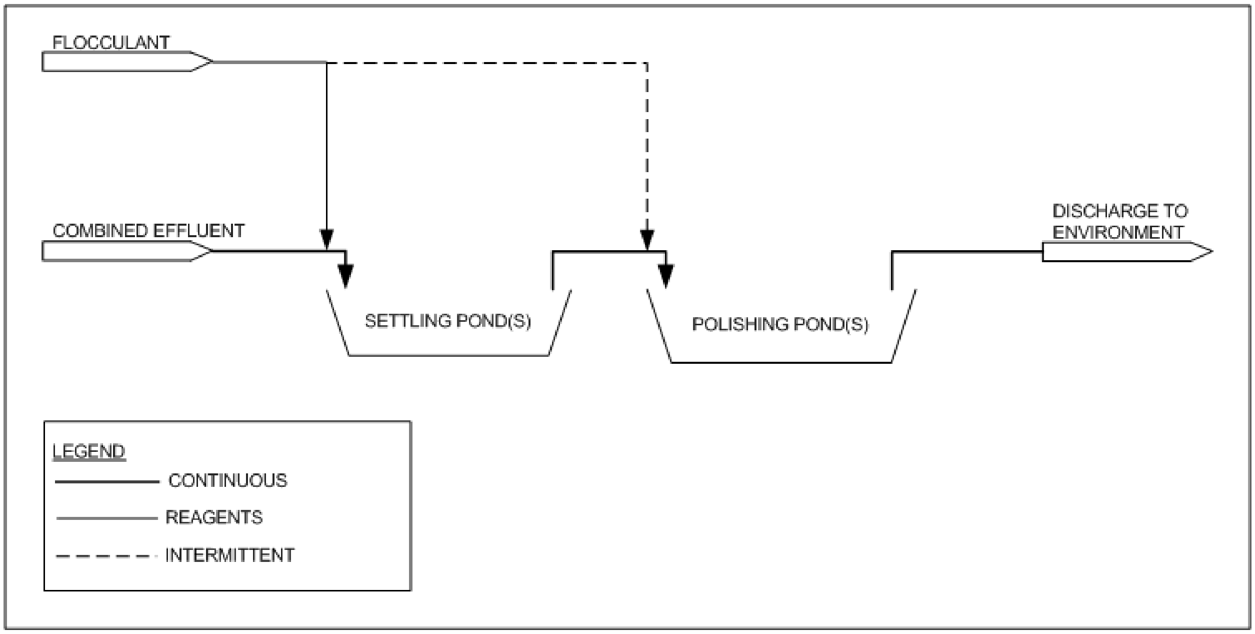

Figure 6-71: Coal Sector Model Effluent Treatment Process

6.6.5.3 *Model Effluent Treatment System Flow Rate*

To establish a flow rate for the typical model treatment system, two sets of data were available for review: the discharge flow rates described in the Stantec Study on Canadian Coal Mining Effluents Report (12), and the average and design flow rate for effluent treatment systems reported by questionnaire respondents.

The Stantec Report data set is an incomplete set of per-second discharge rates for four operations, and thus is a limited data set.

The second source of data reviewed in the process of establishing the model treatment system was treatment flow rate data provided via the operations questionnaire. As part of the questionnaire, operations were prompted to provide the average, design, maximum and minimum treatment flow rates for their effluent treatment systems. This data set is limited to those operations that provided this information as part of their questionnaire responses, however it is a valuable source of information concerning installed design capacities of treatment technologies, which are not apparent from reported discharge volumes. The average flow rates reported via the questionnaire for three operations and seven discharge points were cross-checked against the Stantec report values, and they were not comparable. The design flow rates reported via the operations questionnaire were used in the consideration of the typical effluent treatment system flow rate.

The range, average and median values for these data sets are presented in Table 6-97.

Table 6-97: Summary of Reviewed Discharge and Treatment Flow Rates for the Coal Sector

	Data Set		
	Stantec Report Total Permitted Flow Rate	Questionnaire Reported Average Treatment System Flow Rate	Questionnaire Reported Design/Maximum Treatment System Flow Rate
Range (m^3/h)	1,800 – 55,692	72 – 1,080	144 – 11,520
Average (m^3/h)	29,750	576	3,885
Median (m^3/h)	32,760	576	2,700

For the purposes of this study, the selected value for the design capacity of the coal sector model effluent treatment system is 3,000 m^3/h, as a compromise between the average and median values of the questionnaire reported design/maximum treatment system flow rates. This value will be utilized for capital cost estimating for system augmentation. The selected value for the nominal flow rate of the coal sector model effluent treatment system is 1,000 m^3/h, as a compromise between the average/median and maximum of the range of questionnaire reported average treatment system flow rates. This value will be utilized for operating cost estimating for system augmentation.

6.6.5.4 *Model Effluent Treatment System Effluent Quality*

1

In Revision 0 of this study, the 95th percentile of the effluent quality summary for the entire subsector for each parameter was used to represent the effluent quality that was produced by the model effluent treatment system. It was assumed that for each parameter, the 95th percentile would reflect the concentration in the effluent at the majority of sites and that the 95th percentile value associated with the complete data set would already be weighted to reflect the most common effluent treatment technologies (and therefore the model effluent treatment system), as the most common effluent treatment systems would contribute a larger fraction of the concentration values than other systems.

Feedback received from industry indicated two main concerns with using the 95th percentile of all effluent data as representative of the model effluent treatment system:

1. The total cohort of concentration data originates from many types of effluent treatment systems and not only the model effluent treatment system. This could skew the data as other types of effluent treatment systems may achieve higher or lower concentrations. Thus, using the all concentration data for a subsector may not be representative of the concentrations achieved by the model effluent treatment system.
2. Using all of the concentration data for a subsector for each parameter may result in average and 95th percentile values that are skewed low by the inclusion of concentration data from effluent treatment systems that do not treat or remove a given parameter, as the concentration in the untreated effluent to the treatment system is already very low. For example, when a concentration reported is at or close to the method detection limit, it may be the case that the parameter is not present in water on the site. Using the entire cohort of concentration data does not consider which concentration values reflect where a parameter has actually undergone treatment and thus may not be valid for use as representative of a concentration achieved by a treatment system.

The approach to address these concerns for the other sectors was link concentration data to specific operations and the types of effluent treatment systems they employed, in order to generate concentration statistics (minimum, average, 95th percentile and maximums) for systems that are similar to the model effluent treatment system. In this way, concentrations that are achievable by the model effluent treatment system could be utilized to represent effluent concentrations from model effluent treatment systems in BATEA selection work.

Of the two sets of coal effluent concentration data that were available for this study, the data set provided by the CAC is much more comprehensive than the data set collected as part of the operations questionnaire, as it contains data for 14 to 18 sites (dependent on parameters) in comparison to data set generated by the questionnaire, which contains data for only 2 operations. The CAC data set, however, does not associate effluent concentrations with specific operations, therefore it is not possible to generate concentrations statistics based on the types of effluent treatment system is being used. The information received via operations questionnaire is insufficient to generate concentration statistics that are representative of the coal sector.

Therefore, for the coal sector, the same basis will be used for Revision 1 as was used for Revision 0: the 95th percentile of all the coal sector data will be used to represent effluent concentrations from the model effluent treatment system. The coal sector has less variability in treatment systems than in other sectors (e.g., precious metal), so the concentrations generated by the entire coal effluent quality data set are presumed to be reasonable approximations of concentrations that could be achieved by the model effluent treatment system.

The 95th percentile concentrations estimated to be achieved by model effluent treatment systems are summarized in Table 6-98. These will be used as representative of the concentrations produced by the model effluent treatment system for augmentative technology costing and BATEA selection.

Table 6-98: Concentrations Achieved by the Model Effluent Treatment System in the Coal Sector

Parameter	Concentration
Arsenic	<0.0013 mg/L
Manganese	<0.13 mg/L
TSS	<77 mg/L
Aluminum	<0.90 mg/L
Iron	<0.82 mg/L
Selenium	<0.38 mg/L
Total Ammonia (as nitrogen)	<0.37 mg-N/L

6.7 Summary of Waste Disposal and Water Management Methods

1

In this section, the waste disposal and water management methods for each subsector are summarized into tables. These tables illustrate commonalities and differences between the subsectors in terms of the mining and waste management facilities, and water management methods employed.

Responses that are **bolded** are the options provided in the questionnaire, so these options were prompts provided to operations in the questionnaire; all other responses were provided by operations as 'other' methods.

Shading indicates the prevalence of the use of the various mining and waste management facilities, and water management. No shading or light shading indicate a small percentage of the operations in the subsector utilize the facility or method identified in the row, while darker shading indicates a high percentage of operations utilize the facility or method identified in the row.

Table 6-99: Summary of Mine Facilities

	Base Metal	Precious Metal	Iron Ore	Uranium	Diamond	Coal
No. of Sites Reporting	*41*	*27*	*2*	*12*	*3*	*16*
Underground	78%	70%		25%	67%	13%
Open Pit	46%	26%	100%	83%	67%	63%
Strip Mining			50%			44%
None	10%	11%		8%		

Table 6-100: Mine-Water-Environment Interaction Minimization Methods

	Base Metal	Precious Metal	Iron Ore	Uranium	Diamond	Coal
No. of Sites Reporting	*31*	*22*	*2*	*12*	*3*	*16*
Surface Water Diversion	71%	59%	50%	42%	67%	94%
Groundwater Interception	29%	18%	50%	8%	67%	19%
Seepage Collection	77%	45%	100%	33%	67%	31%
Collection and Treatment of Contact Water	23%					
Seepage Recycling for Site Use	6%					
Mine Flooding				50%		
Re-Use of Contact Water						6%
Ground Water Recovery						6%
Surface Water Collection						6%
Not Applicable	6%	14%				

Table 6-101: Use of Types of Explosives

	Base Metal	Precious Metal	Iron Ore	Uranium	Diamond	Coal
No. of Sites Reporting	*29*	*23*	*2*	*4*	*3*	*16*
Bulk ANFO	48%	57%	100%	50%	33%	38%
Packaged ANFO	38%	48%		50%	33%	19%
Bulk Emulsion	59%	61%		25%	100%	44%
Packaged Emulsion	38%	35%		75%		13%
Packaged Watergel/Slurry	31%	4%				
None	21%					44%

Table 6-102: Ore Stockpiles at Operations

	Base Metal	Precious Metal	Iron Ore	Uranium	Diamond	Coal
No. of Sites Reporting	*31*	*38*	*2*	*4*	*3*	*16*
Ore Stockpiles On Site	58%	58%	50%	100%	67%	81%
No Ore Stockpiles on Site	42%	42%	50%	25%	33%	19%

Table 6-103: Ore Stockpile(s)-Water-Environment Interaction Minimization Methods

	Base Metal	Precious Metal	Iron Ore	Uranium	Diamond	Coal
No. of Sites Reporting	*20*	*22*	*1*	*4*	*2*	*13*
Liner	20%	5%	0%	100%	0%	8%
Cover	15%	18%	0%	0%	0%	8%
Seepage Collection	45%	23%	100%	100%	50%	15%
Groundwater Interception	10%	5%	0%	0%	0%	0%
Surface Water Diversion	45%	32%	100%	50%	0%	54%
Water or Chemical Dust Suppressants Applied	15%	5%	0%	0%	0%	8%
Indoor or Container Storage	20%	5%	0%	0%	0%	0%
Collection and Treatment of Contact Water	40%	0%	0%	100%	0%	0%
None - Non PAG/PML	0%	18%	0%	0%	50%	0%
Short Residence Time	0%	32%	0%	0%	0%	8%
Vegetative Windbreak	0%	0%	0%	0%	0%	8%
Stockpiles on High Ground	0%	0%	0%	0%	0%	8%
Not Applicable	10%	18%	0%	0%	0%	46%

Table 6-104: Current and Historical Waste Rock Disposal Methods

	Base Metal	Precious Metal	Iron Ore	Uranium	Diamond	Coal
No. of Sites Reporting	*26*	*21*	*1*	*9*	*3*	*8*
Stockpiles with no Environmental Controls	15%	24%		11%	33%	38%
Stockpiles in Dedicated Storage Facilities	54%	62%	100%	44%	67%	13%
Backfill for Underground Mine	50%	52%		33%	33%	
In-Pit Disposal	27%	24%		33%		100%
Segregation of PAG and/or PML Waste Rock	19%	33%		56%	67%	13%
Disposed in Tailings Storage Facilities	19%	10%		44%	33%	
Blending / Layering with Neutralizing Materials	4%	5%		11%		38%
Employed as Construction Material	15%	19%				

Table 6-105: Waste Rock-Water-Environment Interaction Minimization Methods

	Base Metal	Precious Metal	Iron Ore	Uranium	Diamond	Coal
No. of Sites Reporting	*26*	*21*	*1*	*11*	*3*	*8*
Surface Water Diversion	62%	43%	100%	27%	33%	75%
Groundwater Interception	15%	0%				13%
Seepage Collection	58%	48%		36%	67%	38%
Progressive Reclamation	31%	24%	100%	18%	67%	63%
Water Cover	27%	5%		27%		13%
Cap/Cover	8%	29%		27%	33%	63%
Liner	19%	14%		36%	67%	
Collection and Treatment of Contact Water		19%		36%		
Capture and Use of Run-Off in Hydrometallurgical Process	4%					
Water Dust Suppression			100%			
Co-Disposal in Tailings Storage Facility				36%		
Not Applicable		19%				

Table 6-106: Current and Historical Tailings Disposal Methods

	Base Metal	Precious Metal	Iron Ore	Uranium	Diamond	Coal
No. of Sites Reporting	*20*	*20*	*2*	*10*	*3*	*4*
Sub-Aerial Disposal in Storage Facility	40%	70%	100%	30%	67%	50%
Sub-Aqueous Disposal in Storage Facility	50%	55%	50%	90%		75%
Backfill for Underground Mine	50%	40%		10%	33%	25%
In-Pit Disposal	5%			30%		50%
Co-Disposal of Tailings in Waste Rock Storage Facility	5%				33%	25%
Employed as Cover for Historical Tailings Deposit	5%					
Historical Sub-Aqueous Disposal in Natural Water Body	5%					
Not Applicable	5%			20%		

Table 6-107: Tailings-Water-Environment Interaction Minimization Methods

	Base Metal	Precious Metal	Iron Ore	Uranium	Diamond	Coal
Total Number of Sites	*18*	*20*	*2*	*10*	*3*	*4*
Surface Water Diversion	61%	60%	100%	50%	33%	100%
Clean Groundwater Interception	6%	5%		20%		25%
Seepage Collection	56%	55%		30%	100%	100%
Progressive Reclamation of Tailings Storage Facility(ies)	61%	10%	50%		67%	25%
Water cover	67%	55%		80%	33%	75%
Cap/Cover	39%	10%	50%	60%	33%	25%
Liner	17%	40%		10%	33%	
Tailings Deposition Plan Minimizes Environmental Interactions	11%					
Collection and Treatment	17%					
Chemical Dust Suppressant Applied	11%					
Watering for Dust Suppression	6%					
Vegetation			50%			
Sacrificial Seeding			50%			
Tailings Neutralization				70%		
Underground Disposal						25%
Not Applicable		10%				

6.8 Relationships between Operations Practices, Effluent Treatment Systems and Effluent Quality

Treated effluent quality is impacted by innumerable factors, including but not limited to ore processing, effluent treatment processes, explosives use practices, ore mineralization, operator attention, etc. These factors are interdependent and their relationship to effluent quality is frequently complex, thus it is difficult to identify firm relationships between these factors and treated effluent quality based on the information and data available to inform this study. Ultimately, effluent quality is site-specific, and for every relationship there is likely an exception. However, as effluent quality and volumes are impacted and can be controlled to some extent through mine operations practices, and the removal efficiencies achieved by effluent treatment systems can often be optimized through proper design and diligent operational practices, relationships between operations practices, effluent treatment systems and effluent quality can be broadly identified.

As part of this study, Hatch performed a high-level review of interactions between mine and mill operations, water management practices and effluent treatment systems that together impact effluent quality to explore the relationships between these factors. The observations presented in this section are largely based on information provided via the operations questionnaire and through communication with operations and have not been subjected to statistical analysis. Therefore, these proposed relationships are not definitive correlations and would benefit from a more rigorous statistical analysis. To perform this analysis, however, more information concerning effluent treatment systems and a more substantial untreated effluent quality data set than was available for this study would be required. Relationships between mine operations practices and effluent quality are discussed below.

Effluent Treatment Systems

Broadly, two types of effluent treatment systems were observed as used by mine and mill operations in Canada: pond-based, and reactor-based systems. Pond-based systems are outdoors and exposed to uncontrollable atmospheric conditions, and are susceptible to upsets due to climatic conditions such as heavy rainfall events, high winds and wave action, and pond turnovers due to temperature inversions, which can significantly affect treated effluent quality. Reactor-based systems can be isolated from atmospheric conditions and thus a greater degree of control can be exerted over the inputs to these systems to better regulate the quality of effluent produced. As a result, it could be posited that on average, reactor-based technologies should perform better than pond-based technologies in terms of contaminant removal efficiency, achievable contaminant concentrations, and reliably producing treated effluent of a consistent quality.

The information collected and reviewed in this study both supports and contradicts this assertion. In some instances, reactor-based systems outperform their pond-based equivalents. An example supporting this assertion is in the uranium (sub)sector, where all reactor-based systems achieve low Ra-226 concentrations, while pond-based systems produce effluents with Ra-226 concentrations that fluctuate above discharge limits, as illustrated in Table 6-108. Both systems use the same treatment process to co-precipitation Ra-226.[24]

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[24] It is worth noting that the pond-based systems in the uranium (sub)sector are at closed sites, and this may also impact their performance as the level of operator attention could differ from the level of operator attention at operating sites.

Table 6-108: Pond-Based vs. Reactor-Based Effluent Treatment Systems Effluent Quality

Type of System	Ra-226 Concentration Range in Untreated Effluent (mg/L)	Ra-226 Concentration Range in Effluent (mg/L)	Removal Efficiency Range
Reactor-Based Systems (Active Sites)	0.03 – 10.40	0.0025 – 0.17	80% – 99.9%
Pond-Based Systems (Closed Sites)	0.02 – 1.8	0.01 – 0.5	52% – 97%

By contrast, in the base metal subsector, precious metal subsector and coal sector, some operations employing pond-based systems achieve low levels of contaminant concentrations and/or high removal efficiencies. There are several examples of pond-based operations that target metals removal via hydroxide precipitation and solid/liquid separation in pond-based systems, achieve high removal efficiencies and would be able to meet proposed *MMER* concentrations. The untreated effluent and treated effluent concentrations associated with one such example is summarized in Table 6-109.

Table 6-109: Pond-Based System Example

Parameter	Untreated Effluent Concentration (mg/L)	Treated Effluent Concentration (mg/L)	Removal Efficiency
Copper	0.7 – 1.5	0.007 – 0.01	98.7% - 99.4%
Iron	5 – 15	0.1 – 0.3	96.4% – 98.6%
Nickel	6.3 – 11.2	0.04 – 0.05	99.3% – 99.6%

According to operations questionnaire respondents, the high removal efficiencies may be attributed to factors such as diligent operator attention, extensive pond treatment systems (with large footprints and retention/settling time), and/or mine operations practices, such as tailings deposition strategies, that provide control of untreated effluent quality upstream of the treatment process. Therefore, that a system is pond-based may not be a factor that prevents the realization of high removal efficiencies and low discharge concentrations.

Ore Processing and Mineralization

The nature and extent of ore processing has an impact on the quality of untreated effluent. This is because ore processing either purposefully (in the case of targeted commodities such as nickel), or incidentally (in the case of non-targeted contaminants such as arsenic), liberates contaminants from ore through physical (e.g., grinding) or chemical (e.g., leaching, oxidation) means. Ore processing can also introduce contaminants into effluent which must later be removed prior to discharge to the environment (e.g., ammonia, cyanide).

Some examples:

- Only precious metal operations (or base metal operations that produce silver or gold as secondary commodities) that employ cyanide in extraction processes have noticeable levels of cyanide in untreated effluent.
- Uranium operations employing ammonia in uranium processing and have no mining on site produce effluents with higher concentrations of ammonia (7 – 24 mg-N/L) than uranium operations that do not use ammonia in processing but have mining on site (<3 mg-N/L). The operations with active mining on site operate under explosives best management plans).
- Coal, diamond, and iron ore processing is typically limited to physical processes, and these operations most often employ physical effluent treatment processes that target suspended parameters rather than chemical treatment processes that target dissolved parameters. The fact that the primary parameter of concern associated with these operations is total suspended solids rather than dissolved solids could be the result of the fact that physical processes may not encourage the dissolution of parameters to the extent that hydrometallurgical processes do.
- The extent to which ore processing is required also impacts the form of contaminants in untreated effluent quality, and as a result, the required effluent treatment processes. Some commodities, such as iron ore and coal, are present in deposits that are almost exclusively the desired commodity and as a result, minimal processing is required and fewer contaminants are released to site water. This untreated effluent requires less intensive effluent treatment systems to achieve required removal efficiencies for discharge (e.g., solid/liquid separation). Commodities that are present in deposits with more complex mineralization (e.g., base metal, precious metal, and uranium) often require hydrometallurgical extraction steps. As a result, contaminants present in untreated effluent are often present as dissolved parameters, and must employ chemical treatment processes that target dissolved fractions for removal.

Explosives Type and Management Practices

Operations where ammonia contamination is primarily a result of explosives use (i.e., those operations that do not use ammonia or cyanide reagents) have reported through the operations questionnaire “significant” reductions in effluent total ammonia concentrations through changes to the type of explosives employed and through the use of explosives best management practices. “Significant” reductions have not been defined in terms of percent reductions, but in some cases the reductions eliminated the need for active ammonia removal effluent treatment processes.

Operations have reported that the use of explosives in emulsion or water gel/slurry forms has reduced effluent total ammonia concentrations, as the water resistance of these explosives is greater than conventional ANFO, and thus they are less likely to dissolve ammonia and nitrate into site water. Operations have also reported that the use of packaged explosives has reduced effluent total ammonia concentrations, as they are less prone to drill hole overfilling and spillage than bulk explosives. Operations may employ several different explosives for blasting depending on blasting conditions. An example of this is the use of emulsions in wet conditions when the risk of explosives transfer into water is higher, and bulk ANFO in dry conditions where the risk of transfer into water is lower.

Best management practices employed by mining operations typically involve measures to isolate explosives from the environment during storage, preparation and transfer, good housekeeping practices to minimize spills and to address spills in a timely manner, blast design measures to maximize blasting efficiency and minimize time between preparation, loading and detonation, and training and enforcement practices to encourage adherence to best management practices.

Operator Attention

Some operations have observed and reported through the operations questionnaire that diligent operator attention and effort was often positively correlated with better system performances. While potentially self evident, this relationship may nonetheless be an important factor at many sites.

Waste Management Practices

Waste disposal practices that isolate mine wastes such as tailings and waste rock from water and the atmosphere were observed to result in better quality of untreated effluents. Examples of the waste management isolation practices for which relationships were observed in operations questionnaire data are:

- Use of water covers on PAG/PML tailings and/or waste rock to reduce exposure to oxygen, limiting oxidation reactions that result in acid generation, and thus also reducing a driving force for metal leaching.
- PAG/PML tailings deposition strategies that minimize the length of exposure of tailings to the atmosphere to reduce exposure to oxygen. These strategies employ rotation of tailings deposition points to areas that have been exposed to the atmosphere for the longest periods of time.

The waste management practices listed above are those observed to correlate to improved untreated effluent quality within the data collected from mine operations for this study. This list, however, does not reflect an exhaustive examination of what waste management technologies *could* improve untreated effluent quality, as the identification of these relationships is limited by the extent of data collection permitted within the scope of this study. It is difficult to identify with confidence relationships between given waste management technologies and untreated effluent quality without more data (e.g., quality data for the effluent stream specifically generated by the waste, baseline leach rate data, mass/volume of waste stored, etc.) which was not collected in this study.

Other waste management practices that may improve untreated effluent quality include, but are not limited to, co-disposal of waste rock and tailings, segregation of PAG/PML waste rock from NAG/NML waste rock, progressive reclamation of wastes, use of covers, utilizing wastes as backfill or construction materials, etc.

Water Management Practices

Water management practices that reduce effluent volumes by preventing contact of clean water with site features that can introduce contamination (e.g., PAG/PML waste rock and tailings, mining operations) can significantly reduce treatment capital and operating costs but may not completely prevent need for treatment. Within the data available for this study, no significant relationships were observed between any specific reported water management practices intended to isolate site features from water and untreated effluent quality. However, it is considered best practice to employ water management measures to reduce the amount of water impacted by mine operations (including water interception/diversion, footprint limitation, progressive reclamation, etc.) and to collect, isolate, recycle if possible, and treat water impacted by mine operations.

Effluent Treatment Practices

Within the data available for this study, no significant relationships were observed between effluent treatment practices intended to target low flow, high contaminant concentration streams and treatment capital and operating costs. However, it is considered best practice to prioritize treatment on low flow, high contaminant concentration streams.

7. Preliminary Identification and Screening of Mine Effluent Treatment Technologies

7.1 Index of Preliminary Effluent Treatment Technologies

Table 7-1 presents an index of effluent treatment technologies according to targeted *MMER* parameters (defined as both existing and proposed *MMER* Schedule 4 “deleterious substances”, as well as pH) and other non-*MMER* parameters treated. In the matrix, dark grey shading indicates that the parameter is targeted by the given technology/technique and light grey shading indicates that the parameter is treated by the given technology/technique.

Table 7-1: Index of Preliminary Technologies by Parameters Targeted and Treated

Preliminary Technologies	pH	Al	As	Cl	Cu	CN	Fe	Pb	Mn	Ni	P	Se	Zn	Ra-226	TSS	NH_3/NH_4^+
Neutralization and Hydroxide Precipitation	■	■	▒		■		■	■	▒	■	▒		■		▒	▒
Sulfide Precipitation			■		■		■	■	■	■		■	■		▒	
Carbonate Precipitation								■		▒			▒		▒	
Ferric Iron or Aluminum Salt Co-Precipitation			■								■	■			▒	
Barium Chloride Co-Precipitation														■	▒	
Ferrous Hydroxide Reduction and Co-Precipitation												■				
Metal Oxidation							■		■							
Reacidification	■															▒
Solid/Liquid Separation		▒	▒		▒		▒	▒	▒	▒	▒	▒	▒	▒	■	
Enhanced Coagulation and Settling		▒	▒	▒	▒		▒	▒	▒	▒	▒	▒	▒	▒	■	
Cyanide Destruction						■										Alkaline chlorination and ozonation
Air Stripping																■
Ion Exchange	▒	■	■	■	■	▒	■	■	■	■	▒	■	■	■		■
Adsorption																
Activated Carbon			■		■	■	■	■	■	■			■			■
Activated Alumina and Functionalized Alumina			■		■			■		■		■	■			
Peat-based Media								■	■	■			■	■		
Zero Valent Iron			▒				▒	▒	▒			■	▒			
Cameco Corporation Technology												■				
Biological Oxidation/Reduction																
Aerobic Biological Oxidation						■										■
Subsurface Nitrification/Denitrification																■
Active Anoxic/Anaerobic Biological Reduction			▒		▒		▒	▒	▒	▒		■	▒			
Electrobiochemical Reduction			▒		▒	▒	▒	▒	▒	▒		■	▒			
Electrochemical Oxidation and Reduction						■						■				■
Membrane Size/Charge Exclusion – Nanofiltration		■	■		■		■	■	■	■	■	■	■	■		
Membrane Size/Charge Exclusion – Reverse Osmosis		■	■	■	■	■	■	■	■	■	■	■	■	■		■
Evaporation		■	■	■	■	■	■	■	■	■	■	■	■	■		▒
Evaporation/Crystallization		■	■	■	■	■	■	■	■	■	■	■	■	■		▒
Passive Treatment																
Natural Degradation						■					▒					■
Aeration Cascades							■		■							
Anoxic Limestone Drains/Open/Oxic Limestone Drains	■	■					■		■							
Aerobic/Anaerobic Wetlands		■	■		■	■	■	■	■	■	■	■	■		▒	■
Passive/Semi-Passive Anoxic/Anaerobic Biological Reduction			▒		▒		▒	▒	▒	▒		■	▒			
Reducing and Alkalinity Producing Systems/Successive Alkalinity Producing Systems	■		■		■			■	■	■			■			
Permeable Reactive Barriers	■	■	■		■		■	■	■	■	■	■	■			
Phytoremediation			■		■	▒		■		■	▒	■	■			▒

Preliminary Technologies	pH	Al	As	Cl	Cu	CN	Fe	Pb	Mn	Ni	P	Se	Zn	Ra-226	TSS	NH_3/NH_4^+

Legend	
Targeted	■
Synergistically Removed	▨

7.2 Preliminary Screening of Effluent Treatment Technologies

Table 7-2 presents a preliminary identification and screening of effluent treatment technologies to carry forward as Best Available Technologies (BAT) for Canadian mining effluent. For each technology, a summary is given of targeted *MMER* parameters (defined as both existing and proposed *MMER* Schedule 4 “deleterious substances”, as well as pH) and other non-*MMER* parameters treated. Then, each technology/technique is screened to determine the following:

- Whether the technology/technique can achieve existing *MMER* authorized limits for targeted existing and proposed parameters, pH, and acute lethality criteria.
- Whether the technology/technique has been demonstrated at full scale on mining effluent.
- Whether the technology/technique has been demonstrated under representative Canadian climate conditions.

These BAT screening criteria were established by MEND in the study Terms of Reference.

If the technology/technique meets all of the above criteria, it is carried forward as a BAT for the treatment of its targeted parameter(s) at Canadian metal, diamond, and coal mining effluent. Technologies that are carried forward as BAT are characterized further in later sections.

Capital and operating costs were not included as screening criteria. Assessment of order of magnitude capital and operating costs is provided in later sections for those technologies that are carried forward as BAT in order to preserve all potentially applicable technologies for consideration as BATEA.

In the Canadian context, representative Canadian climate conditions vary dramatically. Assessment of climate impacts on BAT performance is provided in later sections for those technologies that are carried forward as BAT.

The feasibility of any technology/technique or combination thereof is highly site-specific; should readers be interested in any of the technologies that are not carried forward from the preliminary screening, they may contact the authors of this report requesting additional information.

Table 7-2: Preliminary Screening of Technologies

Technology	Variations	Targeted Existing and Proposed *MMER* Parameter(s)	Other Parameters Treated	Can this technology achieve current *MMER* discharge limits?	Has this technology been demonstrated at full scale on mining effluent?	Has this technology been demonstrated under representative climate conditions?	Carry Forward as BAT?
Neutralization and Hydroxide Precipitation	• Pond-based • Pit-based • Conventional/low density sludge (LDS) • Simple recycle process • High density sludge (HDS) and other sludge recycle processes • Multiple stages with different pH setpoints for specific parameter targeting • Limestone and lime-based • Sodium hydroxide-based • Magnesium hydroxide-based • Aerated	• pH • Al • Cu • Fe (including Fe^{2+} with aerated and/or high pH systems) • Pb • Ni • Zn • Ammonia (for aerated high pH systems)	• As (for aerated lime-based systems) • Mn (including Mn^{2+} if oxidized) • P (PO_4^{3-} fraction for high pH lime-based systems) • TSS (with coagulation/flocculation and solid/liquid separation) • Hardness (if sufficient background alkalinity exists or is added) • Sulfate (for lime-based systems)	Yes	Yes	Yes	Yes
Sulfide Precipitation	• Chemical sulfide reagents (e.g., ChemSulphide® by BioteQ) • Biologically generated sulfide reagent (e.g., BioSulphide® by BioteQ, THIOTEQ™ and SULFATEQ™ by Paques) • Proprietary polymeric organosulfide reagents (e.g., Hydrex™ 6909 by Veolia, NALMET ®1689 by Nalco, and MetClear™ MR2405 by GE)	• As (As^{3+}) • Cu • Fe (Fe^{2+}) • Mn (Mn^{2+}) • Ni • Pb • Se • Zn	• TSS (with flocculation and solid/liquid separation or proprietary polymeric organosulfide reagents) • Sulfate (for SULFATEQ™ process)	Yes; however, there are some risks of downstream toxicity	Yes	Yes	Yes
Carbonate Precipitation	• Inorganic carbonate reagents • Background carbonate concentration	• Pb	• Ni • Zn • Hardness via softening	Yes	No; carbonate precipitation is not commonly employed independently, but in combination with hydroxide precipitation to target Pb. Mining effluent typically does not require treatment for Pb in isolation.	Yes	No

Technology	Variations	Targeted Existing and Proposed *MMER* Parameter(s)	Other Parameters Treated	Can this technology achieve current *MMER* discharge limits?	Has this technology been demonstrated at full scale on mining effluent?	Has this technology been demonstrated under representative climate conditions?	Carry Forward as BAT?
Ferric Iron or Aluminum Salt Co-Precipitation	• Co-precipitation • Basic ferric arsenate precipitation • Phosphate precipitation	• As (including As^{3+} with aerated systems) • P • Se	• TSS via coagulation prior to solid/liquid separation	Yes	Yes	Yes	Yes
Barium Chloride Co-Precipitation	• Co-precipitation with background sulfate • Co-precipitation with sulfate addition	• Radium-226	• TSS (with flocculation and solid/liquid separation) • Sulfate	Yes	Yes	Yes	Yes
Ferrous Hydroxide Reduction	• Reduction and co-precipitation	• Se		N/A; selenium is not regulated under the current *MMER.*	No; has been demonstrated for selenium removal from other sector effluent (e.g., flue gas desulfurization effluent).	Yes	No
Metal Oxidation	• Aeration • Strong oxidant	• Fe (Fe^{2+} fraction) • Mn (Mn^{2+} fraction)		N/A; Fe and Mn are not regulated under the current *MMER.*	Yes; however, metal oxidation is not commonly employed independently, but in combination with hydroxide precipitation and/or coagulation.	• Yes	Yes
Reacidification	• Liquid acid solution • Gaseous carbon dioxide dissolution	• pH	• Ammonia (un-ionized NH3(g) fraction)	Yes for pH. N/A; ammonia is not regulated under the current *MMER*.	Yes	Yes	Yes
Solid/Liquid Separation	• Pond-based settling/sedimentation • Clarifier/thickener-based settling/sedimentation • Media filtration • Flotation • Ultrafiltration (UF) • Microfiltration (MF)	• TSS	• Particulate fraction of metals	Yes	Yes	Yes	Yes

Technology	Variations	Targeted Existing and Proposed *MMER* Parameter(s)	Other Parameters Treated	Can this technology achieve current *MMER* discharge limits?	Has this technology been demonstrated at full scale on mining effluent?	Has this technology been demonstrated under representative climate conditions?	Carry Forward as BAT?
Enhanced Coagulation and Settling (ECS)	- High rate solids contact clarification/thickening (e.g. DensaDeg® by Degremont) - Ballasted flocculation/sedimentation (e.g., ACTIFLO® by Veolia, CoMag™ by Siemens)	- TSS	- Particulate fraction of metals	Yes	Yes; with the exception of CoMag™ by Siemens which has not been demonstrated at full scale on mining effluent.	Yes	Yes
Cyanide Destruction	- Alkaline chlorination	- CN (free, WAD, SAD precipitation) - Previously complexed metals	- OCN^- - SCN^- - Ammonia (via breakpoint chlorination)	Yes	Yes, but now rarely used in mining industry due to high operating costs, inability to remove SAD cyanide, potential for cyanogen chloride evolution if pH is not carefully controlled, and potential for effluent toxicity due to residual free chlorine and chloramines (dechlorination is required).	Yes	No
Cyanide Destruction	- INCO SO_2/Air - CombinOx®	- CN (free and WAD oxidation, and SAD precipitation) - Previously complexed metals	- Small fraction of SCN^-	Yes; however, typically utilized for slurry tailings treatment to achieve 1 to 5 mg/L CN. Addition of copper catalyst may cause non-compliance with copper limit and generation of ammonia may cause toxicity issues if not managed.	Yes	Yes	Yes
Cyanide Destruction	- Hydrogen peroxide	- CN (free and WAD oxidation, and SAD precipitation) - Previously complexed metals depending on pH	- Small fraction of SCN^-	Yes; however, addition of copper catalyst may cause non-compliance with copper limit and generation of ammonia may cause toxicity issues if not managed.	Yes	Yes	Yes
Cyanide Destruction	- Ferrous iron complexation	- CN (free, WAD, and SAD precipitation)		No; difficult to achieve CN <5 mg/L due to residual, soluble ferrocyanide.	Yes	Yes	No
Cyanide Destruction	- Hemlo Gold Process	- CN (WAD and SAD precipitation)	- Mo - Sb	Yes	Yes, but only at the now-closed Golden Giant Mine due to site-specific need	Yes	No; only one demonstration of this technology under

Technology	Variations	Targeted Existing and Proposed *MMER* Parameter(s)	Other Parameters Treated	Can this technology achieve current *MMER* discharge limits?	Has this technology been demonstrated at full scale on mining effluent?	Has this technology been demonstrated under representative climate conditions?	Carry Forward as BAT?
					to control antimony and molybdenum.		site-specific circumstances.
Cyanide Destruction	- Caro's Acid/peroxymonosulfuric acid	- CN (free and WAD)	- SCN^-	No; typically limited to slurry tailings treatment where copper catalyst addition is not possible and treated WAD cyanide concentrations of >5 mg/L are acceptable (16). WAD cyanide concentrations of <0.50 mg/L can be achieved when treating effluent; however, hydrogen peroxide is generally preferred for liquid effluent treatment based on process economics. Generation of ammonia may cause toxicity issues if not managed.	Yes	Yes	No
Cyanide Destruction and Ammonia Removal	- Ozonation	- CN (free and WAD oxidation, and SAD precipitation)	- SCN^- - Ammonia	Yes; however, may react with sulfides and precipitates in solution and cause non-compliance with pH limits and metal limits (particularly for arsenic) and generation of ammonia may cause toxicity issues if not managed.	Ozonation has not been employed as a standalone technique for cyanide destruction due to high operating costs for on-site ozone generation. Ozonation with *in situ* ozone generation was investigated for ammonia removal from a precious metal operation in Ontario; however, the system has not yet been installed and insufficient information is available to evaluate its performance.	Yes	No; insufficient information.
Air Stripping	- Ammonia stripping	- Ammonia (un-ionized NH3(g) fraction)		N/A; ammonia is not regulated under the current *MMER*.	Yes	Yes	Yes
Ion Exchange	- Non-selective ion exchange - Selective ion exchange polishing (e.g., Lewatit® resins by Lanxess, Selen-IX™ by BioteQ)	- Al, As, Cu, Fe, Pb, Mn, Ni, Se, Zn, Cl - Ra-226 - Ammonium (NH_4^+) - Nature of ions removed (cationic or anionic,	- pH, P, Hardness, Nitrates	Yes, but generally requires pre-treatment for bulk removal of targeted parameters and TSS. Can also be used to pre-concentrate contaminants in regenerant solution for downstream removal by other technologies.	Yes, with the exception of full scale ammonia, selenium, and radium-226 removal from mining effluent (19). BioteQ was recently	Yes, with the exception of ammonia, selenium, and radium-226 removal under representative climate conditions (19). However, equipment is	Yes, selective ion exchange is carried forward as BAT except for ammonia, selenium, and radium-226.

Technology	Variations	Targeted Existing and Proposed *MMER* Parameter(s)	Other Parameters Treated	Can this technology achieve current *MMER* discharge limits?	Has this technology been demonstrated at full scale on mining effluent?	Has this technology been demonstrated under representative climate conditions?	Carry Forward as BAT?
		valence state) depends on resin employed. Resins can selectively remove As, Cu, CN, Pb, Ni, Se, Zn, Ra-226, and Ammonia (17) (18).			awarded a contract to demonstrate its Selen-IX™ packed bed ion exchange technology at a pilot scale on effluent from a precious metal project in British Columbia targeting 0.001 mg/L selenium in treated effluent (20). Previously, BioteQ had demonstrated Selen-IX™ at the pilot scale on effluent from a coal operation in British Columbia targeting 0.005 to 0.020 mg/L.	typically installed indoors.	
Ion Exchange	• Clinoptilolite zeolite	• Ammonium (NH_4^+)	• As, Cu, Fe, Pb, Mn, Ni, Zn • Hardness	Yes	Yes	Yes	Yes, clinoptilolite zeolite ion exchange is carried forward as BAT for ammonia removal.

Technology	Variations	Targeted Existing and Proposed *MMER* Parameter(s)	Other Parameters Treated	Can this technology achieve current *MMER* discharge limits?	Has this technology been demonstrated at full scale on mining effluent?	Has this technology been demonstrated under representative climate conditions?	Carry Forward as BAT?
Adsorption	• Activated carbon	• As (21) • Cu (22) • Fe (Fe^{2+}) (23) • Mn (24) • Zn (25) • Ammonia • CN (WAD and SAD)	• Mo • Soluble organics (C4 or greater) • Chlorine	Yes, as a polishing step for the removal of organics and trace dissolved metals.	No. Has been investigated for Mo removal from uranium effluent at the bench and pilot scale. Generally not economically practical for treatment of full scale mining effluent due to replacement/regeneration requirements. May be economically practical for mining operations with carbon systems for ore processing (e.g., precious metal operations).	Yes; demonstrated under representative climate conditions as part of municipal drinking water treatment.	No
Adsorption	• Activated alumina • Functionalized Activated Alumina Media (e.g., Sorbster™ by MAR Systems)	• As • Cu • Pb • Ni • Se • Zn		Yes, depending on untreated effluent concentrations and bed volumes treated.	No. There have been: 1 pilot scale iron ore demonstration 3 pilot scale coal demonstrations 2 bench scale iron ore demonstrations 14 bench scale coal demonstrations	Insufficient information; locations of pilot scale demonstrations have not been provided, but were likely in the Appalachian region of USA.	No
Adsorption	• Peat-based Media (e.g., APTsorb™ by American Peat Technology)	• Pb • Mn • Ni • Zn • Ra-226		Yes	No. There have been: 1 pilot scale closed iron ore mine demonstration in MN, USA (alternative technology selected for further study) 1 full scale metal plating stormwater treatment installation in MI, USA	Yes. MN, USA has similar climate conditions to mines in Northern Ontario and Québec.	No

Technology	Variations	Targeted Existing and Proposed *MMER* Parameter(s)	Other Parameters Treated	Can this technology achieve current *MMER* discharge limits?	Has this technology been demonstrated at full scale on mining effluent?	Has this technology been demonstrated under representative climate conditions?	Carry Forward as BAT?
Adsorption	• Zero Valent Iron (ZVI) • Catalyzed ZVI (catalyzed cementation)	• Se	• As • Fe • Mn • Pb • Zn	N/A; Se, Fe, and Mn are not regulated under current *MMER*. Yes for As, Pb, Zn.	Yes; multiple full scale coal mining installations in USA (26) and multiple full scale uranium mining installations in USA. However, few installations have been in operation for long enough to determine long term feasibility and most installations treat flow rates at least one order of magnitude lower than the (sub)sector design flow rates determined in this study.	Yes	Yes
Adsorption	• Cameco Corporation proprietary selenium adsorption technology	• Se		N/A; selenium is not regulated under current *MMER*.	Yes; commercial scale installation treated 75,000 m^3 of uranium effluent.	No; testing to date conducted in WY, USA.	No
Active Aerobic Biological Oxidation	• Rotating biological contactor (RBC) • Moving bed biofilm reactor (MBBR) • Membrane bioreactor (MBR)	• Ammonia • CN	• OCN^- • SCN^- • TSS/VSS (volatile fraction only)	N/A; ammonia is not regulated under current *MMER*. No for CN.	Yes	Yes	Yes

Technology	Variations	Targeted Existing and Proposed *MMER* Parameter(s)	Other Parameters Treated	Can this technology achieve current *MMER* discharge limits?	Has this technology been demonstrated at full scale on mining effluent?	Has this technology been demonstrated under representative climate conditions?	Carry Forward as BAT?
Subsurface Nitrification and Denitrification	• Attached Growth Bioreactor (e.g., Submerged Attached Growth Reactor [SAGR] and Anaerobic Submerged Attached Growth Reactor [ANSAGR] by Nelson Environmental) • Forced Bed Aeration™/Bioreactor Engineered Wetland (BREW)	• Ammonia (SAGR)	• Nitrate (ANSAGR) • TSS/VSS (SAGR, volatile fraction only)	N/A; neither ammonia nor nitrate are regulated under the current *MMER*.	No; there have been: 8 full scale installations for municipal wastewater treatment in Canada 8 full scale installations for municipal wastewater treatment in USA 1 full scale installation for airport de-icing fluid treatment (cBOD removal) in USA 4 pilot scale demonstrations for municipal wastewater treatment in Canada	Yes; specifically developed as subsurface/submerged systems for cold to moderate climates and demonstrated consistent nitrification at influent temperatures below 0.5 °C.	No
Active Anoxic/Anaerobic Biological Reduction	• Fluidized Bed Reactor (FBR) (e.g., FBR by Envirogen) • Biofilter (ABMet® by GE Power & Water) • iBIO® by Degremont • BioSolve®	• Se	• pH • Nitrate • Sulfate • Dissolved metals if sulfate is reduced to sulfide (see “Sulfide Precipitation)	N/A; selenium is not regulated under the current *MMER*. Yes for pH and other dissolved metals. May require solid/liquid separation and aeration post-treatment to address TSS and toxicity issues associated with low dissolved oxygen and BOD content of treated effluent.	Yes for FBR and ABMet®. However, few full-scale FBR installations have been in operation for long enough to determine long term feasibility. iBIO® has only been demonstrated on flue gas desulfurization effluent (27). BioSolve® has only been demonstrated at the bench and pilot scale for groundwater treatment.	Yes; but pre-heating is required for cold climates as the system operates best ≥ 10 °C.	Yes, with the exception of iBIO® and BioSolve®.

Technology	Variations	Targeted Existing and Proposed *MMER* Parameter(s)	Other Parameters Treated	Can this technology achieve current *MMER* discharge limits?	Has this technology been demonstrated at full scale on mining effluent?	Has this technology been demonstrated under representative climate conditions?	Carry Forward as BAT?
Electrobiochemical Reduction	• Electro-biochemical Reactor (EBR) by Inotec	• Se	• Nitrate • CN • Sulfate • Dissolved metals if sulfate is reduced to sulfide (see "Sulfide Precipitation")	N/A; selenium is not regulated under the current *MMER*. Yes for dissolved metals, except nickel. May require aeration post-treatment to address toxicity issues associated with low dissolved oxygen and BOD content of treated effluent.	Somewhat; there is 1 full scale precious metal installation in the USA which is currently under construction and has not yet started up. There have also been: 2 pilot scale base metal demonstrations in Canada 2 pilot scale precious metal demonstrations in USA 1 pilot scale coal demonstration in Canada	Yes	No
Electrochemical Oxidation and Reduction	• Xogen Reactor by Xogen	• Ammonia (at anode) • CN (at anode) • Se (at cathode)		No: NH_3/NH_4^+ 5.0 mg-N/L CN 0.5 to 5 mg/L (0.5 mg/L MAMMC) does not always meet 0.5 mg/L MAMMC Se 0.010 mg/L	No; emerging technology in pre-commercialization phase. There have been: 1 pilot scale base metal demonstration in Canada 1 pilot scale precious metal demonstration in Canada 1 bench scale base metal demonstration in Canada 1 bench scale precious metal demonstration in Canada	No; pilot scale and bench scale testing completed indoors.	No

Technology	Variations	Targeted Existing and Proposed *MMER* Parameter(s)	Other Parameters Treated	Can this technology achieve current *MMER* discharge limits?	Has this technology been demonstrated at full scale on mining effluent?	Has this technology been demonstrated under representative climate conditions?	Carry Forward as BAT?
Membrane Size/Charge Exclusion	• Nanofiltration (NF) • Reverse Osmosis (RO) • Low pH RO (e.g., AMDRO by Veolia) • Electrodialysis (ED) and electrodialysis reversal (EDR) • Forward Osmosis • Membrane Distillation	• Nanofiltration targets dissolved solids present in solution as multivalent ions(24): Al, As, Cu, Fe, Pb, Mn, Ni, P, Se, Zn, Ra-226 • Reverse osmosis targets total dissolved solids: Al, As, Cl-, Cu, CN-, Fe, Pb, Mn, Ni, P, Se, Zn, Ra-226, Ammonium (NH_4^+)		Yes; significant pre-treatment may be required and permeate may require post-treatment (e.g., alkalinity addition and pH adjustment) or blending with other effluent streams to meet toxicity requirements.	Yes; however: There has only been 1 pilot scale coal mining demonstration of AMDRO technology in PA, USA. There have been no full scale demonstrations of forward osmosis technology on mining effluent. ED/EDR are typically used for treatment for re-use rather than discharge. There have been no full demonstrations of membrane distillation technology on mining effluent.	Yes; however, membrane flux decreases with temperature and pre-heating may be required.	Yes, with the exception of AMDRO, forward osmosis, ED/EDR, and membrane distillation.
Evaporation	• Pond evaporation • Mechanically-enhanced pond evaporation • TurboMist evaporator	• Total dissolved solids: Al, As, Cl^-, Cu, CN, Fe, Pb, Mn, Ni, P, Se, Zn, Ra-226, Ammonia (un-ionized)		N/A; not a discharge technology.	Yes	No; this technology has only been demonstrated in areas of Canada where evaporation exceeds precipitation, which is not representative of many Canadian regions.	No

Technology	Variations	Targeted Existing and Proposed *MMER* Parameter(s)	Other Parameters Treated	Can this technology achieve current *MMER* discharge limits?	Has this technology been demonstrated at full scale on mining effluent?	Has this technology been demonstrated under representative climate conditions?	Carry Forward as BAT?
Evaporative/Crystallization Technologies	• Conventional thermal distillation (MVC, MED, MSF) • Crystallization	• Total dissolved solids: Al, As, Cl^-, Cu, CN, Fe, Pb, Mn, Ni, P, Se, Zn, Ra-226, Ammonia (ionized)		N/A; not a conventional discharge technology. Although distillate is generated and may be discharged, this technique is primarily a waste management technique rather than a discharge technique. Evaporation/crystallization may be used for brine concentration Yes; significant pre-treatment is required for both volume reduction and quality control and distillate may require post-treatment (e.g., alkalinity addition and pH adjustment) or blending with other effluent streams to meet toxicity requirements.	No; however, evaporator has been demonstrated at full scale for tailings brine concentration at an Australian uranium mining operation and evaporator/crystallizer has been demonstrated at full scale for process effluent treatment at a South African precious metal refining operation.	Yes; this method has been demonstrated for oil sands effluent under representative climate conditions.	No
Passive Treatment	• Natural degradation • Enhanced natural attenuation	• Ammonia un-ionized • CN	• P	Yes, seasonally	Yes	Yes, however, natural degradation of ammonia, cyanide, and phosphorus is impeded at low temperatures and by ice/snow cover	Yes
Passive Treatment	• Aeration Cascades	• Fe (Fe^{2+} fraction) • Mn (Mn^{2+} fraction)	• pH	N/A; iron and manganese are not regulated under the current *MMER*.	Yes	Yes	Yes
Passive Treatment	• Anoxic Limestone Drains (ALD) • Open/ Oxic Limestone Drains (OLD)	• pH • Al • Fe • Mn	• Sulfate	Yes, but under strict influent requirements for dissolved oxygen, iron, and aluminum to prevent armouring.	Yes; several installations for coal mine effluent in USA.	Insufficient information; majority of installations have been in the Appalachia region of USA.	No; Canadian mining effluent does not typically meet the strict influent requirements for ALD/OLD.

Technology	Variations	Targeted Existing and Proposed *MMER* Parameter(s)	Other Parameters Treated	Can this technology achieve current *MMER* discharge limits?	Has this technology been demonstrated at full scale on mining effluent?	Has this technology been demonstrated under representative climate conditions?	Carry Forward as BAT?
Passive Treatment	• Aerobic wetlands • Anaerobic wetlands	• Ammonia • CN • Dissolved metals including Se • pH	• TSS • Nitrate	Yes depending on effluent quality and design. However, wetlands cannot typically achieve limits year round as standalone technique (28).	Yes. Wetland Se removal has only been demonstrated on coal ash leachate, refinery effluent, and flue gas desulfurization (FGD) effluent in the USA.	Yes; however, biological activity is impeded at low temperatures, especially for pond wetlands and free water surface wetlands. A full scale constructed aerobic wetland at northwestern Ontario gold mine achieves minimal ammonia removal at temperatures below 10 °C, such that discharge is limited to warmer seasons. Anaerobic wetlands are often subsurface flow wetlands and can operate in cold climates.	No; wetlands have not been demonstrated to consistently achieve limits due to high strength, high flow, and variable temperature nature of effluents at Canadian mines.
Passive/Semi-Passive Anoxic/Anaerobic Biological Reduction	• Passive Biochemical Reactors (BCR) • Upflow Anaerobic Sludge Blanket (UASB)	• Se	• pH • Nitrate • Sulfate • Dissolved metals if sulfate is reduced to sulfide (see “Sulfide Precipitation)	N/A; selenium is not regulated under the current *MMER*. Yes for some other dissolved metals. May require solid/liquid separation and aeration post-treatment to address TSS and toxicity issues associated with low dissolved oxygen and BOD content of treated effluent.	No; for selenium removal, this technique has been demonstrated on mining effluent at the pilot scale and demonstration scale only.	Subsurface nature of BCRs makes them suitable for cold climate operations. UASB requires ≥ 15 °C; pre-heating is required for cold climates.	No; for selenium removal, this technique has been demonstrated on mining effluent at the pilot scale and demonstration scale only.

Technology	Variations	Targeted Existing and Proposed *MMER* Parameter(s)	Other Parameters Treated	Can this technology achieve current *MMER* discharge limits?	Has this technology been demonstrated at full scale on mining effluent?	Has this technology been demonstrated under representative climate conditions?	Carry Forward as BAT?
Passive Treatment	- Reducing and Alkalinity Producing Systems (RAPS)/Successive Alkalinity Producing Systems (SAPS)	- pH	- Sulfate - Dissolved metals if sulfate is reduced to sulfide (see “Sulfide Precipitation”)	Yes; however, cannot reliably achieve limits year round as standalone technique.	Insufficient information to confirm full scale demonstration.	Insufficient information; biological activity is impeded at low temperatures.	No; insufficient information to confirm full scale demonstration.
Passive Treatment	- Permeable Reactive Barriers (PRB)	- Dependent on barrier materials: - Dissolved metals, especially As and Se, with ZVI (see “Zero Valent Iron”) - Ammonia with clinoptilolite zeolite (see “Clinoptilolite Zeolite”) - As, cationic dissolved metals, and P (as PO_4^{3-}) with slag - Cationic dissolved metals and pH with limestone and/or sodium/magnesium carbonate (see “See Hydroxide Precipitation” and “Carbonate Precipitation”) - Cationic dissolved metals and pH with anaerobic biological process in organic substrates (see “Sulfide Precipitation”, “Active Anoxic/Anaerobic Biological	- Nitrate - Sulfate	Yes, depending on barrier materials and application; however, long term performance of PRBs is uncertain. PRB systems may require contingency active treatment measures in the event of failure to meet design criteria.	No; full scale applications have been limited to source zone treatment (typically for *in situ* remediation of groundwater plumes). Arsenic removal via ZVI PRB and slag PRB and cationic dissolved metals removal via organic substrate PRB have been demonstrated at full scale on mining effluent. Selenium removal via ZVI PRB and ammonia removal via clinoptilolite zeolite PRB have only been tested at the laboratory scale. Phosphorus (phosphate) removal via basic oxygen furnace slag PRB has only been tested at the pilot scale. (29)	Yes; subsurface flow systems can operate in cold climates.	No; full scale mining applications have been limited to source zone treatment (typically for *in situ* remediation of groundwater plumes) rather than effluent treatment.

Technology	Variations	Targeted Existing and Proposed *MMER* Parameter(s)	Other Parameters Treated	Can this technology achieve current *MMER* discharge limits?	Has this technology been demonstrated at full scale on mining effluent?	Has this technology been demonstrated under representative climate conditions?	Carry Forward as BAT?
		Reduction", and "Passive Anoxic/Anaerobic Biological Reduction"					
Phytoremediation	- Phytovolatilization - Phytoextraction	- As - Cu - Ni - Pb - Se - Zn - Ammonia	- CN	Insufficient information	No; most applications focus on phytoremediation of solid wastes (e.g., waste rock, tailings, slag) or contaminated groundwater, rather than effluents. Removal of dissolved metals via phytoextraction and phytovolatilization has been demonstrated at the pilot scale. (30)	No; year round phytoremediation would not be possible.	No

8. Technical Characterization of Effluent Treatment Technologies Under Consideration as BAT/BATEA

In this section, a technical characterization is provided for each of the technologies carried forward during preliminary screening based on their ability to achieve current *MMER*, demonstration at full-scale on mining effluent, and demonstration under representative climate conditions. The characterization for each technology in this sector is of a technical nature, and addresses:

- The chemical, physical, or biological mechanism through which the technology removes targeted parameters. The removal efficiency and/or achievable effluent concentrations associated with the technology are based on reported operations data, literature values, or vendor data. It is important to note that achievable concentrations are typical and may not be possible for every application.
- Factors that impact technology performance.
- What residuals are generated by the technology and how they are managed.
- Relative prevalence of the technology in the Canadian mining industry.
- Major equipment required for the technology.
- Major synergies and challenges of the technology.
- Capital cost considerations.
- Operation and maintenance considerations (e.g., reagent requirements, operation attention requirements, maintenance needs, etc.).

For many technologies, sustaining capital costs are associated with the progressive development and closure of residuals disposal areas. For many operations, it may be possible to dispose of residuals within existing on-site features, such as an existing tailings storage facility. As such, sustaining capital costs associated with the progressive development and closure of residuals disposal areas have not been estimated.

8.1 Index of Effluent Technologies Under Consideration as BAT/BATEA

Table 8-1: Index of Effluent Treatment Technologies Under Consideration as BAT/BATEA by Target Parameter

Preliminary Technologies	pH	Al	As	Cl	Cu	CN	Fe	Pb	Mn	Ni	P	Se	Zn	Ra-226	TSS	NH_3/NH_4^+
Neutralization and Hydroxide Precipitation	■	■	▒		■		■	■	▒	■	▒		■		▒	▒
Sulfide Precipitation			■		■		■	■	■	■		■	■		▒	
Ferric Iron or Aluminum Salt Co-Precipitation			■								■	■			▒	
Barium Chloride Co-Precipitation														■	▒	
Metal Oxidation							■		■							
Reacidification	■															▒
Solid/Liquid Separation		▒	▒		▒		▒	▒	▒	▒	▒	▒	▒	▒	■	
Enhanced Coagulation and Settling		▒	▒	▒	▒		▒	▒	▒	▒	▒	▒	▒	▒	■	
Cyanide Destruction						■										
Air Stripping																■
Ion Exchange	▒	■	■	■	■	▒	■	■	■	■	▒	■	■	▒		■
Adsorption																
Zero Valent Iron			▒				▒	▒	▒			■	▒			
Biological Oxidation/Reduction																
Aerobic Biological Oxidation						■										■
Active Anoxic/Anaerobic Biological Reduction			▒		▒		▒	▒	▒	▒		■	▒			
Membrane Size/Charge Exclusion – Nanofiltration		■	■		■		■	■	■	■	■	■	■	■		
Membrane Size/Charge Exclusion – Reverse Osmosis		■	■	■	■	■	■	■	■	■	■	■	■	■		■
Passive Treatment																
Natural Degradation						■					▒					■
Aeration Cascades							■		■							

Legend	
Targeted	■
Synergistically Removed	▒

8.2 Characterization of Technologies Under Consideration as BAT/BATEA

8.2.1 Neutralization and Hydroxide Precipitation

Neutralization and hydroxide precipitation is the most commonly used technology for the neutralization of acidity and removal of metals from Canadian mining effluent.

Hydroxide precipitation may be used to precipitate dissolved metals (typically divalent cationic dissolved metals) as metal hydroxides to low treated effluent concentrations, according to the following generic reaction:

$$Me^{X+} + X(OH)^{-} \leftrightarrow Me(OH)_X(s)$$

Simultaneously, carbonate precipitation of divalent cationic dissolved metals (primarily Pb, Ni, and Zn) as metal carbonates may also occur, provided sufficient background carbonate alkalinity exists, according to the following generic reaction:

$$2Me^{X+} + XHCO_3^{-} \leftrightarrow Me_2(CO_3)_X(s) + XH^{+}$$

It is important to note that acidic effluents are typically low in background carbonate.

The precipitation reactions are carried out at alkaline pH. The target pH depends on the target dissolved metal(s) and desired removal efficiency, as the theoretical minimum solubility for different metal hydroxides occurs at different pH values. The reactions may be carried out in a series of stages to allow for the selective precipitation of multiple metal hydroxides at optimal effluent chemistry (i.e., pH). The metal hydroxide precipitates are separated from the treated effluent via solid/liquid separation technologies. Prior to solid/liquid separation, coagulation and flocculation may be used to agglomerate the metal hydroxide precipitates. The decant stream may require additional polishing or filtration to meet TSS discharge limits and reduction of pH/re-acidification to meet pH discharge limits.

Hydroxide precipitation and solid/liquid separation can be carried out using a wide variety of technologies, including:

- Pond-based systems which involve the mixing of lime with effluent as it flows into a pond where precipitates settle. Decant may flow into a secondary pond for polishing. Pond-based systems require periodic dredging of accumulated low density sludge (typically <3 wt% solids) to ultimate disposal.
- Pit-based systems are similar to pond-based systems, with the exception that an open pit (if available) is utilized for precipitate settling and sedimentation. The pit itself is normally the ultimate disposal destination for the low density sludge (typically <3 wt% solids), depending on pit capacity. Decant is pumped out of the pit utilizing a floating barge system that does not disturb settled precipitates.
- Conventional/Low Density Sludge (LDS) systems utilize reaction tank(s) for lime and effluent mixing and clarifiers for precipitate settling and sedimentation. Conventional/LDS systems generate low density sludge, typically <5 wt% solids.
- Simple sludge recycle systems are similar to conventional/LDS systems; with the exception that clarifier underflow is recycled to the reaction tank(s). Simple recycle systems may generate sludge with up to 15 wt% solids.

- High Density Sludge (HDS) systems and other sludge recycle processes (Heath Steele Process, Geco Process, Staged-Neutralization) are more complex sludge recycle systems. These systems can generate sludge with up to 30 wt% solids.

The applicability of the above technologies is highly site-specific. The variations of the technology are shown in order of increasing capital expenditure, process control, treatment efficiency (both in terms of achievable treated effluent quality and reagent consumption), and sludge density. Variations involving sludge recycle utilize reagents more efficiently, generate denser sludge streams, and experience less scaling. The variations are discussed in greater detail in Aubé and Zinck's paper, "Lime Treatment of Acid Mine Drainage in Canada" (31).

Neutralization reagents for hydroxide precipitation include limestone ($CaCO_3$), dolomitic limestone ($CaCO_3$ containing $MgCO_3$), quicklime (CaO), hydrated lime ($Ca(OH)_2$), sodium hydroxide (NaOH), soda ash (Na_2CO_3), and magnesium oxide (MgO). Of these, quicklime and hydrated lime are the most commonly used reagents due to their ability to reach high target pH, their low relative cost to other reagents, and their coagulating properties. The calcium in limestone and lime also aids in hardness removal (if sufficient background alkalinity exists or is added, e.g., via soda ash addition), sulfate removal via precipitation as calcium sulfate ("gypsum"), arsenic (as pentavalent arsenic) removal via precipitation as calcium arsenate (see Section 8.2.5), and phosphorus (as phosphate) removal via precipitation as hydroxylapatite. These reactions are represented below:

$$Ca^{2+} + SO_4^{2-} \leftrightarrow CaSO_4(s)$$

$$2AsO_4^{3-} + 3Ca^{2+} \leftrightarrow Ca_3(AsO_4)_2(s)$$

$$6PO_4^{3-} + 10Ca^{2+} + 2OH^{-} \leftrightarrow Ca_{10}(OH)_2(PO_4)_6(s)$$

Quicklime is typically slaked on-site to produce hydrated lime slurry. However, it may be more economical for effluent treatment operations with lower lime demand to purchase hydrated lime to avoid the capital and operating costs associated with on-site slaking. Hydrated lime is then mixed with water to produce hydrated lime slurry. Dry feeding of reagents is not commonly practiced due to the long retention times required for dissolution of dry reagents.

Sodium hydroxide is the next most commonly utilized reagent for hydroxide precipitation. Sodium hydroxide is typically supplied as a solid or a liquid at <50 wt%. Sodium hydroxide is easier to handle than lime, but sodium hydroxide solution requires heating to protect against freezing in cold climates at this concentration.

Although relatively inexpensive, limestone utility as a neutralization reagent is limited to the precipitation of dissolved aluminum and dissolved ferric iron which can precipitate at acidic to circum-neutral pH (pH 4 to 6). Limestone may be used to pre-neutralize effluent prior to treatment with lime to achieve higher target pH.

Carbon dioxide injection and sulfuric acid dosing may be used for post-treatment pH adjustment. A wide variety of flocculants are used to facilitate solid/liquid separation.

Reagent selection for hydroxide precipitation is site-specific and dependent on effluent quality, reagent costs and availability, reagent handling requirements, reagent reactivity, reaction kinetics, buffering capacity, product solubility, reagent residuals, and desired sludge characteristics.

Good removal efficiencies for dissolved metals can be achieved, depending on operating pH, and technique utilized for precipitation and solid/liquid separation. Typical achievable concentrations from neutralization and hydroxide precipitation are summarized in Table 8-2. TSS is also removed in the solid/liquid separation step of the hydroxide precipitation process.

Table 8-2: Typical Achievable Concentrations from Hydroxide Precipitation after Solid/Liquid Separation

Parameter	Achievable Concentration (mg/L)	Reference	Site Data Exceptions
Al	<0.5	(32)	
As	~5	(33)	
Cu	<0.07	(34)	
Fe	0.1	(32)	
Pb	<0.05	(35)	<3.36[25]
Ni	<0.2	(34)	<0.36[26]
P (as PO_4^{3-})	1	(34)	
Zn	<0.4	(35)	

Hydroxide precipitation performance is impacted by the presence of chelants (e.g., ammonia) and metal complexing agents (e.g., cyanide). Ammonia interferes with hydroxide precipitation by competing with hydroxyl ions for metals, according to the following generic reaction:

$$Me(NH_3)_4^{2+} + 2(OH)^- \leftrightarrow Me(OH)_2(s) + 4NH_3(aq)$$

The presence of ammonia drives the generic reaction to the left, thereby preventing metal hydroxide precipitation. Cyanide interferes with hydroxide precipitation through the formation of stable organometallic complexes.

Although ferrous iron can be precipitated as ferrous iron hydroxide, it is often first oxidized via aeration to ferric iron. Ferric iron hydroxide is more stable, less viscous, and precipitates at a lower pH than ferrous iron hydroxide. Additionally, co-precipitation effects with ferric iron hydroxide can have synergistic effects on the precipitation of other metals. However, aeration adds operating cost. For more information, see Section 8.2.3 and Section 8.2.5.1.

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[25] Based on testwork completed by a development with 5.26 mg/L lead in untreated effluent from lock-cycle testwork using hydroxide precipitation with lime alone. The poor removal efficiency is possibly due to residual milling reagents, although this could not be verified by Hatch based on the information provided by the developer.

[26] Table 6-20 concentration achieved by model and model equivalent effluent treatment systems. The higher value may be an artefact of more systems treating for the removal of nickel from high untreated effluent concentrations.

Minor variations in effluent quality and flow rate can be managed by modifications to reagent dosing regimes; however, major variations in loadings can cause insufficient reaction and sedimentation times, negatively affecting treated effluent quality. For pond-based and pit-based systems, sudden increases in flow rate, heavy rainfall events, high winds and wave action, and pond inversions can re-suspend precipitates, potentially causing downstream non-compliance.

Variations in temperature have little effect on hydroxide precipitation process performance; however, as with all effluent treatment systems, freezing must be prevented. Depending on climate, systems may be installed indoors with climate control, or outdoors with adequate insulation and heat tracing.

Residuals

Metal hydroxide sludge is generated by hydroxide precipitation. Sludge quantity and characteristics depend on effluent quality and pH, effluent flow rate, neutralization reagent, and process configuration. Depending on effluent quality, hydroxide precipitation with lime may generate greater quantities of sludge than sodium hydroxide due to acid salt and gypsum ($CaSO_4$) precipitation. However, sludge from hydroxide precipitation with lime is easier to settle and dewater than sodium hydroxide sludge. Sludge is typically disposed of in-situ for pond-based and pit-based systems, or in on-site features including tailings storage facilities, engineered dewatering ponds, open pits, underground mine workings, co-disposal with waste rock, etc. Sludge may be mechanically dewatered (i.e., via filter press or centrifuge) prior to disposal. At some environmentally-sensitive sites or sites with limited disposal area, off-site sludge disposal may be required.

Sludge dessication and dusting are issues for some sites (1).

It should be noted that calcium arsenate is not stable, as it reacts with atmospheric carbon dioxide to form calcium carbonate and releases soluble arsenic. It is preferable to co-precipitate arsenic (see Section 8.2.3).

Major Equipment

Major equipment depends on the technique utilized for precipitation and solid/liquid separation and may include:

- Reagent make-up/storage systems (e.g., lime silo, slaker, agitated slurry tank, and recirculation pumps and loop for lime-based hydroxide precipitation; heated storage tank for sodium hydroxide-based hydroxide precipitation) and feed systems (e.g., dosing pumps, valves) for neutralization reagent and any additional reagent (e.g., coagulant, flocculant, post-treatment pH adjustment reagent).
- Agitated reaction tank(s), if required.
- Clarifier/thickener(s), if required.
- Media filter, if required.
- Residuals management equipment (e.g., underflow tank, pumps to disposal, mechanical dewatering equipment), if required.

Synergies and Challenges

As the most common effluent treatment technology, hydroxide precipitation is commonly used with other technologies. Synergies are thus dealt with below in those sections.

As noted above, co-precipitation with ferric iron hydroxide can have synergistic effects on the precipitation of other metals. If lime is used there is the added benefit of lime acting as a coagulant to aid settling, where sodium hydroxide does not.

Challenges associated with hydroxide precipitation include:

- Equalization of flows and/or loadings is required for stable operation of hydroxide precipitation technology.
- Downstream pH adjustment may be required to meet discharge limits.
- Chelant and complexing agent interference.
- Calcium from lime will react with sulfate in effluent to form gypsum solids if above saturation.

Relative Prevalence in Industry

Neutralization and hydroxide precipitation is the most prevalent technique for the treatment of effluent from Canadian mining operations.

Costs

Capital

Capital costs are proportional to effluent pH, quality, and flow rate and depend on the technique utilized for precipitation and solid/liquid separation.

In 1994, SENES Consultants developed total installed cost curves for lime-based basic neutralization and high density sludge processes at three different effluent flow rates and three different effluent acidities (36). The costs include building and foundation costs, neutralization equipment costs, solid/liquid separation equipment costs, services and utilities, polishing pond costs, instrumentation and electrical costs, construction costs (including engineering, procurement, and product management), installation, spare parts, and contingency. Flow equalization, standalone utilities, post-treatment (e.g., filtration and pH adjustment), and sludge disposal costs are excluded.

The ratio of preliminary 2013 Chemical Engineering Plant Cost Index (CEPCI) to 1994 CEPCI is 1.53. The capital cost curves have been adjusted accordingly, and are presented in Figure 8-1.

These cost curves were cross checked against a July 2013 cost estimate for a 7.5 m^3/s (27,000 m^3/h) HDS system planned to treat acidic effluent (predicted pH 2.5 to 3.5 and 1,850 mg/L sulfate) for the Seabridge Gold KSM Project (37). For this system, a direct capital cost including civil works of CAD$170,000,000 was estimated. This capital cost is consistent with costs estimated from Figure 8-1 and lays estimates generated by the HDS - 500 mg/L acidity curve and the HDS - 5,000 mg/L acidity curve. 1

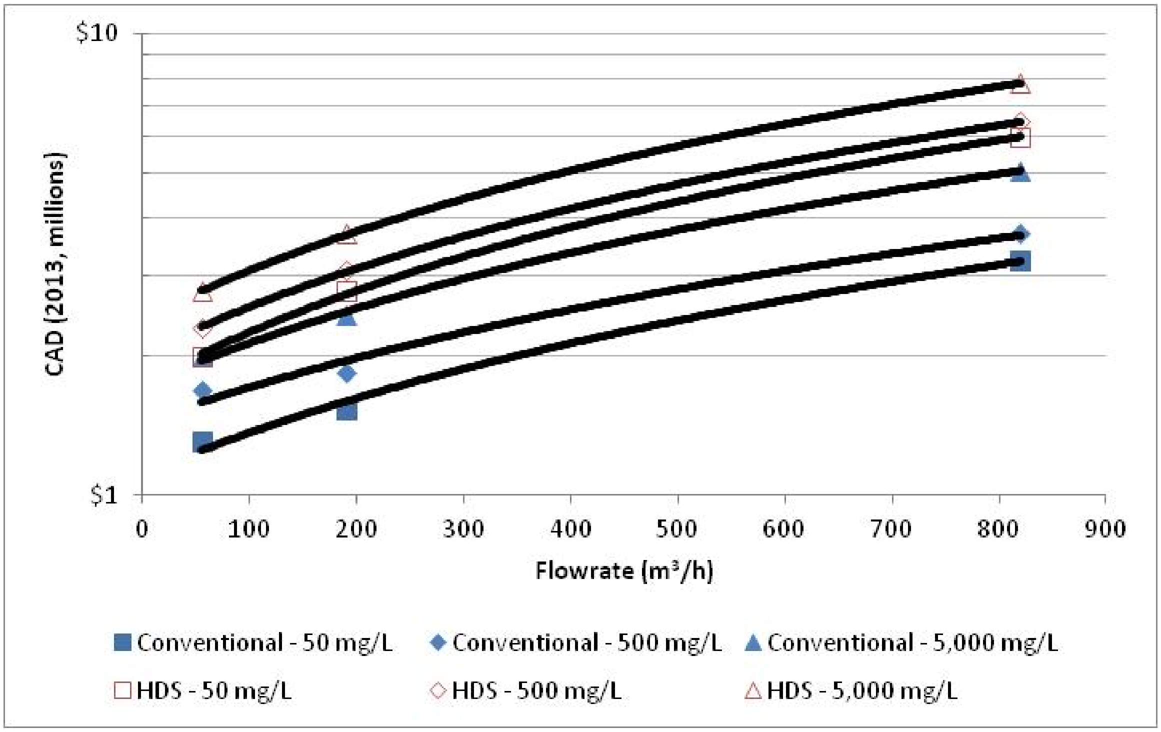

Figure 8-1: Adjusted Total Installed Costs for Hydroxide Precipitation Process

Zinck and Griffith recently reported that, based on a survey and independent research, capital costs for neutralization and hydroxide precipitation range widely from CAD$120,000 to CAD$42,000,000 (CAD$7,000,000 average) for basic neutralization process and CAD$1,000,000 to CAD$24,000,000 (CAD$9,000,000 average) for high density sludge processes (1). Of these costs, approximately 60% was for the treatment plant, 10% was for polishing ponds, and 30% was for residuals management infrastructure. It is assumed that the 60% of capital cost devoted to the treatment plant includes treatment plant infrastructure such as buildings.

Operating

Operating costs are proportional to effluent pH, quality, and flow rate and dependent upon the site location and technologies utilized.

Reagent consumption is proportional to effluent flow rate, pH, dissolved metals concentration and required removal efficiency and final pH, as well as technique, as the technique determines the efficiency of reagent use. Jar testing/titration is recommended to verify treatability and dosage(s). In all cases stoichiometric excess of hydroxide must be maintained during precipitation. Table 8-3 summarizes typical neutralization and hydroxide precipitation reagent costs.

Table 8-3: Neutralization and Hydroxide Precipitation Reagent Costs

Reagent	Format	Cost (CAD$/kg)
Limestone	dry	\$0.01 - \$0.05 (38)
Quicklime	dry	\$0.19 - \$0.26
Hydrated Lime	dry	\$0.17 - \$0.30
Sodium hydroxide	50 wt% solution	\$0.46 - \$1.89
Soda Ash	dry	\$0.17 - \$0.35 (39) (38)
Flocculant	dry, powder	\$3.00 - \$10.00[27]
	15-40 wt% solution	\$3.70 - \$8.73

Note: Delivered costs reported via operations questionnaire except where otherwise noted.

Power consumption is proportional to treatment flow rate and technique for pumping, agitation, and raking equipment.

Operating labour and maintenance are proportional to technique and generally increase in proportion to technique complexity.

In 1994, SENES Consultants developed operating costs for lime-based basic neutralization and high density sludge processes at three different effluent flow rates and three different effluent acidities (36). The costs include reagents, operating labour, maintenance labour and consumables, and power. The costs have been converted to a CAD\$/m^3 treated basis, adjusted to CAD 2013 using CEPCI, and are presented in Figure 8-2.

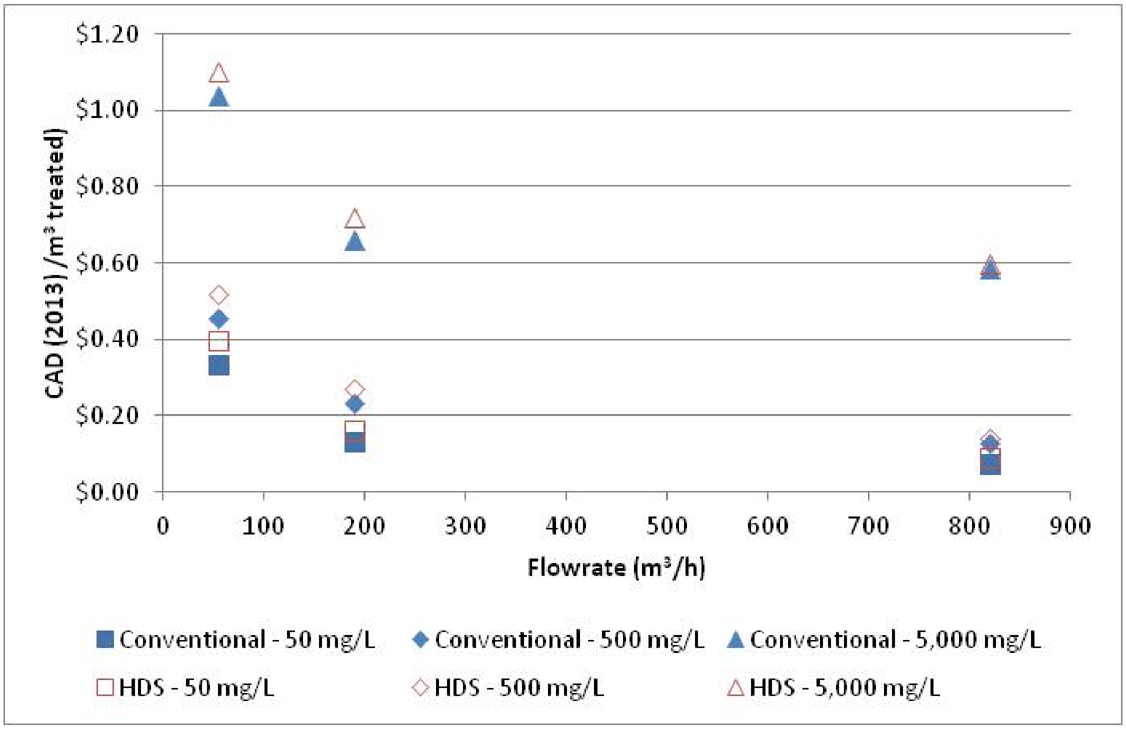

Figure 8-2: Operating Costs for Hydroxide Precipitation Process

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[27] A few operations reported dry, powdered flocculant costs exceeding \$8.50/kg, though at one of the operations, the cost is likely inflated due to delivery costs to Nunavut.

Zinck and Griffith recently reported that, based on a survey and independent research, operating costs for neutralization and hydroxide precipitation range widely from CAD\$0.02/m^3 to CAD\$7.11/m^3 (CAD\$1.52/m^3 average) for basic neutralization process and CAD\$0.04/m^3 to CAD\$8.55/m^3 (CAD\$1.54/m^3 average) for high density sludge processes (1). These minimum and average operating cost values concur with those determined by SENES.

8.2.2 *Sulfide Precipitation*

8.2.2.1 Sulfide Precipitation

Process Description

Sulfide precipitation may be used to precipitate dissolved metals (typically divalent cationic dissolved metals but also trivalent arsenic) as metal sulfides to very low treated effluent concentrations, according to the following generic reactions:

$$Me^{2+} + S^{2-} \leftrightarrow MeS(s)$$

$$Me^{2+} + HS^{-} \leftrightarrow MeS(s) + H^{+}$$

$$As^{3+} + 3S^{2-} \leftrightarrow As_2S_3(s)$$

The fast reaction is carried out at slightly alkaline pH to promote sulfide ion formation. The target pH depends on the target dissolved metals and desired removal efficiency, as the theoretical minimum solubility for different metals occurs at different pH values. The reaction may be carried out in a series of stages to allow for the selective precipitation and recovery of multiple metal sulfides at optimal effluent chemistry (i.e., pH). The metal sulfide precipitates are separated from the treated effluent via solid/liquid separation technologies, most commonly sedimentation in a clarifier/thickener and/or media filtration. Prior to solid/liquid separation, coagulation and flocculation may be used to agglomerate the metal sulfide precipitates, which are often small particulate and colloidal in nature. Further processing of clarifier/thickener underflow solids, such as dewatering via filter press, may be required where metal sulfides are to be recovered to a smelter.

Sulfide reagents include hydrogen sulfide (H_2S) gas, and sodium hydrosulfide (NaHS), sodium sulfide (Na_2S), calcium sulfide (CaS), and ferrous sulfide (FeS). Of these, sodium hydrosulfide is the most commonly used reagent.

Hydrogen sulfide can be supplied as a gaseous reagent, or generated on-site via biological generation from elemental sulfur or sulfate by sulfate reducing bacteria (aka, “biogenic sulfide production”). Biodegradable carbon source (electron donor) and nutrient reagents are required to support biological function. Downstream aerobic polishing may be required for sulfide precipitation processes involving biogenic sulfide production to counter low dissolved oxygen concentrations and prevent effluent toxicity.

Ferrous sulfide is used in the insoluble sulfide precipitation (ISP) process and due to its instability must be generated on-site from sodium sulfide and ferrous sulfate.

As sulfide reagents can be expensive to purchase or generate on-site (as much as ten times the cost of hydroxide reagents), sulfide precipitation is typically only used to target dissolved metals where value recovery is possible (e.g., Cu, Co, Mo, Ni, Re, V, and Zn) from high volumetric flow rate effluent streams. Where value recovery is possible, less residuals storage may be required. Thus, this technology may be more economic for operations that process base metal concentrate. However, sulfide precipitation may be used as a polishing step to treat these and other metals where no value recovery is possible (e.g., Ba, Cd, Fe^{2+}, Hg, Mn^{2+}, Pb, Sb, Se, Sr).

Very high removal efficiencies for dissolved metals can be achieved, depending on operating pH, effluent chemistry, and reagent dosage. Typical achievable concentrations from sulfide precipitation are summarized in Table 8-4. TSS is also removed in the solid/liquid separation step of the sulfide precipitation process.

Table 8-4: Typical Achievable Concentrations from Sulfide Precipitation after Solid/Liquid Separation

Parameter	Achievable Concentration (mg/L)	Reference	Site Data Exceptions[28]
As^{3+}	<0.05	(34)	
Cu	<0.03	(34) (40)	
Fe^{2+}	<0.30	(41)	
Mn^{2+}	<0.05	(41)	
Ni	<0.05	(41)	<0.30[29]
Pb	<0.05	(41)	<0.30[30]
Se	<0.05	(34)	
Zn	<0.02	(40) (41)	

Sulfide precipitation is effective over a wider pH range than hydroxide precipitation so less pre- and post-treatment pH adjustment may be possible. Moreover, sulfide precipitation is relatively insensitive to the presence of weak chelants (e.g., ammonia up to 45 mg-N/L) which can interfere with hydroxide precipitation. Minor variations in flow rate can be managed by modifications to reagent dosing regimes; however, major variations in flow rate can cause insufficient reaction/detention and sedimentation times, negatively affecting treated effluent quality. Variations in temperature have little effect on process performance; however, as with all effluent treatment systems, freezing must be prevented. Depending on climate, systems may be installed indoors with climate control, or outdoors with adequate insulation and heat tracing.

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[28] It should be noted that achievable concentrations demonstrated by full scale operating data are not necessarily achievable concentrations; they are often concentrations achieved when operating to achieve a specific limit (which may be substantially higher than what is achievable for a given technology).

[29] Operating site with ~23 mg/L nickel in influent to effluent treatment system.

[30] Based on testwork completed by a development with 36 mg/L lead untreated effluent from lock-cycle testwork and treatment via aging followed by pH adjustment to 4.5, sulfide precipitation with sodium sulfide, hydroxide precipitation with lime to pH 12, coagulation with ferric sulfate, and flocculation. The developer asserts that hydroxide precipitation with lime alone could not achieve required lead removal, possibly due to residual milling reagents, although this could not be verified by Hatch based on the information provided by the developer. Refer to Table 8-2.

BioteQ Environmental Technologies Inc., based in British Columbia, specializes in sulfide precipitation via their patented ChemSulphide® and BioSulphide® processes. Paques, based in the Netherlands, specializes in sulfide precipitation via their patented THIOTEQ™ and SULFATEQ™ processes. BioteQ's ChemSulphide® and BioSulphide® processes are depicted in Figure 8-3.

Residuals

Metal sulfide sludge is generated by sulfide precipitation. Lower mass/volume of sludge is produced by metal sulfide precipitation than metal hydroxide precipitation, largely due to the fact that gypsum ($CaSO_4$) is not precipitated in sulfide precipitation. Metal sulfide sludge is easier to thicken and dewater than metal hydroxide sludge.

If the content of valuable metals in the sludge is high, the sludge can be dewatered and recovered to a refinery process for value recovery to offset effluent treatment costs.

Metal sulfides are less likely to resolubilize due to pH variation in the storage environment than metal hydroxides (42). However, metal sulfide sludge is less stable than metal hydroxide sludge under oxidizing conditions and requires disposal in reducing conditions. Nonetheless, most operations that employ sulfide precipitation technology do so with the intent of recovering saleable metals and do not, in practice, dispose of their residuals.

Major Equipment

- Reagent make-up/storage systems (mainly mixing and/or in agitated tanks) and feed systems (mainly dosing pumps) for sulfide reagent and any additional reagent (e.g., pH adjustment chemicals, coagulant, flocculant).
- Agitated reaction tank(s).
- Clarifier/thickener(s) and/or media filter.
- Residuals management equipment (e.g., pumps to disposal, mechanical dewatering equipment).
- Aerobic polishing equipment (e.g., aeration, MBR, MBBR), if required.

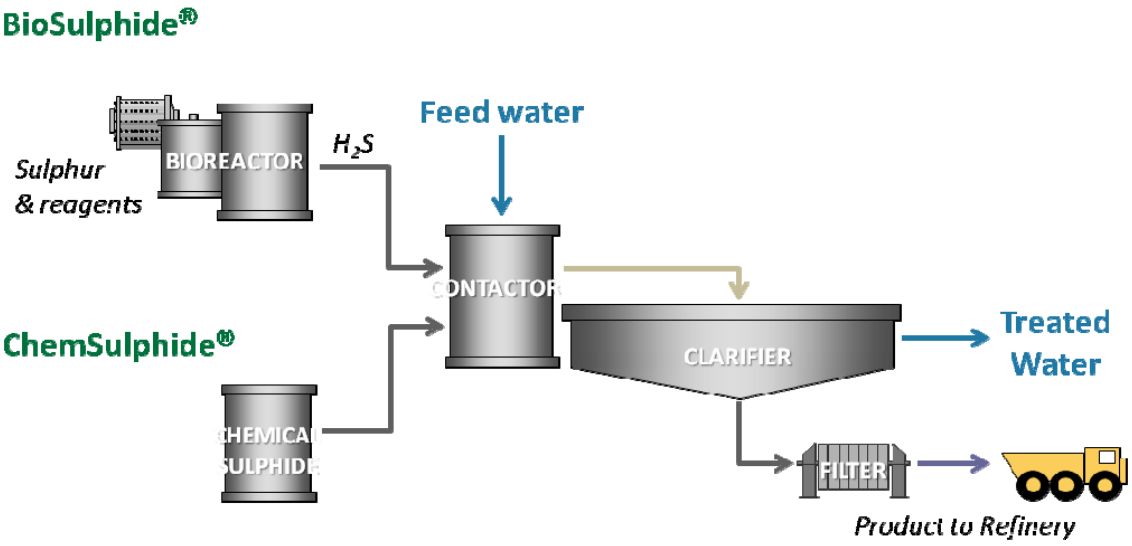

Figure 8-3: Simplified BioSulphide® and ChemSulphide® Process Flow Diagram (43)

Synergies and Challenges

Sulfide precipitation can be employed synergistically with hydroxide precipitation. Applied upstream of hydroxide precipitation, sulfide precipitation can be used to selectively recover metal. Applied downstream of hydroxide precipitation, sulfide precipitation can be used to polish the final effluent by reducing dissolved metals concentrations. Advantages of sulfide precipitation in contrast to hydroxide precipitation include:

- Low residual metal concentrations can be achieved due to low metal sulfide solubilities, leading to very high removal efficiencies.
- Generally, faster reaction times allowing for smaller equipment.
- Operable over a wide pH range, allowing for less or no upstream pH adjustment (with the exception of ISP).
- Relatively insensitive to the presence of weak chelants.
- Value recovery from sludge is possible.
- Lower masses/volumes of residuals are generated (with the exception of ISP) and residuals are easier to thicken/dewater and less likely to resolubilize due to changes in pH.

Challenges associated with sulfide precipitation include:

- Equalization of flows and/or loadings is required for stable operation of sulfide precipitation technology.
- Small particle size and colloidal nature of metal sulfide precipitates requires efficient solid/liquid separation.

- Risk of hydrogen sulfide evolution if pH of reaction is not carefully controlled or if evolved hydrogen sulfide gas is not captured by enclosing and vacuum evacuating process equipment. This increases operating labour to manage and monitor pH.
- Risk of downstream oxidation of residual reagent sulfide, potentially causing sulfate and acidity generation and oxygen depletion, and risk of toxicity of residual reagent sulfide. Residual sulfide oxidation may be required prior to discharge (e.g., via aeration or hydrogen peroxide) (35).
- Reagent cost makes the technology more suitable for applications where value recovery is possible or other criteria are imposed (e.g., effluent limits are stringent, sludge storage is limited or expensive so sludge mass/volume reduction is required).
- Downstream aerobic polishing may be required for sulfide precipitation processes involving biogenic sulfide production to counter low dissolved oxygen concentrations and prevent effluent toxicity.
- Residuals must be stored under reducing conditions to avoid oxidation and resolubilization of metals.
- Removal of selenium as selenite using sulfide precipitation may be impeded by the presence of mercury (44).

Relative Prevalence in Industry

The ChemSulphide® process is utilized at a base metal operation in Quebec to remove and recover nickel from effluent and ion exchange regenerant solution, and at a base metal operation in Yukon Territory to remove and recover copper from effluent. The BioSulphide® process has previously been employed at a base metal operation in New Brunswick to remove and recover zinc from effluent upstream of a hydroxide precipitation system, to reduce downstream operating costs and sludge generation (45).

Costs

Costs must consider whether or not a recoverable product is generated. If no recoverable product is generated, costs for sludge handling and disposal must be considered. If recoverable product is generated, costs for sludge dewatering and transport must be considered.

Capital

The chemical sulfide cost curve information presented in Figure 8-4 was in part provided by BioteQ as part of their vendor questionnaire submission for the ChemSulphide® process. The cost curve was augmented with publicly available costs for generic chemical sulfide precipitation processes corrected to 2013 costs using the Chemical Engineering Plant Cost Index (CEPCI) (46).

The GARD Guide estimates that biological sulfate removal (e.g. Paques SULFATEQ™ process) has a capital cost investment between CAD$800 and CAD$1,500 per m^3/day treatment capacity (38) and curves representing the low and high range estimates are presented in Figure 8-4.

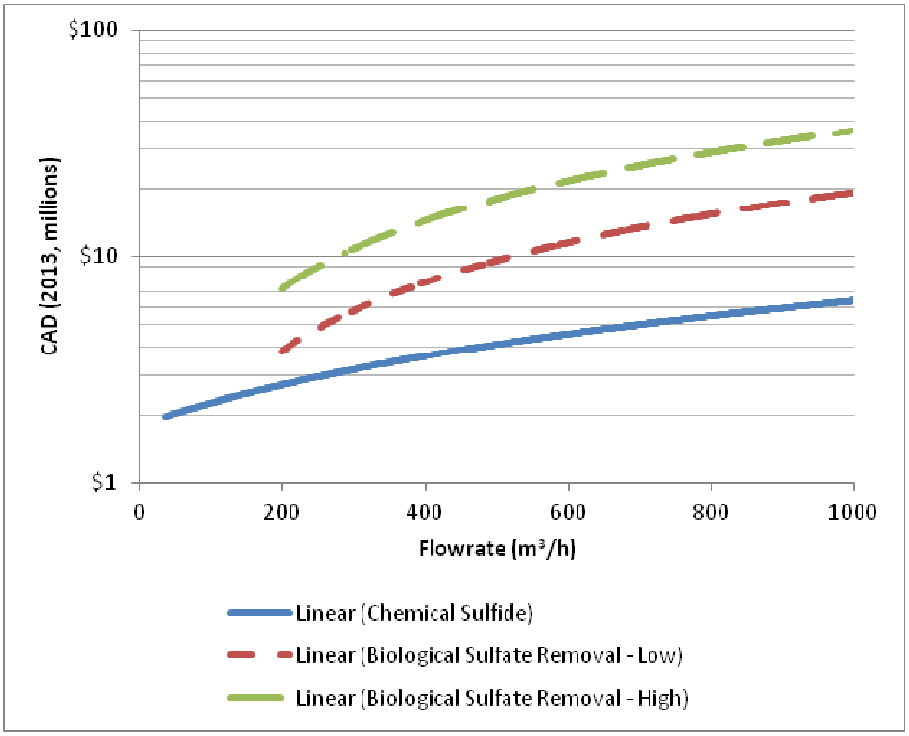

Figure 8-4: Total Installed Costs for Chemical Sulfide Precipitation Process Without and With Biological Sulfate Removal

Operating

Operating costs are proportional to effluent pH, quality, and flow rate and dependent upon the site location and technologies utilized.

Reagent consumption is proportional to effluent flow rate, pH, dissolved metals concentration and required removal efficiency and final pH, as well as technique. Jar testing/titration is recommended to verify treatability and dosage(s). In all cases a stoichiometric excess of sulfide must be maintained.

Table 8-5: Sulfide Precipitation Reagent Costs[31]

Reagent	Format	Cost (CAD$/kg)
NaHS (47)	44-46 wt% solution	$0.62
	70-72 wt% flake in bags	$0.89
Na_2S (39)	60-62 wt% flake in bags	$0.31
$FeSO_4$ (48)	moist heptahydrate	$0.02
	dry heptahydrate	$0.18
	dry monohydrate	$0.28
S (39)	dry prills	$0.47

Power consumption is proportional to treatment flow rate for pumping, agitation, and raking equipment.

Operating labour requirements are high for this process, with a vendor-recommended minimum of two operators present at all times.

BioteQ estimates an annual plant maintenance requirement of approximately one to two weeks of personnel time.

BioteQ estimates an operating cost of CAD$0.30 to CAD$0.90/m^3 treated for reagents and power. Other estimates range from CAD$0.97/$m^3$ to CAD$8.90/$m^3$ including operating labour, annual maintenance, utilities, reagents, and sludge disposal costs (46). The GARD Guide estimates that biological sulfate removal (e.g. Paques SULFATEQ™ process) has an operating cost between CAD$0.70 and CAD$1.50 per m^3 treatment capacity (38).

8.2.2.2 Sulfide Precipitation with Proprietary Polymeric Organosulfide Chemicals

Process Description

As described in Section 8.2.2.1 above, sulfide precipitation may be used to precipitate dissolved metals as metal sulfides to very low effluent concentrations. Proprietary chemicals, such as MetClear™ by GE, NALMET® 1689 by Nalco, and Hydrex™ 6909 by Veolia are polymeric chemicals with anionic sulfur-containing functional groups. The polymeric nature of the chemicals allows them to act as both sulfide precipitant and coagulant/flocculant, to attempt to overcome the challenge of small particle size/colloidal nature associated with conventional sulfide precipitation. However, in some cases additional coagulant/flocculant chemicals may be required to aid agglomeration. One operator using proprietary polymeric organosulfide chemicals at two sites reported that no offset of coagulant/flocculant has been achieved.

The chemicals are supplied as dilute solutions in 1000 L/1 m^3 intermediate bulk containers (IBCs). The chemicals may be transferred into a bulk tank if the rate of consumption is high, such that unreasonably frequent IBC swap out would be required. None of the proprietary reagents investigated require agitation, so neither tote nor bulk storage tank agitation is required.

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[31] Not including delivery costs.

The proprietary chemicals may be dosed neat or diluted into the final reaction tank or clarifier/thickener of an existing process (e.g., hydroxide precipitation) or into a separate agitated reaction tank. When effluent metal concentrations are high, it is preferable to perform the sulfide precipitation with proprietary chemicals in a separate agitated reaction tank, to avoid interference with hydroxide precipitation reactions and minimize the consumption of the more expensive proprietary chemical.

Very high removal efficiencies for dissolved metals can be achieved, depending on operating pH, effluent chemistry, and reagent dosage. Typical achievable concentrations from sulfide precipitation with proprietary chemicals are summarized in Table 8-6. TSS is also removed in the solid/liquid separation step of the process.

Table 8-6: Typical Achievable Concentrations from Sulfide Precipitation with Proprietary Chemicals after Solid/Liquid Separation

Parameter	Typical Achievable Concentration (mg/L)	Reference[32]	Site Data Exceptions[33]
As	<0.05	(34)	
Cu	<0.03	(34) (40)(49)	<0.005[34] <0.05[35] <0.35[36]
Fe^{2+}	<0.30		
Mn^{2+}	<0.05		
Ni	<0.05	(41)	<0.20 <0.35[37]
Pb	<0.05		<0.12
Se	<0.05	(34)	
Zn	<0.02	(41)	<0.17

The proprietary chemicals are associated with a lower risk of hydrogen sulfide evolution than conventional sulfide precipitation reagents.

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[32] Where no reference is given, the value is a conservative estimate compiled from theoretical metal sulfide equilibrium concentrations at circum-neutral pH, achievable concentrations reported in literature (including laboratory, bench-scale, pilot-scale, and full scale data from appropriate industries where available), and achievable concentrations from limited full scale operating data provided by vendors and operations.

[33] It should be noted that achievable concentrations demonstrated by full scale operating data are not necessarily achievable concentrations; they are often concentrations achieved when operating to achieve a specific limit (which may be substantially higher than what is achievable for a given technology).

[34] Operating site after enhanced coagulation and settling plus filtration.

[35] Operating site that completed jar tests on proprietary polymeric organosulfide reagents plus filtration.

[36] Operating site with residual process chelant and <3.11 mg/L copper (P95) in influent to effluent treatment system which also includes lime-based equipment-based hydroxide precipitation.

[37] Operating site with residual process chelant and <14.55 mg/L nickel (P95) in influent to effluent treatment system which also includes lime-based equipment-based hydroxide precipitation.

Due to their polymeric nature, the proprietary chemicals are associated with a lower risk of downstream oxidation of residual reagent sulfide and a lower risk of downstream toxicity, as polymers are less bio-available to aquatic organisms. The chemicals may be acutely lethal to rainbow trout and *Daphnia magna* at certain residual chemical concentrations in effluent. Table 8-7 summarizes aquatic toxicology information for the chemicals. It is expected that the majority of reagent will be retained with precipitated metals in a solid/liquid separation step rather than reporting to the environment. However, sludge carryover and/or cycling up of residual chemical concentration due to effluent recirculation (e.g., for mill process re-use, for effluent treatment process re-use, or for return of off-spec effluent for re-treatment) may pose risk of non-compliance with toxicity requirements. It is advised to verify that treated effluent complies with toxicity requirements (i.e., residual chemical concentration is below lethality thresholds).

Unfortunately, due to the proprietary nature of the chemical formulations, it is not simple to develop a methodology to measure residual chemical concentrations. Moreover, there is no readily available real-time monitoring method for measuring residual chemical concentrations. To overcome this challenge, one vendor recommended on-line or grab sample luminometry to provide real-time biotoxicity indicators and correlating the luminometric results to standard acute and chronic toxicity testing results.

Table 8-7: Aquatic Toxicology Information for Proprietary Polymeric Organosulfide Chemicals (50) (51) (52)

Product	Rainbow Trout[38]	*Daphnia magna*[39]
MetClear 2405™ (GE)	8 mg/L LC_{50} and 3.1 mg/L 0% mortality	240 mg/L LC_{50} and 62 mg/L No Effect Level
NALMET® 1689 (NALCO)	74 mg/L LC_{50}	73 mg/L LC_{50} 18 mg/L EC_{50}
Hydrex™ 6909 (Veolia)	no aquatic toxicity data provided in MSDS, but “contains a substance which causes risk of hazardous effects to the environment”	

Residuals

Metal sulfide sludge is generated by sulfide precipitation. The metal sulfide sludge generated by sulfide precipitation with proprietary chemicals can be less voluminous but also less easy to thicken and dewater than conventional sulfide precipitation sludge, due to the polymeric nature of the reagents.

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[38] 96 hour exposure.

[39] 48 hour exposure.

Metal sulfides are less likely to resolubilize due to pH variation in the storage environment than metal hydroxides (42). However, metal sulfide sludge is less stable than metal hydroxide sludge under oxidizing conditions and requires disposal in reducing conditions. Similar to sulfidic mine wastes (e.g., potentially acid generated tailings and waste rock), metal sulfide sludge stored under oxidizing conditions may generate acid through sulfide oxidation and may leach remobilized metals. Moreover, it is known from the collective industry experience with sulfidic mine waste management to be technically challenging to create and maintain reducing disposal conditions in the long term (e.g., via water cover, dry cover. permafrost disposal, blending and layering, backfill, etc.).

Little is known about whether the polymer chains of proprietary polymeric organosulfide chemicals lend increased stability to metal sulfide sludge under pH variation or oxidizing conditions. Unfortunately, no literature discussing the long term stability of this specific sludge could be found and no case studies or independent research were available through the three reagent vendors contacted nor those operations known to presently utilize the technology.

Industry has expressed concern about the long term stability of metal sulfide sludge from proprietary polymeric organosulfide chemicals, especially due to the proprietary nature of their formulations.

Major Equipment

- Bulk reagent storage tank, if required.
- Reagent feed system (positive displacement dosing pumps for dosing of neat chemical).
- Agitated reactor tank, if required.

Synergies and Challenges

Sulfide precipitation with proprietary chemicals can be employed synergistically with hydroxide precipitation. The high cost of the proprietary chemicals normally limits the process to downstream application to polishing dissolved metals concentrations.

Challenges associated with proprietary polymeric organosulfide precipitation include:

- Equalization of flows and/or loadings is required for stable technique operation.
- Soluble oils and high concentrations of non-metallic suspended solids may interfere with sulfide precipitation via adsorption onto proprietary chemicals.
- High acidity (effluent pH <4.0) may inactivate the proprietary chemicals.
- Risk of hydrogen sulfide evolution if pH of reaction is not carefully controlled or if evolved hydrogen sulfide gas is not captured by enclosing and vacuum evacuating process equipment. This increases operating labour to manage and monitor pH.
- Proprietary reagents are high cost consumables.
- Proprietary reagents are liquid formulations. Their application may be constrained by shipping logistics.

- Potential for chemical to change sludge density and increase risk of carry-over from solid/liquid separation systems, potentially causing non-compliance.
- Potential for downstream aquatic toxicity depending on chemical dosage, residual chemical concentration, and management of treated effluent (i.e., discharge to environment or recirculation). Bench and/or pilot scale treatability and toxicity testing is advised.
- Proprietary nature of formulation makes it difficult to develop a methodology to measure residual chemical concentrations, to investigate causes of impacts to aquatic species, and to predict long term stability of residuals. Little is known about the ultimate environmental fate of these chemicals.

Relative Prevalence in Industry

MetClear™ MR2405 (and previously NALMET 1689) is utilized to polish hydroxide precipitation effluent for copper and nickel at a base metal mining operation in Ontario under chelating conditions caused by a process reagent, largely during the winter when residual chelant is not oxidized due to ice cover. At this site, there is no concern about reagent accumulation, as very little treated effluent is recycled and no toxicity issues have been traced to the use of proprietary polymeric organosulfide reagents. Recently, the operator has been able to phase out the use of proprietary polymeric organosulfide reagents due to reductions in intensity of process reagent use.

The same operator uses MetClear™ MR2404[40] at a closed base metal (Ni/Cu) operation in Ontario where chelating conditions are not of concern, but operating costs are. The use of MetClear™ MR2404 instead of a conventional lime-based hydroxide precipitation process is intended to reduce costs associated with lime transport, post-pH adjustment, and sludge dredging(53). This closed operation has experienced toxicity issues due to residual reagent accumulation due to recycling of non-compliant treated effluent. The operator estimates that due to recycling, up to 50 mg/L residual reagent accumulated from an initial dosage of 15-25 mg/L reagent. Initial dosages have since been reduced. Mobile activated charcoal treatment was required to address reagent accumulation.

MetClear™ MR2405 is also utilized to polish hydroxide precipitation effluent for nickel at two other base metal mining operations in Ontario. Both operations have experienced acute *Daphnia magna* toxicity failures with sub-optimal pH adjustment and MetClear™ MR2405 dosages. It is not known whether the failures are attributable to residual dissolved nickel or reagent. Since optimization of pH target and MetClear™ MR2405 dosage according to influent nickel concentration, no toxicity failures have occurred.

Hydrex® 6909 is utilized to polish a ferric chloride co-precipitation effluent with a high ammonia concentration at a base metal mining operation in New Brunswick. The chemical is dosed into a common reactor/clarifier system and hydroxide sludge and sulfide sludge are thus comingled. Very recently, this operation experienced toxicity issues of unknown cause and has attempted to address the issues by modifying operational targets.

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[40] It should be noted that MetClear™ 2404 is not a polymeric organosulfide reagent, but a simple sulphide reagent, and as such, has lower toxicity thresholds.

Costs

Capital

Minimal capital costs are associated with this technology for reagent feed apparatus. In some cases, a dedicated agitated reactor tank may be required.

Operating

Operating costs are proportional to effluent pH, quality, and flow rate and dependent upon the site location and technologies utilized.

Reagent consumption is proportional to flow rate, dissolved metals concentration and required removal efficiency. GE offers a preliminary rule of thumb of 10 mg/L per mg/L target metal dosage for its MetClear™ MR2405 product. Nalco recommends preliminary dosages for its NALMET® 1689 product based upon specific target metal, as summarized in Table 8-8. Veolia calculates preliminary dosages for its Hydrex™ 6909 product based upon effluent quality using a proprietary dosage calculator. Jar testing is recommended to verify treatability and dosage. Costs for the proprietary reagents are given in Table 8-9.

Table 8-8: Recommended Preliminary Dosage for NALMET® 1689

Parameter	Dosage (mg/L/mg/L)
Cu	15.4
Fe^{2+}	17.6
Mn^{2+}	17.9
Ni	16.8
Pb	4.8
Zn	15.0

Table 8-9: 2013 Budgetary Quotations for Proprietary Reagents Delivered to Northern Ontario

Chemical	Unit Cost ($/kg)	Tote Cost (CAD$, 2013)
MetClear MR2405™ in 1000 L IBC	7.39	8,587
NALMET® 1689 in 1000 L IBC	6.93	11,857
Hydrex® 6909 in 1040 L IBC	5.95	6,545

Power consumption is proportional to flow rate for chemical dosing, although this is expected to represent a minute proportion of treatment costs.

Operator attention requirements are low for this process, with swapping of IBCs or refilling of bulk reagent tank undertaken as required based on required dosing rates, along with regular process monitoring and equipment inspection. It is assumed that no more than one hour of operator attention is required per day for this process. Annual plant maintenance is likewise minimal.

8.2.3 Ferric Iron or Aluminum Salt Co-Precipitation

Iron salts (e.g., ferric sulfate ($Fe_2(SO_4)_3$), ferric chloride ($FeCl_3$)) and aluminum salts (e.g., alum ($Al_2(SO_4)_3$), aluminum chloride ($AlCl_3$), and polyaluminum chloride) are cationic coagulants that can be utilized to precipitate and/or co-precipitate some metals (arsenic, phosphorus, and selenium among others) at acidic pH. Ferric iron and aluminum salts are also frequently used as coagulants to aid TSS removal in solid/liquid separation processes. Coagulants neutralize the charges on particles in order to destabilize small particulate and colloidal solids.

The oxidation of trivalent arsenic (arsenic (III), arsenite) to pentavalent arsenic (arsenic (V), arsenate) is required for arsenic co-precipitation (see Section 8.2.5). Pentavalent arsenic can be precipitated with ferric iron salts as basic ferric arsenate at slightly acidic pH, according to the following reaction:

$$Fe_2(SO_4)_3 + 2H_3AsO_4 + 2H_2O \leftrightarrow 2FeAsO_4 \cdot H_2O(s) + 3H_2SO_4$$

The precipitation of stable basic ferric arsenate requires careful control of ferric iron to arsenic molar ratio (i.e., Fe:As > 4) (33).

Dissolved phosphorus (as PO_4^{3-}) may be precipitated with alum as aluminum phosphate or with ferric iron as ferric phosphate at slightly acidic pH, according to the following reactions:

$$Al_3^{+} + PO_4^{3-} \leftrightarrow AlPO_4(s)$$

$$Fe_3^{+} + PO_4^{3-}- \leftrightarrow FePO_4(s) \text{ (34)}$$

Selenium as selenite (SeO_3^{2-}) may be co-precipitated with ferric iron at slightly acidic to circum-neutral pH (pH 4 to 6). Selenium as selenate may also be co-precipitated with ferric iron; however, sulfate can reduce the effectiveness of co-precipitation. The United States Environmental Protection Agency (USEPA) designated the technology a Best Demonstrated Available Technology for selenium removal (54). However, the USEPA conducted a pilot study of the technology at Kennecott Utah Copper Corporation's Garfield Wetlands-Kessler Springs site which showed that although the technology was effective in reducing selenium concentrations (but not to the regulatory discharge concentration of 0.005 mg/L), it would not be economically feasible to use at a large scale.

Adjustment of pH may be required to achieve the desired coagulation pH. The precipitates are separated from the treated effluent via solid/liquid separation technologies. Flocculation may be used to agglomerate the precipitates. The decant stream may require additional polishing or filtration to meet TSS discharge limits and adjustment of pH to meet pH discharge limits.

Reagent selection for co-precipitation is site-specific and dependent on reagent costs and availability, product solubility, reagent residuals, and desired sludge characteristics. Ferric iron salts are most common in treatment processes that include high pH unit operations or high pH storage where aluminum hydroxide may resolubilize, releasing coagulated metals.

Typical achievable concentrations from co-precipitation are summarized in Table 8-10.

Table 8-10: Typical Achievable Concentrations from Co-precipitation after Solid/Liquid Separation

Parameter	Achievable Concentration (mg/L)	Reference
As	<0.1	(33) (55)
P	<0.5	(35) Demonstrated by performance of uranium and diamond (sub)sector effluent treatment systems including co-precipitation
Se	0.090	(44)

Minor variations in effluent quality and flow rate can be managed by modifications to reagent dosing regimes; however, major variations in loadings can cause insufficient reaction/detention and sedimentation times, negatively affecting treated effluent quality.

Variations in temperature have little effect on process performance; however, as with all effluent treatment systems, freezing must be prevented. Depending on climate, systems may be installed indoors with climate control, or outdoors with adequate insulation and heat tracing.

Residuals

Sludge is generated by co-precipitation and coagulation; sludge quantity and characteristics depend on effluent quality, pH, flow rate, and neutralization reagent. Sludge is typically disposed of in on-site features including tailings storage facilities, engineered dewatering ponds, open pits, underground mine workings, co-disposal with waste rock, etc. Sludge may be mechanically dewatered (i.e., via filter press or centrifuge) prior to disposal. At some environmentally-sensitive sites or sites with limited disposal area, off-site sludge disposal may be required.

Basic ferric arsenate is much more stable than calcium arsenate generated through lime precipitation (33). Sludge has the potential to release selenium as ferrihydrite crystallizes to more stable phases (44).

TCLP testing during the aforementioned Garfield Wetlands-Kessler Springs pilot study indicated the residuals to be hazardous waste (54). Little is known about the long term stability of residuals and the potential for selenium remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.

Major Equipment

- Reagent make-up/storage systems and feed systems for co-precipitation reagent and any additional reagent (e.g., pre-treatment pH adjustment reagent, flocculant, post-treatment pH adjustment reagent).
- Agitated reaction tank(s), if required.
- Clarifier/thickener(s), if required.

- Media filter, if required.
- Residuals management equipment (e.g., underflow tank, pumps to disposal, mechanical dewatering equipment), if required.

Synergies and Challenges

Coagulation may be synergistically employed with other effluent treatment processes to specifically target arsenic, phosphorus, and selenium for removal. For example, ferric iron coagulant is commonly added to hydroxide precipitation processes to co-precipitate arsenic.

Challenges associated with coagulation include:

- Equalization of flows and/or loadings is required for stable operation of coagulation technology.
- Aluminum hydroxide may resolubilize at high pH, releasing coagulated metals.
- Coagulation cannot remove selenium in the form of selenate (SeO42-).
- Downstream pH adjustment may be required to meet discharge limits.
- Reagents add proposed *MMER* substances (e.g., Fe, Al) into effluent, and process may require optimization to prevent non-compliance for these substances.
- Reagents add total dissolved solids (e.g., sulfate, chloride) into effluent, which may be undesirable, depending on downstream processes or receiving bodies.

Relative Prevalence in Industry

Co-precipitation is utilized to remove phosphorus from effluent at diamond mining operations in Ontario and the Northwest Territories. Ferric sulfate coagulation is used to co-precipitate arsenic at a base metal operation in Newfoundland & Labrador. Ferric sulfate coagulation is used to co-precipitate arsenic and antimony at precious metal operations in Ontario. Ferric sulfate coagulation is also used at uranium mining operations in Saskatchewan to precipitate molybdenum and selenium and forms part of the uranium subsector model effluent treatment process (see Figure 6-48).

At many operations, ferric sulfate is added as a coagulant to help agglomerate precipitates formed during neutralization and hydroxide precipitation and sulfide precipitation processes. At one operation in the Yukon, aluminum chloride is added as a coagulant to help agglomerate precipitates formed during a sulfide precipitation process.

Costs

Capital

Capital costs are proportional to effluent pH, quality, and flow rate and would be similar to those of hydroxide precipitation for arsenic and phosphorus co-precipitation applications (see Section 8.2.1).

For selenium co-precipitation applications, a +100%/-50% capital investment cost curve of total installed costs for greenfield installation of ferric co-precipitation technology for selenium (as selenite) removal in stirred-tank reactor configuration has been developed by CH2MHill (44). The estimates are expected to be inflated, as they include clarification, media filtration, residuals dewatering, standalone utilities, and a control room building, which may not be required for all applications. The equipment is assumed to be installed outdoors with adequate insulation and heat tracing with heated buildings/housings provided for pumps and electrical equipment. For extreme cold climates, installation in climate controlled buildings may be required, which could add to capital costs. Flow equalization infrastructure costs are omitted. For the base case of 182 m^3/h (800 gpm), a total installed cost of CAD$10,600,000 (USD$10,100,000) was estimated (2010). The ratio of preliminary 2013 Chemical Engineering Plant Cost Index (CEPCI) to 2010 CEPCI is 1.03. Adjusting for this ratio brings the cost to CAD$10,900,000. It should be noted that CH2MHill cost estimates for selenium removal technologies are not on the same accuracy basis as other technology costs estimates given in this report. Based on comparisons between CH2MHill cost estimates and cost estimates provided by vendors for other selenium removal technologies (see section 8.2.14), CH2MHill capital cost estimates may be inflated by over 200% over base technology costs due to the inclusion of wrap-around equipment and infrastructure which may not be required for all applications. For example, an older (2001) additional cost reference offered by CH2MHill for a 68 m^3/h system factored to 182 m^3 utilizing the rule of six-tenths generates a much lower cost of CAD$6,100,000. However, a more recent (2013) additional cost reference offered by the USEPA for a 158 m^3/h system factored to 182 m^3/h utilizing the rule of six-tenths generates a cost of CAD$10,000,000, which is more consistent with the CH2MHill costs.

Operating

Reagent consumption is proportional to effluent flow rate, pH, dissolved metals concentration, required metal removal efficiency, and final pH. Jar testing/titration curve determination is recommended to verify treatability and ferric iron and aluminum salt dosage.

Table 8-11 summarizes coagulation reagent costs.

Table 8-11: Coagulation Reagent Costs[41]

Reagent	Format	Cost (CAD$/kg)
Ferric sulfate	50 - 66 wt% solution	$0.20 - $0.60
Ferric chloride	dry, 100% basis	$0.66 - $0.77 (39)
Aluminum chloride	dry, anhydrous, 100% basis	$0.44 - $0.45 (39)[42]
Aluminum sulfate (alum)	17 wt% (as Al_2O_3) solution	$0.34 - $0.43 (39)

Other operating costs would be similar to those of hydroxide precipitation for arsenic and phosphorus co-precipitation applications (see Section 8.2.1).

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[41] Delivered costs reported via operations questionnaire except where otherwise noted.

[42] A delivered cost of CAD$3.21/t of proprietary aluminum chloride reagent was reported by an operation in the Yukon Territory.

For selenium co-precipitation applications, a +100%/-50% operating cost curve for technology for selenium removal in stirred-tank reactor configuration has been developed by CH2MHill (44). The estimates include reagents, power, cleaning, maintenance, labour, and on-site residue disposal costs (residuals are assumed to be non-hazardous). For the base case of 182 m^3/h (800 gpm), a total operating and maintenance cost of CAD$2.78/$m^3$ treated (USD$2.64/$m^3$) was estimated (2010). It should be noted that CH2MHill cost estimates for selenium removal technologies are not on the same accuracy basis as other technology costs estimates given in this report. Based on comparisons between CH2MHill cost estimates and cost estimates provided by vendors for other selenium removal technologies (see Section 8.2.14), CH2MHill operating cost estimates may be inflated by as much as 200% over base technology costs due to the inclusion of wrap-around equipment and infrastructure which may not be required for all applications. However, additional cost references offered by the USEPA for a 158 m^3/h system and CH2MHill for a 68 m^3/h system generates costs of CAD$3.28/$m^3$ to CAD$3.53/$m^3$, which are both higher than the CH2MHill estimate.

8.2.4 Barium Chloride Co-Precipitation

Radium-226 may be co-precipitated with barium chloride ($BaCl_2$) as barium radium sulfate ($BaRa(SO_4)_2$), according to the following generic reactions:

$$BaCl_2(s) \rightarrow Ba^{2+}(aq) + 2Cl^{-}(aq)$$

$$Ba^{2+}(aq) + Ra^{2+}(aq) + 2SO_4^{2-}(aq) \rightarrow BaRa(SO_4)_2(s)$$

The residual concentration of dissolved radium-226 is controlled by the solubility of barium sulfate, which is very low (<2 mg/L). Background sulfate concentrations in the effluent may be sufficient, or the addition of a sulfate containing reagent (e.g., ferric sulfate, alum) may be required.

The precipitates are separated from the treated effluent via solid/liquid separation technologies. Coagulation/flocculation is typically used to agglomerate the fine slow settling precipitates that are formed. The decant stream may require additional polishing or filtration to meet TSS discharge limits.

Barium chloride is most commonly supplied as dry/powder barium chloride dihydrate. The dry reagent is made up to a 15-20 wt% solution prior to dosing into the effluent treatment process.

Typical achievable concentrations from barium chloride co-precipitation with flocculation and filtration are summarized in Table 8-12.

Table 8-12: Typical Achievable Concentrations from Barium Chloride Co-Precipitation after Solid/Liquid Separation

Parameter	Achievable Concentration (Bq/L)
Ra-226	<0.37[43]

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[43] Demonstrated by performance of uranium (sub)sector effluent treatment systems including barium-chloride co-precipitation.

Minor variations in effluent quality and flow rate can be managed by modifications to reagent dosing regimes; however, major variations in loadings can cause insufficient reaction/detention and sedimentation times, negatively affecting treated effluent quality.

Variations in temperature have little effect on process performance; however, as with all effluent treatment systems, freezing must be prevented. Depending on climate, systems may be installed indoors with climate control, or outdoors with adequate insulation and heat tracing.

Residuals

Barium radium sulfate sludge is generated by barium chloride co-precipitation. Sludge is typically disposed of in on-site features including tailings storage facilities, engineered dewatering ponds, open pits, underground mine workings, co-disposal with waste rock, etc. Sludge may be mechanically dewatered (i.e., via filter press or centrifuge) prior to disposal. At some environmentally-sensitive sites or sites with limited disposal area, off-site sludge disposal may be required.

Barium radium sulfate sludge is stable in aerobic environments but may be prone to leaching at extreme pH or via biological sulfate reduction in anoxic/anaerobic conditions (56).

Major Equipment

- Reagent make-up/storage systems and feed systems for barium chloride reagent and any additional reagent (e.g., flocculant).
- Agitated reaction tank(s), if required.
- Clarifier/thickener(s), if required.
- Media filter, if required.
- Residuals management equipment (e.g., underflow tank, pumps to disposal, mechanical dewatering equipment), if required.

Synergies and Challenges

Barium chloride co-precipitation of radium-226 may be synergistically employed in both high pH and low pH effluent treatment processes. For example, in the uranium mining subsector, barium chloride co-precipitation is incorporated into both the high pH hydroxide precipitation process and the low pH metals co-precipitation processes (see Figure 6-48).

Challenges associated with barium chloride precipitation include:

- Equalization of flows and/or loadings is required for stable operation.
- Downstream TSS removal may be required to meet discharge limits.
- Sludge may be prone to leaching if stored at extreme pH or under anoxic/anaerobic conditions.

Reagent adds total dissolved solids (e.g., chloride) into effluent, which may be undesirable, depending on downstream processes or receiving bodies.

Relative Prevalence in Industry

Barium chloride precipitation is utilized for radium removal from Canadian uranium effluents. It is also utilized in a few site-specific cases for radium removal from Canadian base metal effluents.

Costs

Capital

Capital costs are proportional to effluent quality and flow rate and would be similar to those of hydroxide precipitation (see Section 8.2.1).

Operating

Reagent consumption is proportional to effluent flow rate, dissolved radium-226 concentration, overall total dissolved solids content, and required removal efficiency. Table 8-13 summarizes barium chloride dihydrate reagent costs. Costs vary widely depending on bulk quantity and site location.

Table 8-13: Barium Chloride Dihydrate Reagent Costs[44]

Reagent	Format	Cost (CAD$/kg)
Barium chloride dihydrate	dry, powder	$0.05 - $0.65

8.2.5 Metal Oxidation

8.2.5.1 Aeration

Process Description

Aeration may be used to convert soluble dissolved metals to minimally soluble metals via oxidation. Most commonly, aeration is used to convert ferrous (II) iron to ferric (III) iron with dissolved oxygen, according to the following generic reaction:

$$Fe^{2+} + \frac{1}{4}O_2 + 2OH^- + \frac{1}{2}H_2O \leftrightarrow Fe(OH)_3(s)$$

The ferric hydroxide oxidation product is insoluble and forms precipitate that is subsequently removed by some form of solid/liquid separation. As aeration is typically integrated with hydroxide precipitation, the form of solid/liquid separation employed will be that which follows the hydroxide precipitation process. As ferric hydroxide is a coagulant itself, only the addition of a flocculant may be required to further aid settling.

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[44] Delivered costs reported via operations questionnaire except where otherwise noted.

The most common methods of aeration are water-fall aeration, where effluent is sprayed through air as small droplets or a thin film, and air diffusion, where pressurized air is diffused into a vessel containing effluent. Of these methods, air diffusion is the most efficient in terms of mass transfer and it is also the most common method when aeration is integrated with a hydroxide precipitation process. Water-fall aeration is most common when aeration is integrated with passive treatment processes (see Section 8.2.16.2). Air diffusion can be accomplished by surface aeration or subsurface aeration. Surface aeration via floating surface aerators and paddlewheel aerators is typically utilized for aeration of equalization ponds. Subsurface aeration via venturi jet aeration or coarse, medium, and fine bubble aeration is typically utilized for aeration of effluent treatment process vessels, as surface aeration is less efficient.

Good removal efficiencies for dissolved ferrous iron can be achieved, depending on operating pH and contact time.

Table 8-14: Typical Achievable Concentrations from Aeration after Solid/Liquid

Parameter	Achievable Concentration (mg/L)	Reference
Fe (total)	<0.3 at pH 7.5 to 8.0[45]	(32)

The rate of oxidation via aeration is affected by pH, with the most efficient ferrous iron oxidation taking place in the range of pH 7.5 to 8.0.

The process is relatively insensitive to variation in temperature, due to the competing effects of effluent temperature on oxygen solubility (higher at lower temperatures) and rates of oxidation reaction (higher at higher temperatures).

Minor variations in flow rate can be managed by modifications to aeration regimes; however, major variations in flow rate can cause insufficient reaction/detention and sedimentation times, negatively affecting treated effluent quality.

Residuals

Ferric hydroxide precipitate residuals are produced via aeration. As aeration is typically integrated with hydroxide precipitation, the precipitates typically report to a clarifier/thickener underflow sludge stream, to be managed as discussed in Section 8.2.1.

Major Equipment

For the purposes of this study, it is assumed that aeration is integrated with agitated hydroxide precipitation process tanks. Depending on tank height and hydraulic head, either blower or compressor equipment may be required.

- Air blower(s)/compressor(s) with air-inlet filter, air-inlet and outlet silencer, and/or enclosure.
- Diffuser(s).

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[45] Assuming aeration plus solid/liquid separation.

Synergies and Challenges

Aeration can be employed synergistically with any processes that achieve better removal of metals in oxidized state versus metals in reduced states.

The process may also increase effluent pH/decrease effluent acidity via decarbonation, that is via driving off dissolved carbon dioxide gas.

A minor decrease in un-ionionized ammonia gas ($NH_{3(g)}$) may result, if the initial pH is high and if there is a sufficient air to liquid ratio to promote volatilization.

Although the reactions are slow and inefficient, trivalent arsenic and manganese may be oxidized to pentavalent arsenic and manganese dioxide, respectively. Manganese dioxide is an insoluble compound while pentavalent arsenic is subsequently precipitated as a hydroxide (see Section 8.2.1) or co-precipitated with iron salts (see Section 8.2.3).

Challenges associated with aeration include:

- High energy costs for air blowing or compression.
- High maintenance requirements due to scaling, fouling, and plugging of diffusers (especially fine bubble diffusers).
- Dissolution of carbon dioxide from air into effluent may increase neutralization reagent demand and sludge production.
- Equalization of flows and/or loadings is required for stable operation of aeration equipment.
- Via aeration alone, there is insufficient and slow oxidation of manganese (II) and trivalent arsenic at pH <9.5. Therefore, a strong oxidant (e.g., chlorine, hydrogen peroxide, ozone, or permanganate) is typically utilized to carry out the oxidation (see Section 8.2.5.2).

Relative Prevalence in Industry

Aeration is utilized at base metal mining operations in Ontario in conjunction with hydroxide precipitation. Aeration is also utilized at many mining operations in Canada to enhance the natural degradation of ammonia and cyanide (see Section 8.2.16.1).

Costs

Capital

Capital costs for air blower(s)/compressor(s) and diffuser(s) are highly dependent on effluent dissolved metals concentrations, required removal efficiencies, effluent flow rate, the dimensions of the vessel to be aerated, the type of diffuser to be utilized, and the type of air blower/compressor to be utilized (e.g., positive displacement vs. centrifugal). Due to this specificity, cost curves are not presented for this technique.

Operating

The primary cost of aeration is power consumption by air blower(s)/compressor(s). Power consumption is proportional to oxygen demand, which is proportional to dissolved metals concentrations, required removal efficiencies, effluent flow rate, dimensions of the vessel to be aerated, type of diffuser to be utilized, and the type of air blower/compressor to be utilized.

Operator attention requirements are low for this process, necessary only for regular process monitoring and equipment inspection. It is assumed that no more than one hour of operator attention is required per day for this process.

Annual plant maintenance is moderate and includes regular cleaning of diffusers and routine maintenance for air blower(s)/compressor(s).

8.2.5.2 *Strong Oxidant*

Process Description

Chemical oxidation with a strong oxidant may be used to convert soluble dissolved metals to minimally soluble metals via oxidation and to convert trivalent arsenic to pentavalent arsenic to promote its subsequent precipitation as a hydroxide (see Section 8.2.1) or co-precipitation with iron salts (see Section 8.2.3). Such strong oxidants include chlorine (e.g., ClO_2, Cl_2, HOCl), hydrogen peroxide, permanganate (MnO_4), and ozone (O_3) (34). Aeration is generally first utilized as described in Section 8.2.5.1 to convert easily oxidizable soluble metals to less soluble metals. Strong oxidants are then added to achieve lower efficiency oxidations.

The removal of manganese (II) is inefficient and slow with aeration alone and a strong oxidant (e.g., chlorine, hydrogen peroxide, ozone, or potassium permanganate) is typically utilized to oxidize manganese.

Table 8-15: Typical Achievable Concentrations from Strong Oxidant Oxidation after Solid/Liquid Separation

Parameter	Achievable Concentration (mg/L)	Reference
Mn (total)	<0.05	(57)

Although chlorination has been reported to oxidize manganese, potassium permanganate is a more effective oxidizing agent which can be utilized at neutral pH to achieve the concentrations described in Table 8-15.

Residuals

Manganese dioxide and other metal precipitate residuals are produced via chemical oxidation. Depending on the feed concentration of the metal, the precipitates typically report to a clarifier/thickener underflow sludge stream, to be managed as discussed in Section 8.2.1.

Major Equipment

- Reagent make-up/storage systems and feed systems.
- Agitated reaction tank(s), if required.

- Solid/liquid separation equipment such as clarifier/thickener(s) or media filter(s), if required.
- Residuals management equipment (e.g., underflow tank, pumps to disposal, mechanical dewatering equipment), if required.

Synergies and Challenges

Chemical oxidation can be employed synergistically with any processes that achieve better removal of metals in oxidized state versus metals in reduced states.

Challenges associated with chemical oxidation include:

- High chemical costs.
- Equalization of flows and/or loadings is required for stable operation of chemical dosing equipment.
- Increased demand on chemical where organics are present.
- Reagents add total dissolved solids (e.g., sulfate, chloride) into effluent, which may be undesirable, depending on downstream processes or receiving bodies.

Relative Prevalence in Industry

Chemical oxidation is also utilized at several mining operations in Canada to oxidize metals for subsequent removal via solid/liquid separation.

Costs

Capital costs are proportional to effluent quality and flow rate and would be similar to those of hydroxide precipitation (see Section 8.2.1).

Operating

Reagent consumption is proportional to effluent flow rate, dissolved metals (mainly, iron and manganese), overall total dissolved solids content, organics content, and required removal efficiency. Costs vary widely depending on bulk quantity and site location.

Operator attention requirements are low for this process, for regular process monitoring and equipment inspection. It is assumed that no more than one hour of operator attention is required per day for this process. Annual plant maintenance is likewise minimal.

8.2.6 Reacidification

Reacidification may be utilized to neutralize effluents with alkaline pH to meet pH discharge limits (pH 6.0 to 9.5) and to change the fraction of ammonia as un-ionized ammonia in effluent to meet toxicity requirements. Carbon dioxide (CO_2) and sulfuric acid (H_2SO_4) are the two most commonly used reagents for reacidification of Canadian mining effluents. Of these two, carbon dioxide reacidification is most often preferred, as it does not add sulfate to effluent, it is easier to control, and it is safer to handle and store than sulfuric acid. Carbon dioxide will also add alkalinity to the effluent, which may be desirable for some operations. Moreover, sulfuric acid is a regulated toxic substance in some jurisdictions, and therefore may be associated with a higher regulatory burden for operations than carbon dioxide. In a carbon dioxide-based reacidification system, liquid carbon dioxide is first vapourized to gaseous carbon dioxide via heat exchange and then injected into the effluent via spargers/diffusers. Gaseous carbon dioxide can be injected directly into the effluent via spargers/diffusers.

Residuals

Normally, reacidification does not generate residuals unless there is sufficient hydroxide alkalinity and calcium in the effluent.

Major Equipment

A carbon dioxide based reacidification system has been assumed. Carbon dioxide gas suppliers also supply storage and vapourizer equipment, sometimes under equipment lease arrangements.

- Gaseous or liquid carbon dioxide storage tank.
- Vapourizer, if required.
- Diffuser(s).

Synergies and Challenges

Reacidifcation can be employed synergistically with any process.

Challenges associated with reacidification include:

- Regular maintenance of pH instrumentation required to ensure proper pH control feedback loop function.
- Equalization of flows and/or loadings is required for stable operation.
- Reagents may add total dissolved solids (e.g., sulfate, chloride) into effluent, which may be undesirable, depending on downstream processes or receiving bodies.

Relative Prevalence in Industry

Carbon dioxide reacidification is widely utilized across the Canadian mining industry to adjust treated effluent pH in order to meet pH discharge limits and toxicity requirements.

Costs

Capital

Capital costs for carbon dioxide based reacidifcation systems can be minimal, as equipment can be provided under lease arrangements with liquid carbon dioxide suppliers. Capital costs for diffusers are proportional to feed pH, target pH, and flow rate, which determine carbon dioxide demand.

Operating

Reagent consumption is proportional to feed pH, target pH, and flow rate, which determine carbon dioxide demand.

Operator attention requirements are low for this process, for regular process monitoring, and equipment and instrumentation inspection. It is assumed that no more than one hour of operator attention is required per day for this process. Annual maintenance is likewise minimal.

Table 8-16 summarizes carbon dioxide reagent cost. Costs vary widely depending on bulk quantity.

Table 8-16: Carbon Dioxide Reagent Costs[46]

Reagent	Format	Cost (CAD$/kg)
Carbon dioxide	gaseous	\$0.35 - \$1.80
Carbon dioxide	liquid	\$0.27 - \$1.28
Sulfuric Acid	93% solution	\$0.17 - \$0.60

8.2.7 Solid/Liquid Separation

Solids requiring solid/liquid separation can consist of gravity settleable solids and non-settleable particulate or colloidal solids. Solid/liquid separation is normally accomplished by coagulation (small particulate/colloid destabilization via charge neutralization), flocculation (agglomeration of destabilized particles), and settling/sedimentation, in both pond and clarifier based systems. However, solid/liquid separation can also be accomplished by filtration and flotation. Coagulation can be accomplished with ferric iron and aluminum salts (Section 8.2.3) as well as low molecular weight water soluble cationic polyelectrolytes. Flocculation can be accomplished with high molecular weight water soluble polyeletrolytes (anionic, cationic, or nonionic).

Settling/sedimentation theory is outside of the scope of this study.

8.2.7.1 Pond or Pit-based Settling/Sedimentation

Pond and pit-based settling/sedimentation achieve TSS removal via gravity. Pond or pit-based settling/sedimentation systems do not require equipment for TSS removal, with the exception of flocculant make-up and dosing systems, where required. However, large surface areas are required to achieve adequate settling, and it may be impossible to remove small particulate and colloidal TSS in pond or pit-based systems. Moreover, depending on pond and pit depth, settled solids can be easily disturbed by inflow and outflow upsets as well as wind and wave action and pond inversions. Periodic dredging is required to counter solids accumulation at low density within the pond (see Section 8.2.1). Although TSS <10 mg/L has been reported for pond or pit-based settling/sedimentation, it is not as consistent nor as reliable as mechanical settling/sedimentation. Pond-based sedimentation is widely used for effluent treatment across all Canadian mining sectors/subsectors. Canadian coal operations achieve a TSS <50 mg/L via pond-based settling/sedimentation supplemented with flocculation where required(12).

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[46] Delivered costs reported via operations questionnaire except where otherwise noted.

8.2.7.2 *Conventional Clarification*

Conventional clarification achieves TSS removal via gravity settling/sedimentation. Conventional clarifiers are available in a variety of configurations, such as horizontal flow in rectangular, circular, or square basins, upflow, sludge blanket, and solids-contact. Clarifiers may contain tube settlers or plate settlers ("lamella") to increase surface area, decrease specific overflow rate, and promote settling. Settled solids are removed from the clarifier as sludge to be dewatered, if required, and disposed of in an appropriate location. Clarification can produce a more dense sludge than pond-based settling/sedimentation (see Section 8.2.1). TSS <15 mg/L can be achieved via conventional clarification; however, process upsets can cause occasional excursions. Treated effluent quality is a function of contaminant and hydraulic loading (i.e., feed TSS and clarifier rise rate) and proper chemistry (i.e., coagulant and/or flocculant control); TSS <15 mg/L can be obtained provided optimal clarifier design and operation. Conventional clarification is widely used for effluent treatment across all Canadian mining sectors/subsectors.

Figure 8-5 presents equipment cost curve information for clarification systems. The cost information presented in this figure is per in-house references and one reference provided by industry.

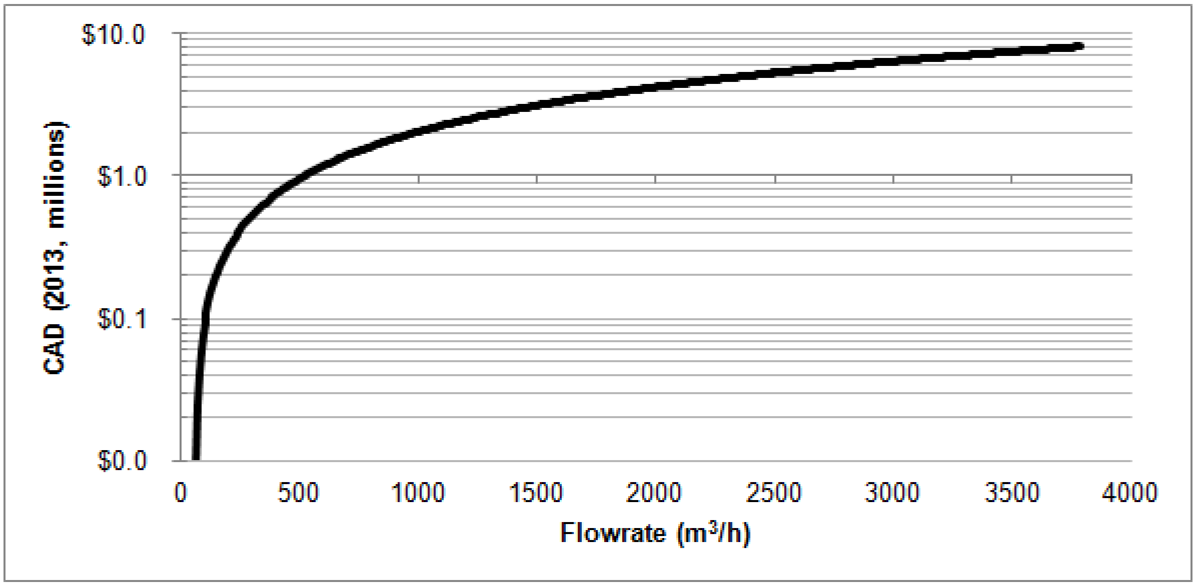

Figure 8-5: Clarification Equipment Costs

8.2.7.3 *Dissolved Air Flotation*

Dissolved air flotation (DAF) achieves TSS removal via buoyant separation on air bubbles. The air bubbles diffused into coagulated/flocculated effluent, are adhered or adsorbed to floc surface or entrapped under floc, and then float to the effluent surface. Float sludge is then skimmed or hydraulically flooded off of the effluent surface. Skimmed float sludge can be comprised of up to 3 to 6 wt% solids. DAF is not commonly used in the treatment of mining effluents as it is not effective for dense solids.

8.2.7.4 Media Filtration

Media filtration achieves TSS removal primarily via size exclusion, but also via adhesion and adsorption. Pressure media filtration is most commonly used for polishing after upstream TSS removal via other methods but can be used directly for low turbidity effluents. Sand (quartz, silica) and anthracite are the most common filter media; however, garnet, magnetite, and other media are also used. In multi-media filtration, multiple filter media are used with coarse, less dense media at the top of the filter and finer, more dense media at the bottom of the filter.

In the media filtration process, effluent is pumped under pressure to the top of the media filters. Filter aid (e.g., flocculant polymer) may be added through an in-line mixer prior to the filters to agglomerate very fine particles. The effluent is then sent through multi-media filters to remove suspended solids. Filtered effluent (“filtrate”) is collected from the bottom of the filter through collection laterals. Periodically, the media filters must be taken out of service to undergo backwashing to remove the build-up of suspended solids. The frequency of backwash depends on the TSS particle size and loading to the filter and filter design. Backwash water is pumped from a backwash water storage tank. A portion of the filtrate produced by the media filtration process is utilized to supply backwash water to the backwash storage tank. Prior to backwash, the filters are partially drained and then scoured with air using an air blower. This helps break up media so that entrained solids are released. The backwash water then enters from the bottom of the filters and exits through the top. Spent backwash water is generated and must be disposed of. Often, spent backwash water is recycled to equalization ponds which feed the effluent treatment process.

Depending on loading (i.e., feed TSS), design, and operation, TSS <5 mg/L can readily be achieved via media filtration depending upon the TSS load, solids characteristics and media properties. Media filtration is used for effluent treatment across all Canadian mining sectors/subsectors where final effluent polishing is required.

Figure 8-6 presents equipment cost curve information for media filtration systems. The cost information presented in this figure is per in-house references.

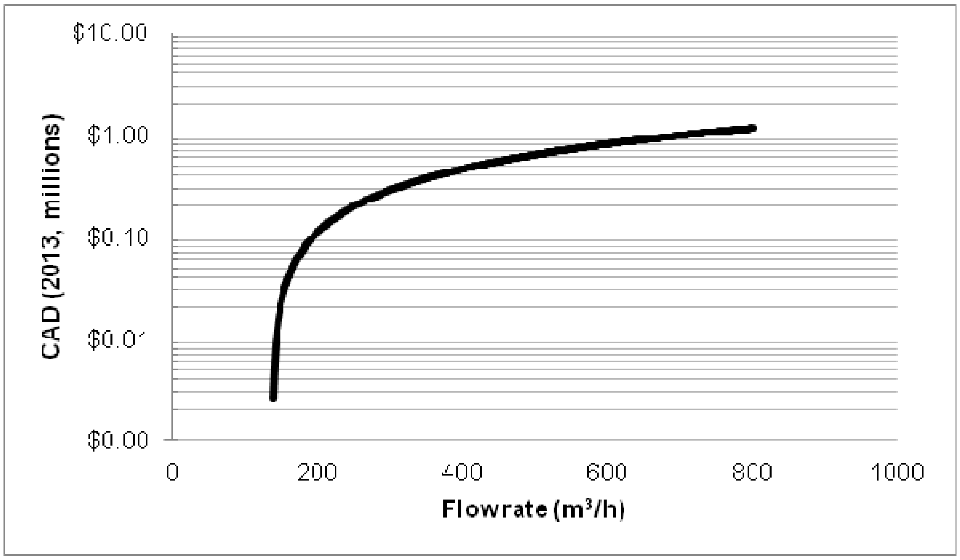

Figure 8-6: Media Filtration Equipment Costs

8.2.7.5 *Ultrafiltration and Microfiltration*

Ultrafiltration (UF) and microfiltration (MF) are membrane-based technologies that achieve TSS removal via size exclusion (34). UF and MF are most commonly used for polishing after upstream TSS removal via other methods but can be used directly for low turbidity effluents. They are particularly effective on fine and colloidal TSS. UF and MF technologies are quite similar, but have different pore size ranges and can remove different size fractions of TSS; while UF can remove TSS between 0.001 µm and 0.1 µm, MF can remove TSS between 0.1 µm and 10 µm. Membranes are available in many materials and in different configurations, including tubular, hollow fibre, spiral-wound (UF only), pleated cartridge (MF only), and flat sheet. Hollow fibre configuration is the most common for industrial effluent treatment. Membranes can be operated in dead-end or cross-flow configuration and with constant pressure or constant flux. Cross-flow configuration with constant flux is most common for industrial effluent treatment.

Low pressure or vacuum is used to drive effluent through the membranes to the permeate side while TSS greater than a specific size is retained on the reject side. Feed to UF and MF systems must be pre-treated through strainers to protect the membranes from clogging and damage. Coagulants may be added prior to the UF or MF system to agglomerate very fine particles.

Periodically, the membranes must be taken out of service to undergo backwashes (via flow reversal or with air) to remove the build-up of suspended solids and restore membrane flux. The frequency of backwash depends largely on the effluent quality, the type of membrane, and membrane configuration. Less frequent chemically-enhanced backwash and/or chemical cleaning cycles (“clean-in-place” or “CIP”) are also required to counter membrane scaling/fouling and restore flux. Replacement of membranes is required when irreversible scaling or fouling occurs or membranes otherwise reach the end of their operational life. Pre-treatment waste, reject, and spent cleaning solutions may be recycled to equalization ponds which feed the effluent treatment process.

TSS concentrations of well below 1 mg/L are readily achieved via UF and MF; however, neither technology is commonly used for effluent treatment in Canadian mining sectors/subsectors. No operations questionnaire respondents reported the application of UF or MF technology. However, Pall Canada Ltd. ("Pall") a manufacturer of MF technology, reported the application of MF for effluent treatment in one emergency situation at a base metal operation in Manitoba and at numerous mining operations in the USA, Africa, and Australia (most commonly as pre-treatment for nanofiltration and reverse osmosis systems).

8.2.8 Enhanced Coagulation and Settling

Enhanced coagulation and settling technologies (ECS) are variations on high rate clarification that have advantages over traditional clarification, particularly a reduction in footprint which can result in capital cost savings, the ability to handle large variations in feed total suspended solids (TSS), which can improve treated effluent quality, and the ability to handle variations in feed flow rate, unlike conventional clarification. ECS technologies have solidified their place in the municipal water treatment market and have been entering the industrial effluent treatment market over the past decade. The main competing technologies can be grouped as follows:

- Ballasted flocculation/sedimentation:
  - ACTIFLO® by Veolia (microsand ballasted flocculation with lamella clarification).
  - CoMag™ by Siemens (magnetite ballasted flocculation and clarification).
- High rate solids contact clarification/thickening: DensaDeg® by Degremont (flocculation with chemically conditioned sludge recycle with settling tubes clarification).

Of these technologies, ACTIFLO® by Veolia and DensaDeg® by Degremont are most prominent in the mining effluent market. Siemens is attempting to compete with the recent release of their CoMag™ system which has had limited use in the mining effluent market at this time. Siemens CoMag™ has many full scale municipal installations in the USA but just one pilot scale base metal demonstration and one pilot scale precious metal demonstration, both in the mid-western USA.

ACTIFLO® is a combination of chemical precipitation, microsand enhanced flocculation, and lamella clarification. Figure 8-7 illustrates the features of this process.

ACTIFLO® consists of four separate compartments – coagulation tank, injection tank, maturation tank and settling tank. The process begins with the addition of a coagulant to destabilize suspended solids and colloidal matter. The feed effluent enters the coagulation tank for flash mixing with coagulant and then overflows into the injection tank where microsand is added. The microsand provides nuclei for floc formation which increases the specific gravity and settling velocity of the particles. By adding ballast to the chemical mixing and flocculation process, effluent can be treated at a higher rate with a fraction of the footprint of conventionally designed clarifiers. Polymer may either be added in the injection tank or at the next step, the maturation tank. Mixing is slower in the maturation tank, allowing the polymer to help bond the microsand to the destabilized suspended solids. From this tank, the fully formed ballasted floc enters a settling tank equipped with inclined lamella plates or settling tubes, depending on the application, which provide large surface area for the removal of the microsand/floc sludge. The clarified effluent is collected and exits the unit via a series of weirs and collection troughs. The sand and sludge mixture is collected at the bottom of the settling tank with a conventional scraper system and pumped to a hydrocyclone, located above the injection tank. The hydrocyclone converts the pumping energy into centrifugal forces to separate the higher-density sand from the lower-density sludge. The sludge is discharged out of the top of the hydrocyclone while the sand is recycled back into the process for re-use. Minor amounts of microsand are lost to the waste sludge and fresh microsand must be periodically added to the system.

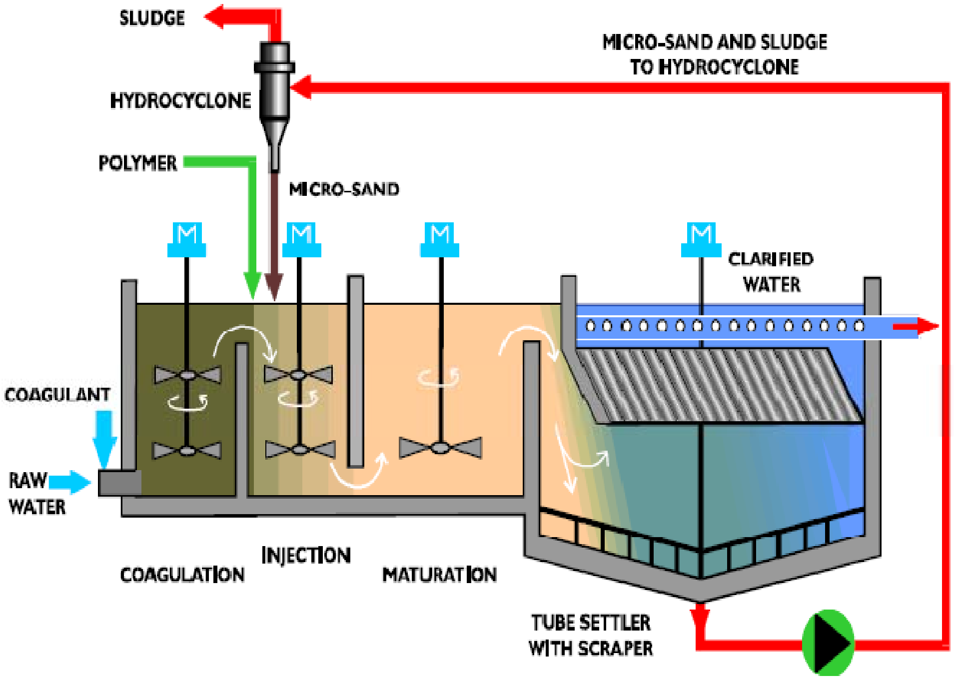

Figure 8-7: ACTIFLO® Process

DensaDeg® is a high rate solid contact clarifier with an integrated three stage process operating in two conjoined vessels. DensaDeg® combines optimized flocculation, internal and external solids recirculation, and thickening to maximize hydraulic loading and treatment efficiencies.

The process, shown in Figure 8-8, begins with the addition of a coagulant (alum or ferric chloride) to destabilize suspended solids and colloidal matter. The feed effluent enters the coagulation tank for flash mixing with coagulant and then overflows into the reactor tank where recycle sludge and polymer are added. A draft tube and mixer in the reactor tank allow for thorough mixing of the reactor tank contents. The recycle sludge provides nuclei for floc formation, allowing solids to grow and settle more quickly, and thereby requiring a smaller footprint than conventional clarification. The mixed reactor tank contents flow through an up-flow piston zone over a weir and into the clarifier. The clarifier is equipped with settling tubes which provide large surface area for the removal of the floc. The clarified effluent exits the process by overflowing weirs above the settling tubes. Settled sludge is thickened progressively in the bottom of the clarifier through the use of a rotating scraper mechanism. A portion of this thickened sludge is recycled back to the reactor tank and the remainder is periodically removed via a separate sludge pump (not shown in Figure 8-8).

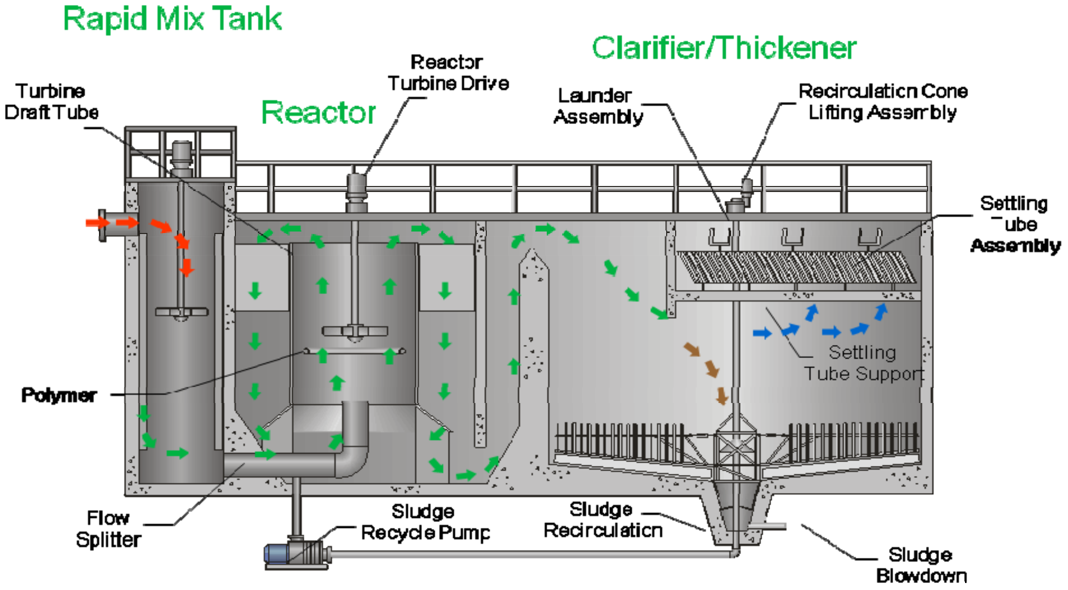

Figure 8-8: DensaDeg® Process

ECS processes are typically integrated downstream of chemical precipitation processes (i.e., hydroxide precipitation, sulfide precipitation, co-precipitation, etc.). Good removal efficiencies for TSS can be achieved with ECS technologies. As a portion of TSS is typically represented by total metals, good removal efficiencies for total metals (precipitated metals) can also be achieved. Typical achievable concentrations from ECS are summarized in Table 8-17.

Table 8-17: Typical Achievable Concentrations from ECS

Parameter	Achievable Concentration (mg/L)	Reference
TSS	<10	(58)

Treated effluent quality is a function of contaminant and hydraulic loading, the type of chemical precipitation process employed, if any, and proper chemistry (i.e., coagulant and/or flocculant control); TSS <10 mg/L can be obtained provided optimal system design and operation.

In contrast to conventional clarification technology which takes long periods to achieve steady state operation, ECS technology reaches steady state operation following start-up in less time than conventional clarifiers.

ECS technologies operate at much higher loading rates than conventional clarification technology, allowing for significant reductions in required footprint and potentially significant cost savings. This also allows ECS units to be modular in nature resulting in lower installation costs than conventional clarifiers.

The recycle of microsand or sludge in ECS processes can be utilized to maintain TSS loading to the system despite variations in feed TSS. The ACTIFLO® process can accommodate up to 2,500 mg/L feed TSS.

ECS technologies offer lower chemical consumption based on the internal recirculation of solids in the DensaDeg® and the microsand ballast in the ACTIFLO®.

The ACTIFLO® process can operate between 25 and 130% of its nominal design capacity via alterations to microsand loading, allowing it to handle substantial variations in feed flow rate.

Variations in temperature have little effect on process performance; however, as with all effluent treatment systems, freezing must be prevented. Depending on climate, systems may be installed indoors with climate control, or outdoors with adequate insulation and heat tracing.

Residuals

Sludge quantity and characteristics generated by ECS technologies depend on upstream treatment technologies (i.e., hydroxide precipitation, sulfide precipitation, co-precipitation, etc.). The ACTIFLO® process generates a sludge stream of approximately 0.5 to 2 wt% solids. In contrast, the DensaDeg® process generates a sludge stream of approximately 2 to 6 wt% solids.

Major Equipment

Upstream chemical precipitation process equipment is omitted here. Major equipment depends on the system utilized and may include:

- Reagent make-up/storage systems and feed systems for coagulant and flocculant/polymer.
- Residuals management equipment (e.g., underflow pump(s), underflow tank, pump(s) to disposal, mechanical dewatering equipment), if required.

Synergies and Challenges

ECS technologies can be employed synergistically with any process that requires a solid/liquid separation step.

Challenges associated with ECS include:

- Equalization of flows and/or loadings is recommended for stable operation, especially if there is upstream chemical precipitation.
- Downstream residuals management equipment may be required to increase sludge density, especially for the ACTIFLO® process.

- With respect to the ACTIFLO® process, monitoring of the microsand concentration is important to maintain TSS effluent quality.
- With respect to the DensaDeg® process, maintaining the optimum sludge bed height is important to achieve/maintain TSS effluent quality.
- Scaling of the lamella sections within the ECS technologies.
- Coagulation reagents add proposed *MMER* substances (e.g., Fe, Al) into effluent, and process may require optimization to prevent non-compliance for these substances.
- Coagulation reagents add total dissolved solids (e.g., sulfate, chloride) into effluent, which may be undesirable, depending on downstream processes or receiving bodies.

Relative Prevalence in Industry

ACTIFLO® by Veolia has at least seven full scale base metal installations in Quebec, seven full scale precious metal installations in Canada, one full scale diamond installation in Canada, and many more full scale installations in the USA. DensaDeg® by Degremont has at least one full scale base metal installation in Quebec, one full scale iron ore installation in Quebec, one full scale uranium installation in Saskatchewan, and two full scale diamond installations in the Northwest Territories.

Costs

Capital

Capital costs are proportional to effluent flow rate. Overall, the equipment costs for ACTIFLO® and DensaDeg® are comparable. The DensaDeg® total cost is expected to be about 5-10% higher than that of ACTIFLO® due to a larger unit footprint for a similar flow. Both technologies can be implemented as modular systems, with ACTIFLO® providing capital cost advantages beyond the nominal design capacity where DensaDeg® is no longer modular.

A recent 2012 Hatch study found that for treatment of 500 m^3/h mine dewatering effluent in northern Saskatchewan, the total installed cost for a conventional clarifier was over 2.5 times greater than an ACTIFLO® system. Moreover, the ACTIFLO® system could be pre-fabricated and delivered on the back of a drop down trailer which would reduce on-site fabrication and installation time.

Figure 8-9 presents equipment cost curve information for ACTIFLO® systems. The cost information was provided by Veolia as part of their vendor questionnaire submission and was augmented by cost information from other Hatch studies. Equipment costs from the past have been adjusted to 2013 values using the appropriate CEPCI conversion factor. The equipment costs include the complete ACTIFLO® unit as well as coagulant dosing system, flocculant polymer preparation and dosing system, instrumentation, controls, and engineering. Sludge handling and dewatering equipment is not included.

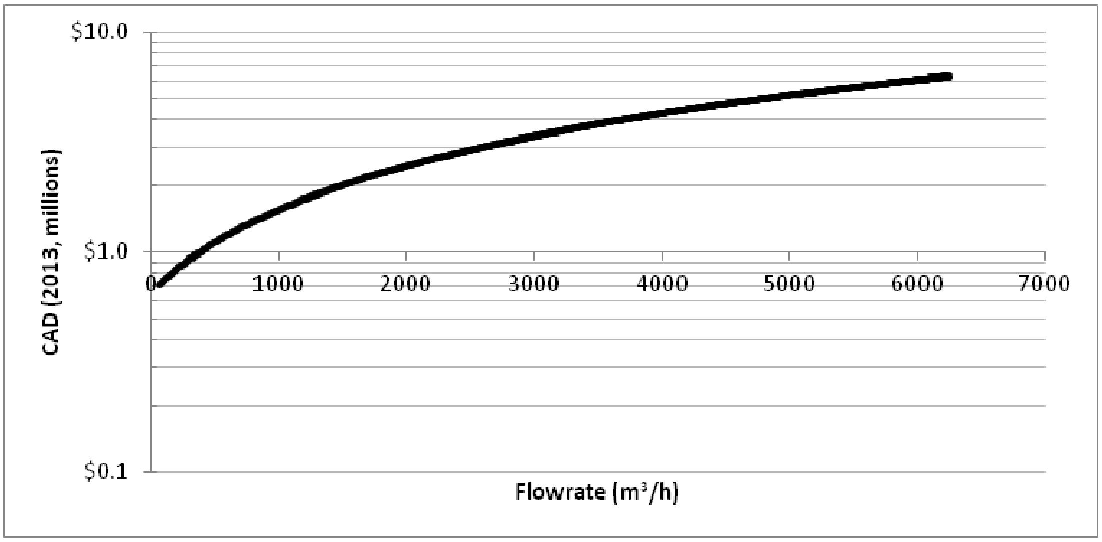

Figure 8-9: Equipment Costs for ACTIFLO® Systems

Operating

Reagent consumption is proportional to effluent flow rate. Jar testing is recommended to verify dosage. Table 8-18 summarizes ECS reagent costs.

Table 8-18: ECS Reagent Costs and Typical Dosages[47]

Reagent	Format	Cost (CAD$/kg)	Typical Dosage
Ferric sulfate (coagulant)	50 - 66 wt% solution	\$0.20 - \$0.60	15 mg-Fe/L
Flocculant	dry, powder	\$3.00 - \$10.00[48]	1 mg/L
	15 - 40 wt% solution	\$3.70 - \$8.73	1 mg/L
Microsand			typical loss of 1-2 g/m^3 treated

Power consumption is proportional to treatment flow rate, sludge density and concentration and technique for agitation, rake mechanism, and pumping equipment.

Operating labour requirements for ECS systems are minor for process monitoring adjustment of reagent dosages, make-up of microsand, and adjustment of sludge recycle/waste. More operator attention is required to accommodate changes in feed chemistry, TSS, and flow rate. It is assumed that no more than one hour of operator attention is required per day for this process; however, it is highly dependent on the availability of equalization in front of these

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[47] Delivered costs reported via operations questionnaire except where otherwise noted.

[48] A few sites reported dry, powdered flocculant costs exceeding \$8.50/kg, though at one of them the cost is likely inflated due to delivery costs to Nunavut.

technologies. Annual plant maintenance is moderate. ACTIFLO® systems may have higher maintenance demands as the apex component of hydrocyclones may require frequent replacement. Veolia estimates an annual plant maintenance requirement of 150 h.

Several Hatch studies have evaluated the operating costs associated with conventional clarification against ECS systems, and while both technologies have comparable chemical and operating labour requirements, conventional clarifiers have much larger rake mechanisms than ECS systems, and therefore have higher power demand. For example, when compared to a conventional clarifier, the operating costs of an ACTIFLO® system were estimated to be 7% lower as a result of the energy savings for raking. It has also been reported by vendors that the amount of chemical, in particular flocculant, may be significantly reduced for ECS systems.

Veolia estimates an operating cost of CAD\$0.11/m^3 for coagulant, flocculant polymer, microsand, power at CAD\$0.08/kWh, and spare parts. Operating and maintenance labour and sludge handling and disposal are excluded from this estimate.

8.2.9 *Cyanide Destruction*

The following discusses active cyanide destruction processes. For passive cyanide destruction, see also Section 8.2.16.1.

8.2.9.1 *INCO SO_2/Air*

The INCO SO_2/Air process is used to destroy cyanide via oxidation of free and weak acid dissociable (WAD) cyanide, and via precipitation of strong acid dissociable (SAD) cyanide as base metal-iron-cyanide complexes. The INCO SO_2/Air process is most commonly used to treat tailings slurries, but is also used to treat effluent. The process utilizes sulfur dioxide (SO_2) and oxygen (from air) in the presence of copper catalyst to oxidize cyanide to cyanate, according to the following generic reactions:

$$SO_2 + O_2 + H_2O + CN^- \overset{Cu^{2+}\text{ catalyst}}{\leftrightarrow} OCN^- + SO_4^{2-} + 2H^+$$

$$4SO_2 + 4O_2 + 4H_2O + Me(CN)_4^{2-} \overset{Cu^{2+}\text{ catalyst}}{\leftrightarrow} 4OCN^- + 4SO_4^{2-} + 8H^+ + Me^{2+},$$

$$SO_2 + 2O_2 + 2Fe(CN)_6^{3-} \leftrightarrow SO_4^{2-} + 4H_+ + 2Fe(CN)_6^{4-}$$

$$2Me^{2+} + 2Fe(CN)_6^{4-} \leftrightarrow Me_2Fe(CN)_6(s)$$

CN^- represents free cyanide, $Me(CN)_4^{2-}$ represents WAD cyanide, $2Fe(CN)_6^{3-}$ represents SAD cyanide, and Me^{2+} represents a divalent cationic dissolved metal (specifically, copper, nickel, or zinc) (16). The process may be optimized to preferentially treat WAD or SAD cyanide depending on equipment configuration, operating pH, and copper catalyst dosage.

Thiocyanate may be oxidized to a limited extent in the presence of nickel catalyst, according to the following reaction:

$$SCN^- + 4SO_2 + 4O_2 + 5H_2O \leftrightarrow OCN^- + 5SO_4^{2-} + 10H_+$$

Cyanate generated from the various cyanide and thiocyanate oxidation reactions then hydrolyzes to ammonia, according to the following reaction:

$$OCN^- + H^+ + 2H_2O \leftrightarrow HCO_3^- + NH_4^+$$

Sulfur dioxide can be provided as liquid sulfur dioxide or generated from sodium sulfite (Na_2SO_3) or sodium metabisulfite ($Na_2S_2O_5$). Sulfur may also be provided via sulfur burner using sulfur prill. Reagent selection is site-specific and dependent on reagent costs and availability. Oxygen is provided via air sparging into the reaction tank. Copper catalyst is provided as hydrated copper sulfate ($CuSO_4{\cdot}H_2O$) if insufficient background copper is available in the effluent.

The reaction is carried out at alkaline pH (typically 8.3 to 10.5). The pH target and neutralization of hydrogen ions generated by the reaction are achieved via lime addition. The high pH and liberation of complexed metals from metal cyanide complexes allows for the precipitation of dissolved metals as metal hydroxides (see Section 8.2.1). The pH target must balance both cyanide destruction and metals precipitation. The precipitates are separated from the treated effluent via solid/liquid separation technologies. Prior to solid/liquid separation, coagulation and flocculation may be used to agglomerate the metal hydroxide precipitates. The decant stream may require additional polishing or filtration to meet TSS discharge limits and reduction of pH/reacidification to meet pH discharge limits. Due to the generation of ammonia via cyanate hydrolysis, downstream ammonia removal may be required to meet ammonia discharge limits, if any, and/or pH adjustment may be required to reduce the fraction of ammonia present as un-ionized ammonia to meet toxicity requirements.

Typical achievable concentrations from INCO SO_2/Air cyanide destruction are summarized in Table 8-19 and are dependent upon the feed concentration of CN and overall composition of the stream.

Table 8-19: Typical Achievable Concentrations INCO SO_2/Air Cyanide Destruction

Parameter	Achievable Concentration (mg/L)	Reference
CN_{total}	<5	(16)

Minor variations in effluent quality and flow rate can be managed by modifications to reagent dosing regimes; however, major variations in loadings can cause insufficient reaction/detention and sedimentation times, negatively affecting treated effluent quality.

Variations in temperature have little effect on process performance; however, as with all effluent treatment systems, freezing must be prevented. Depending on climate, systems may be installed indoors with climate control, or outdoors with adequate insulation and heat tracing.

A patented variation of the INCO SO_2/Air process, the CombinOx® process, utilizes both sulfur dioxide and hydrogen peroxide to generate the same end products as the INCO SO_2/Air process, and claims to have lower capital cost, lower operating cost, and greater ability to handle variations in effluent quality and quantity (cyanide loading).

Residuals

Base metal-iron-cyanide and metal hydroxide precipitates are generated in the INCO SO_2/Air cyanide destruction process. Sludge quantity and characteristics depend on effluent quality, pH, and flow rate. Sludge is typically disposed of in on-site features including tailings storage facilities, engineered dewatering ponds, open pits, underground mine workings, co-disposal with waste rock, etc. Sludge may be mechanically dewatered (i.e., via filter press or centrifuge) prior to disposal. At some environmentally-sensitive sites or sites with limited disposal area, off-site sludge disposal may be required.

Major Equipment

- Reagent make-up/storage systems and feed systems.
- Agitated reaction tank(s), if required.
- Air compressor/blower.
- Diffuser(s).
- Clarifier/thickener(s), if required.
- Media filter, if required.
- Residuals management equipment (e.g., underflow tank, pumps to disposal, mechanical dewatering equipment), if required.

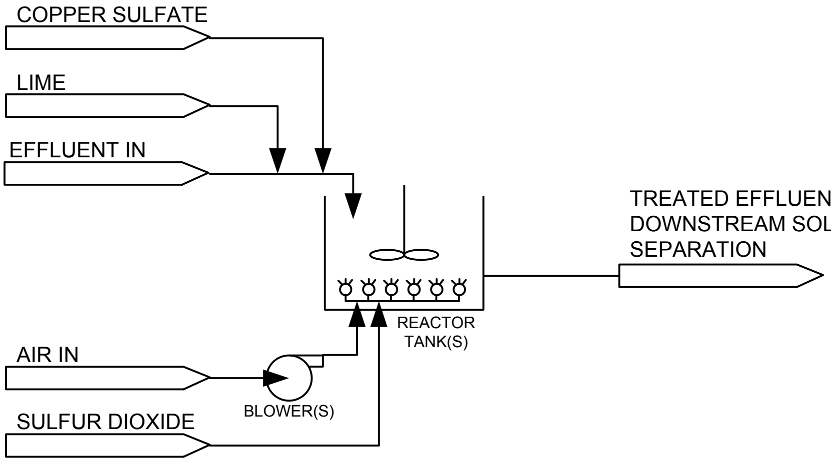

Figure 8-10: Simplified INCO SO_2/Air Cyanide Destruction Process Flow Diagram

Synergies and Challenges

The INCO SO_2/Air process is well established for the destruction of cyanide in effluent from Canadian mining operations. It can be utilized on slurry based effluents. The process removes free, WAD, and SAD cyanide from effluent and may remove a small fraction of SCN^-.

Challenges associated with INCO SO_2/Air cyanide destruction include:

- Equalization of flows and/or loadings is required for stable operation of coagulation technology.
- Addition of copper catalyst may cause non-compliance with copper limit if not adequately precipitated and separated from effluent. One precious metal operation in Quebec reported an alternative hydrogen peroxide process which utilizes silicon dioxide as a catalyst for cyanide destruction in place of copper catalyst; however, the operation also appears to have sufficiently high background dissolved copper to act as a catalyst.
- Generation of sulfate may be undesirable, depending on downstream processes or receiving bodies.
- Generation of ammonia may cause non-compliance with potential future ammonia limit as well as toxicity issues if not managed.
- Downstream pH adjustment may be required to meet discharge limits.
- Retention time may vary between 30 minutes and 2 hours; at minimum, bench-scale testing is recommended to determine required retention time.

Relative Prevalence in Industry

The INCO SO_2/Air process is well established for the destruction of cyanide in effluent from Canadian mining operations. The CombinOX® process was planned for, but not installed at, a precious metal operation in Quebec.

Costs

Capital

Capital costs are proportional to effluent pH, quality, flow rate, and reactor retention time.

Operating

Reagent consumption is proportional to effluent pH, quality (cyanide concentration and dissolved copper concentration), and flow rate. Table 8-20 summarizes reagent costs and typical dosages. Background concentrations of dissolved copper may offset copper catalyst dosage/demand and reduce operating costs. At minimum, bench-scale testing is recommended to determine reagent dosages.

Table 8-20: INCO SO_2/Air Cyanide Destruction Reagent Costs[49]

Reagent	Format	Cost (CAD$/kg)	Typical Dosage
Sulfur dioxide	liquid	$0.60	3-5 g SO_2/g CN_{WAD}
Sodium metabisulfite	dry	$1.00	
Copper sulfate hydrate	dry	$2.90 - $4.62	10-50 mg Cu^{2+}/L
Oxygen	air	n/a	to maintain > 4 mg/L
Limestone	dry	$0.01 - $0.05 (38)	to target pH
Quicklime	dry	$0.19 - $0.26	to target pH
Hydrated Lime	dry	$0.17 - $0.30	to target pH

8.2.9.2 *Hydrogen Peroxide*

Hydrogen peroxide is used to destroy cyanide in solutions (i.e., not tailings slurries) via oxidation of free and weak acid dissociable (WAD) cyanide and via precipitation of strong acid dissociable (SAD) cyanide as base metal-iron-cyanide complexes in the presence of copper catalyst, according to the following generic reactions:

$$H_2O_2 + CN^- \overset{Cu^{2+}\text{ catalyst}}{\leftrightarrow} OCN^- + H_2O$$

$$4H_2O_2 + Me(CN)_4^{2-} \overset{Cu^{2+}\text{ catalyst}}{\leftrightarrow} 4OCN^- + 4H_2O + Me^{2+}$$

$$2Me^{2+} + 2Fe(CN)_6^{4-} \leftrightarrow Me_2Fe(CN)_6(s)$$

CN^- represents free cyanide, $Me(CN)_4^{2-}$ represents WAD cyanide, $2Fe(CN)_6^{4-}$ represents SAD cyanide, and Me^{2+} represents a divalent cationic dissolved metal (specifically, copper, nickel, or zinc) (16).

Although not routinely practiced, thiocyanate may be oxidized to a limited extent, according to the following reaction:

$$SCN^- + 5/2H_2O_2 \leftrightarrow OCN^- + SO_4^{2-} + 5H^+$$

Cyanate generated from the various cyanide and thiocyanate oxidation reactions then hydrolyzes to ammonia, according to the following reaction:

$$OCN^- + H^+ + 2H_2O \leftrightarrow HCO_3^- + NH_4^+$$

Excess hydrogen peroxide decomposes to oxygen and water, which does not add total dissolved solids to the treated effluent, unlike the INCO SO_2/Air process which generates sulfate.

Hydrogen peroxide is provided as a concentrated solution. Copper catalyst is provided as hydrated copper sulfate solution ($CuSO_4 \cdot H_2O$) if insufficient background copper is available in the effluent.

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[49] Delivered costs reported via operations questionnaire except where otherwise noted.

The reaction is carried out at alkaline pH. The pH target and neutralization of hydrogen ions generated by the reaction are commonly achieved via lime addition. The high pH and liberation of complexed metals from metal cyanide complexes allows for the precipitation of dissolved metals as metal hydroxides (see Section 8.2.1). The pH target must balance both cyanide destruction and metals precipitation. The precipitates are separated from the treated effluent via solid/liquid separation technologies. Prior to solid/liquid separation, coagulation and flocculation may be used to agglomerate the metal hydroxide precipitates. The decant stream may require additional polishing or filtration to meet TSS discharge limits and reduction of pH/reacidification to meet pH discharge limits. Due to the generation of ammonia via cyanate hydrolysis, downstream ammonia removal may be required to meet ammonia discharge limits, if any, and/or pH adjustment may be required to reduce the fraction of ammonia present as un-ionized ammonia to meet toxicity requirements.

Typical achievable concentrations from hydrogen peroxide cyanide destruction are summarized in Table 8-21.

Table 8-21: Typical Achievable Concentrations from Hydrogen Peroxide Cyanide Destruction

Parameter	Achievable Concentration (mg/L)	Reference
CN_{total}	<1	(16)

Minor variations in effluent quality and flow rate can be managed by modifications to reagent dosing regimes; however, major variations in loadings can cause insufficient reaction/detention and sedimentation times, negatively affecting treated effluent quality.

Variations in temperature have little effect on process performance; however, as with all effluent treatment systems, freezing must be prevented. Depending on climate, systems may be installed indoors with climate control, or outdoors with adequate insulation and heat tracing.

Residuals

Base metal-iron-cyanide and metal hydroxide precipitates are generated in the hydrogen peroxide cyanide destruction process. Sludge quantity and characteristics depend on effluent quality, pH, and flow rate. Sludge is typically disposed of in on-site features including tailings storage facilities, engineered dewatering ponds, open pits, underground mine workings, co-disposal with waste rock, etc. Sludge may be mechanically dewatered (i.e., via filter press or centrifuge) prior to disposal. At some environmentally-sensitive sites or sites with limited disposal area, off-site sludge disposal may be required.

Major Equipment

- Reagent make-up/storage systems and feed systems.
- Agitated reaction tank(s), if required.
- Clarifier/thickener(s), if required.
- Media filter, if required.

- Residuals management equipment (e.g., underflow tank, pumps to disposal, mechanical dewatering equipment), if required.

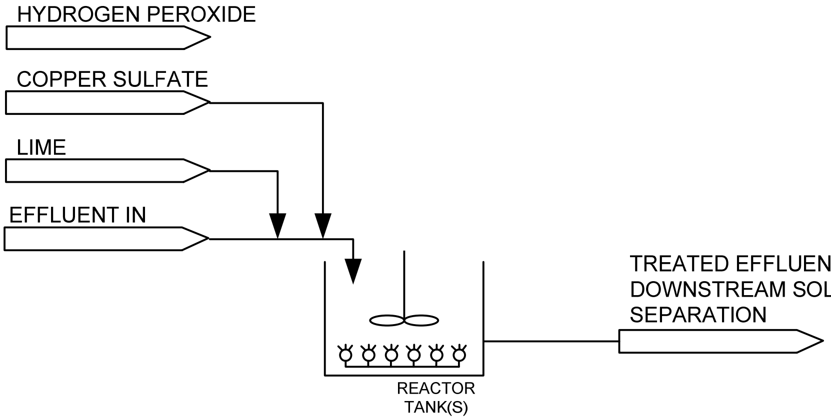

Figure 8-11: Simplified Hydrogen Peroxide Cyanide Destruction Process Flow Diagram

Synergies and Challenges

Hydrogen peroxide cyanide destruction is well established for the destruction of cyanide in effluent from Canadian mining operations. The process removes free, WAD, and SAD cyanide from effluent and may remove a small fraction of SCN^- while not adding total dissolved solids to the treated effluent.

Challenges associated with hydrogen peroxide cyanide destruction include:

- Equalization of flows and/or loadings is required for stable operation.
- Addition of copper sulfate catalyst may cause non-compliance with copper limit if not adequately precipitated and separated from effluent. Addition of sulfate may be undesirable, depending on downstream processes or receiving bodies.
- Generation of ammonia may cause non-compliance with potential future ammonia limit as well as toxicity issues if not managed.
- Downstream pH adjustment may be required to meet discharge limits.
- Retention time may vary between 30 minutes and 3 hours; at minimum, bench-scale testing is recommended to determine required retention time.

Relative Prevalence in Industry

Hydrogen peroxide cyanide destruction is well established for the destruction of cyanide in effluent from Canadian mining operations. Hydrogen peroxide is also used at some Canadian mining operations for the oxidation of metals and thiosalts.

Costs

Capital

Capital costs are proportional to effluent pH, quality, flow rate, and reactor retention time.

Operating

Reagent consumption is proportional to effluent pH, quality (cyanide and thiocyanate concentration), and flow rate. Table 8-22 summarizes reagent costs and typical dosages. At minimum, bench-scale testing is recommended to determine reagent dosages.

Table 8-22: Hydrogen Peroxide Cyanide Destruction Reagent Costs[50]

Reagent	Format	Cost (CAD$/kg)	Typical Dosage
Hydrogen peroxide	50 wt% solution	\$0.45 - \$1.70	5 g H_2O_2/g CN_{WAD}
	70 wt% solution	\$0.69 - \$1.23	
Copper sulfate hydrate	dry	\$2.90 - \$4.62	10-50 mg Cu^{2+}/L
Limestone	dry	\$0.01 - \$0.05 (38)	to target pH
Quicklime	dry	\$0.19 - \$0.26	to target pH
Hydrated Lime	dry	\$0.17 - \$0.30	to target pH

8.2.10 Air Stripping

Process Description

Air stripping may be used to volatilize un-ionized ammonia gas (NH_3) from effluent at alkaline pH. The proportion of total ammonia available to be removed as un-ionized ammonia is pH and temperature dependent, with the most efficient ammonia removal achieved at pH greater than 11.5.

$$NH_4^+ + OH^- \leftrightarrow NH_3(g) + H_2O$$

The effluent is pH adjusted, typically with lime or sodium hydroxide, and then pumped to the top of a tower(s) and distributed evenly across the tower(s). Typically atomizing spray nozzles distribute the effluent droplets evenly across the tower(s). As the effluent droplets fall by gravity through a bed of packing, ambient or heated air is blown counter-current to the effluent flow. The tower(s) contains packing which provide surface area for mass transfer. Un-ionized ammonia gas is stripped from the effluent to the air (59). Then, the pH of the effluent is re-adjusted to meet discharge limits, typically with carbon dioxide, prior to discharge.

Systems are designed to achieve a specified ammonia removal efficiency. However, the typical lower achievable limit for ammonia is 3 mg-N/L. The process efficiency is highly sensitive to variation in effluent and ambient temperatures. Ammonia solubility decreases and the proportion of total ammonia as un-ionized ammonia increases as feed temperature increases. For example, at 20 °C, typical removal efficiency of 90 to 95% can be achieved, while at 10 °C, removal efficiency falls to 75%. Fogging and icing also impede ammonia removal by decreasing the rate of mass transfer of ammonia from effluent to air. As such, pre-heating of effluent and/or air, and/or seasonal operation may be required.

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[50] Delivered costs reported via operations questionnaire except where otherwise noted.

The air stripping process is best suited to total ammonia concentrations in the range of 10 to 100 mg-N/L, but is otherwise relatively insensitive to variations in effluent quality. However, pre-treatment for total suspended solids may be required to counter plugging of the stripping tower packing and treatment for hardness, iron, manganese, phosphate, and microorganisms may be required to counter scaling/fouling of the stripping tower and packing. Minor variations in flow can be managed provided they do not exceed the system process design.

Residuals

Air stripping is a mechanical process that creates no residual stream. Scale may be occasionally removed via hydraulic cleaning processes and disposed of according to chemical composition.

Major Equipment

- Upstream solid/liquid separation system, if required.
- Heating and heat exchange system, if required for cold weather operation. Heat exchange systems may include burners, air/effluent heat exchangers, and effluent/treated effluent heat exchangers (for energy recovery).
- Reagent make-up/storage systems (e.g., lime silo and slaker, sodium hydroxide storage tank, carbon dioxide gas storage tank, sulfuric acid storage tank, etc.) and feed apparatus (e.g., dosing pumps, diffusers).
- pH adjustment tank.
- Pumps (feed and discharge).
- Stripping tower(s) (complete with packing, demister, distributors, enclosure, clearwell, and blowers).
- Off-gas treatment/scrubbing tower(s), if required (e.g., for ammonia capture in sensitive airsheds, for energy conservation during cold weather operation).

Figure 8-12 illustrates a simplified air stripping process. Heating and heat exchange systems and reagent make-up/storage and dosing systems are not shown.

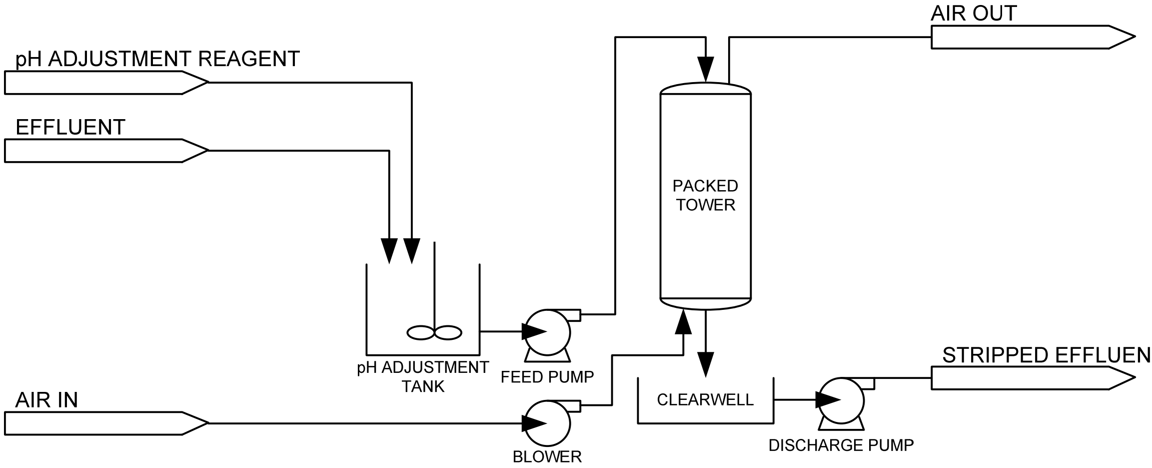

Figure 8-12: Simplified Air Stripping Process Flow Diagram

Synergies and Challenges

Air stripping can be employed synergistically with hydroxide precipitation.

Challenges associated with air stripping include:

- High energy costs associated with pre-heating effluent/air, pumping effluent to top of tower, and tower blowers.
- High maintenance requirements due to scaling and fouling of stripping tower packing.
- Ammonia discharge to atmosphere, even at low concentrations, may be unacceptable in some airsheds or under some permits. If this is the case, off-gas treatment/scrubbing may be required, which adds to treatment complexity and costs.
- Equalization of flows and/or loadings is required for stable operation of air stripping technology.
- Downstream pH adjustment is required to meet discharge limits. pH adjustment reagents may add total dissolved solids (e.g., sulfate, chloride) into effluent, which may be undesirable, depending on downstream processes or receiving bodies.

Relative Prevalence in Industry

Air stripping is utilized year-round at a precious metal operation in Quebec to remove ammonia from underground mine dewatering effluent. Prior to stripping, the effluent is equalized, filtered to remove TSS, and the pH is adjusted to 11.5 with sodium hydroxide. After the effluent passes through the stripping tower and before it is discharged to the environment, the pH is decreased via carbon dioxide injection. The operation achieves less than 50% ammonia removal efficiency during winter periods due to low air temperatures. To counter this, the operation increases operating pH and heats the stripping air with natural gas, leading to increased operating costs. The operation also experiences carbonate scaling of the stripping tower and packing, which increases maintenance costs.

Air stripping is also utilized year-round at a precious metal operation in Quebec to remove ammonia from effluent between two stages of aerobic biological oxidation.

A small scale air stripping system was installed at a uranium operation in Saskatchewan for ammonia removal from groundwater.

Air stripping equipment is also included in the Certificate of Approval for a base metal mine in Ontario to remove ammonia from spent regenerant from an ion exchange ammonia removal system, but there is uncertainty over whether the combined ion exchange and stripping system is currently in operation; the operation may have achieved compliance with ammonia limits via alternate technologies and techniques, such as the use of an explosives best management plan.

Costs

Capital

The bulk of the capital cost data reviewed for ammonia stripping equipment for this study varied widely between CAD$6,750 and CAD$20,000 per m^3/h of installed capacity. One operation provided an example of a small scale stripping process to remove ammonia from groundwater with a unit capital cost of approximately CAD$88,250 per m^3/h of installed capacity. The data was taken from in-house cost data and cost data reported in operations questionnaires. At the higher end of the range is a complete system including equalization, filtration, pH adjustment tank, reagent storage and dosing system, stripping towers, clearwells, blowers, forwarding pumps, and carbon dioxide storage and injection system.

Operating

Power consumption for effluent pumping and air blowing represents the largest portion of air stripping operating costs, and is proportional to tower dimensions, which are determined by feed total ammonia concentration, required removal efficiency, flow rate, and effluent and air temperature. One operations questionnaire respondent reported a range of CAD\$0.57/m^3 to CAD\$1.14/m^3 treated for two different systems; however, for one of the systems the figures include operating costs for related MBBR systems. Cost estimates for another operation ranged from CAD\$0.49/m^3 (for a 45,000 m^3/d system operating during summer months only) to CAD\$4.38/m^3 treated (for a 5,000 m^3/d system operating during summer months only) (60). However, these costs assumed that air emissions control would be required and accounted for sulfuric acid demand for scrubbing.

Reagent consumption is proportional to feed pH, feed temperature, treated effluent pH limit, and flow rate.

Operator attention requirements are low for this process, with reagent refill as required and regular process monitoring and equipment inspection. It is assumed that no more than one hour of operator attention is required per day for this process.

The tower must be periodically inspected for scaling/fouling and cleaned (e.g., hydraulic cleaning, chemical cleaning).

8.2.11 Ion Exchange

8.2.11.1 Selective Ion Exchange Polishing

Process Description

Ion exchange (IX) is the adsorption of ions of a given charge (either cation or anion) in a solution onto the surface of a solid material (ion exchange resin) and replacement in the solution by an equivalent quantity of ions of similar charge from the solid material surface. The resin is insoluble in water but hydrated and may be a salt, acid or base. Resins are formed through a polymerization process and functional groups added in various activation methods. A wide variety of functional groups can be grafted onto these polymers which are then used to selectively uptake ions, principally metals. The functional groups of the polymers are initially associated with ions such as sodium (Na^+), hydrogen (H^+), chloride (Cl^-), and hydroxide (OH^-). The functional groups and resin polymer dictate what ions can be exchanged by the resin. Many resins are designed to target and selectively remove one or only a few parameters. To achieve the removal of a wide suite of parameters, several ion exchange steps in series, each with a specialized resin to target certain parameters may be required.

As the effluent passes through the column, functional group associated ions are displaced from the resin by the targeted ions due to the higher affinity of the resin for the targeted ions (e.g., Ni^{2+} Cu^{2+} or other multivalent metals, and ammonia depending on the resin employed) than for the functional group associated ions. The targeted parameters are immobilized onto the resin and the functional group associated ions are released into the effluent exiting the column. The generic exchange chemistry is represented below, where T is the target ion, R is the resin functional group and Na^+ and Cl^- are the ions originally associated with the resin functional groups, though these could also be OH^- or H^+ ions.

$$\text{Cationic exchange resin: } T^{2+} + R\text{-}Na^{+} \leftrightarrow R\text{-}T^{2+} + 2Na^{+}$$

$$\text{Anionic exchange resin: } T^{2-} + R\text{-}Cl^{-} \leftrightarrow R\text{-}T^{2-} + 2Cl^{-}$$

When resins become saturated with the targeted ions, they are regenerated by passing concentrated solution(s) (“regenerant”) containing the replaced ions (e.g., NaOH, H_2SO_4, NaCl, HCl) through the column. Spent regenerant exits the column with the targeted ions in solution and may require further treatment prior to permanent disposal. The column is then flushed to remove residual regenerant, and effluent treatment can re-commence.

Traditionally, the ion exchange process is utilized to polish a pre-treated, weakly acidic or weakly basic effluent stream by passing it through vessels (“columns”) containing a selective resin. Resins are selected based on their affinity for certain metals and their capacity. Unlike traditional strong acid cation resins with sulfonic functional groups, selective ion exchange affinity for cations is not based on increasing charge or increasing atomic number; the preferential affinity is dependent on the specific resin, and effluent chemistry and most importantly pH (a property which is exploited to regenerate the resin).

The following compares the affinity of Lewatit® MonoPlus SP 112 which is a strong acidic, macroporous cation exchange resin based on a styrene-divinylbenzene copolymer with that of Lewatit® TP 207, a weakly acidic, macroporous cation exchange resin with chelating iminodiacetate groups for the selective uptake of heavy metal cations.

Lewatit® SP 112 Affinity

Barium > Lead > Strontium > Calcium > Nickel > Cadmium > Copper > Cobalt > Zinc > Iron(II) > Magnesium > Potassium > Ammonium > Sodium > Hydrogen .

Lewatit® TP 207 Affinity

Copper > Vanadium > Uranium > Lead > Nickel > Zinc > Cadmium > Iron(II) > Beryllium > Manganese > Calcium > Magnesium > Strontium > Barium >>> Sodium.

The removal efficiency of ion exchange columns is highly dependent on the selected resin and the effluent chemistry. Resins have been reported to achieve removal efficiencies of over 90% for targeted metal ions with removal efficiencies of over 99% reported in literature for arsenic, copper, lead and nickel. However, in treatment of complex effluents with many ions competing for functional sites on the resin, removal efficiencies may be significantly lower. To significantly reduce the concentrations of a number of different parameters in complex effluents, multiple ion exchange steps in series using a number of different resins that selectively remove parameters of concern may be required. The use of a single resin and single step may not achieve high removal efficiencies of all parameters of concern.

Ion exchange for selenium removal was reviewed in a CH2M Hill report, *Review of Available Technologies for the Removal of Selenium from Water* (44). This report found examples of removal of selenium to 0.001 - 0.1 mg/L by ion exchange. Data provided by vendor questionnaire suggest that selenium concentrations as low as 0.01 mg/L have been demonstrated by ion exchange on mine effluent. Selenium-containing effluent often also contains sulfate at much higher concentrations than selenium. As most ion exchange resins selectively remove sulfate before selenium, all sulfate must be removed before selenium is removed. Thus, the presence and concentration of sulfate in effluent has a major impact on the economics of ion exchange for selenium removal, as it impacts system sizing and regeneration frequency. Because of this, ion exchange is not typically economically achievable for selenium removal from mining effluent (61).

Reported achievable effluent concentrations are summarized in Table 8-23. In compiling this table, reported discharge effluent qualities from operations questionnaires, literature values, other treatment review reports and information provided by vendor Lanxess Sybron were reviewed.

Table 8-23: Reported Achievable Concentrations from Use of Selective Ion Exchange

Parameter	Reported Achievable Concentration (mg/L)	Reference
Al	<0.05	Operations Questionnaires
As	<0.005	Operations Questionnaires
Cu	<0.03	Operations Questionnaires
Fe	<0.2	Operations Questionnaires
Pb	<0.02	Operations Questionnaires
Mn	<0.5	Operations Questionnaires
Ni	<0.01	Operations Questionnaires
Se	<0.01	(44)
Zn	<0.02	Operations Questionnaires

It should be noted that the achievable concentrations reported in Table 8-23 cannot be achieved simultaneously, as resins are ion-selective. To achieve removal of multiple ions, several ion exchange systems in series may be required.

The performance of ion exchange columns is affected by the presence of organic substances (which can foul the resins), suspended solids (which result in high pressure drop causing resin attrition), low solubility ions (e.g., calcium, sulfate, aluminum) and competing ions in the feed. Competing ions are resin and targeted ion specific, and compete with targeted ions for active sites on the resin. The presence of oxidizing agents (e.g., hydrogen peroxide) degrade the resin via attack on resin polymer cross-linking.

Ion exchange may also be used to pre-concentrate specific contaminants for bulk removal with more efficient processes (e.g., pre-concentration of a specific metal prior to bulk removal via hydroxide precipitation).

Ion exchange can tolerate variations in feed quality and temperature with minimal effect on effluent quality, but has limited capacity to tolerate variations in flow rate outside of design parameters. Equalization of flows is required for stable operation of ion exchange technology.

Residuals

The spent regenerant solutions, after being used to regenerate the resin, are the main residuals produced by the use of ion exchange in an effluent treatment process. These solutions contain the targeted ions (e.g., metals, ammonia, selenium) at pH and concentrations which are not suitable for release to the environment and thus require further management. These solutions can be neutralized (optimally via mixing of spent cationic resin regenerant and spent anionic resin regenerant) and then ultimately managed by:

- Conventional treatment (e.g., hydroxide precipitation, sulfide precipitation), either in a downstream treatment step or by return to the feed of an upstream treatment process, followed by sludge dewatering and disposal in an isolated storage facility.
- Evaporation, crystallization, and drying to produce a solid waste to be disposed of via landfill or hazardous waste disposal.
- For selenium removal systems, spent regenerant could be treated by biological treatment processes or ZVI adsorption (see Section 8.2.12.1).

Ion exchange resins will degrade over time and thus typically require replacement over the operational life of the system. Cationic resins require replacement approximately every 10 years, while anionic resins require replacement more frequently, every 4 to 5 years. The resin must be disposed of, either via landfilling or return to the vendor.

Major Equipment

Pre-treatment may be required to control fouling and to minimize damage to the resins, depending on what treatment comprises the upstream process. At a minimum, treatment for suspended solids would be required to minimize pressure drop between regeneration cycles. If packed bed technology is utilized, filtration of solids becomes more important since this technology does not have a backwashing step in its regeneration cycle.

The major equipment for ion exchange system is as follows:

- Feed and treated effluent pumps, as necessary.
- Ion exchange columns.

- Resin(s).
- Regenerant chemical totes/tanks and dosing pumps.
- Feed, spent regenerant, and treated effluent tanks, as necessary.

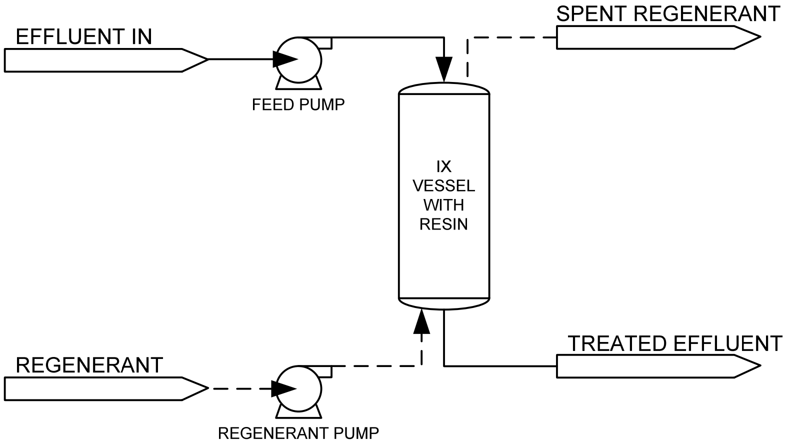

Figure 8-13: Simplified Ion Exchange Process Flow Diagram

Synergies and Challenges

Selective ion exchange can be employed following chemical and physical bulk removal processes (e.g., hydroxide or sulfide precipitation, ferrous hydroxide co-precipitation and adsorption) as a polishing step to achieve low effluent concentrations. Alternatively, it could be used a pre-treatment step to generate a lower volume and higher concentration stream to reduce the capital cost and removal efficiency of treatment by other means.

Challenges associated with selective ion exchange include:

- Ion exchange capacity loss is experienced year over year. It is important to understand and manage the capacity loss in order to account for the increased operational costs associated with resin replacement. Capacity loss comes from attrition, oxidation, irreversible fouling (organics etc.), and age.
- Management and disposal of spent regenerant is site-specific and must be considered carefully; spent regenerant treatment equipment can add significant capital and operating costs.
- Achieving high removal efficiencies may be difficult depending on target parameters and effluent chemistry (e.g., pH and the presence of competing ions may lower removal efficiencies).
- Scale formation on resin, which may be an especially significant issue when considering mining effluents in which low solubility species such as calcium and sulfate (which together form gypsum) are frequently present.
- Fouling by organic compounds (oil and grease).
- Equalization of flows is required for stable operation of ion exchange technology.

Relative Prevalence in Industry

A base metal mine in Manitoba and a precious metal mine in Ontario reported active use of selective ion exchange for mine effluent treatment through the operations questionnaire. These operations employ selective ion exchange for metals polishing. One operation uses ion exchange as a polishing step following conventional bulk removal treatment processes, and the other uses only ion exchange in the treatment of their mine effluent for metals removal. No additional operations utilizing selective ion exchange were identified during independent research efforts.

Historically, discharge limits have not necessitated the use of this technology on effluents; however, it is frequently used for water softening and other uses at mining and mineral processing sites and thus is a familiar technology.

Costs

Capital

Capital cost data reviewed for ion exchange equipment for this study fell between CAD$2,000 and CAD$6,000 per m^3/h of installed capacity (m^3/h of feed basis). The data was taken from in-house cost data, vendor supplied data, and questionnaire responses. Some of the quotations reviewed included spent regenerant treatment, including dewatering equipment, and start-up and commissioning costs, etc.; these quotes represent the higher values in the range.

Sustaining Capital

Resin replacement costs are proportional to vessel size, which is proportional to effluent quality and flow rate. Resin replacement frequency depends on resin type and feed quality. Resins costs are typically between CAD$2 and CAD$20 per litre.

Operating

Reagent consumption is proportional to feed quality; higher concentrations of target and competing ions saturate the resin more quickly and accordingly the resin must be regenerated more often. Typical regenerant chemicals are NaOH, H_2SO_4, NaCl and HCl.

Power consumption is required for feed and effluent pumping, and is proportional to total flow rate through the system.

Ion exchange systems are largely automated, requiring several hours of dedicated operator attention per day and monitoring on a continuous basis. Full operator attention is required during regeneration, the frequency of which depends on effluent chemistry.

Monthly maintenance may be required for mechanical upkeep. Annual maintenance would be required for thorough system cleaning and equipment replacement as necessary.

Operating cost data reviewed range between CAD$0.30 and CAD$0.70 per m^3 treated.

8.2.11.2 *Clinoptilolite Zeolite Ion Exchange*

Process Description

Zeolites are a family of naturally-occurring crystalline hydrated aluminosilicates that have high ion-exchange capacities and high specific-surface area, and demonstrate an affinity for cations, especially ammonium ions (NH_4^+). A type of zeolite called clinoptilolite has been identified as particularly suitable for ammonium removal, due to its high ammonium selectivity, adsorptive capacity and performance at low temperatures (62).

This material is utilized for the removal of ammonia (in dissolved form as ammonium) from effluent in the same manner as a synthetic ion exchange resin: naturally occurring cations affixed to the zeolite crystals (frequently sodium, calcium, potassium, and magnesium in virgin zeolite) are exchanged for ammonium ions in effluent as it passes through the zeolite, due to the higher affinity of the zeolite for ammonium than for many other cations.

The cation selectivity of zeolite is as follows:

$$\mathrm{Cs^{+} > Rb^{+} > K^{+} > NH4^{+} > Ba^{2+} > Sr^{2+} > Na^{+} > Ca^{2+} > Fe^{3+} > Al^{3+} > Mg^{2+}} \quad (63)$$

The operation and maintenance of a zeolite exchange process is essentially the same as the selective ion exchange systems (see Section 8.2.11.1). Ammonium is removed from effluent by cation exchange until the zeolite is saturated, at which point the zeolite is regenerated with a salt solution at elevated pH to displace ammonium ions; the regenerant can be a solution of one of the following salts: sodium chloride (NaCl), sodium hydroxide (NaOH), potassium chloride (KCl), sodium nitrate ($NaNO_3$), sodium sulfate (Na_2SO_4), calcium chloride ($CaCl_2$), calcium carbonate ($CaCO_3$) or calcium hydroxide ($Ca(OH)_2$). This process generates a spent regenerant which must be managed.

The performance of ion exchange columns is dependent on a number of factors including the zeolite purity and its surface area, the Si/Al ratio, the ammonium feed concentration and effluent requirement, temperature, pH, the presence of competing cations (e.g., potassium). number of regenerant cycles, and the presence of suspended solids. Several of these factors are elaborated on below:

- The silica:alumina ratio impacts the net charge of the zeolite compound and thus its cation exchange ability. Higher silica:alumina ratios in the zeolite structure lower the charge of the zeolite, and thus also lower the total cation exchange capacity. (63)
- Cations other than ammonium present in feed water can compete with ammonium for ion exchange sites, thereby reducing the total exchange capacity of the zeolite for ammonium. Though the selectivity of clinoptilolite zeolite is reported to be greater for ammonium than other common cations such as calcium and magnesium, it has been reported that the presence of these ions reduce the exchange capacity and therefore overall removal efficiency of ammonium from effluent.

- It has been reported both by operations and in literature that the removal efficiency of zeolite decreases with subsequent loading and regeneration cycles (63) (64). The reason for this phenomena is not well understood, but can greatly impact the maintenance requirements and cost associated with the use of zeolite. It has been reported that high ammonium concentrations can result in a frequency of zeolite replacement which renders its use impractical and uneconomical.

One precious metal operation in Ontario has reported the use of zeolite for ammonia removal from effluent. The removal efficiency at this operation ranges between 60% and 80%. The zeolite ion exchange treatment system receives effluent from holding ponds without any pre-treatment, though some ammonia degradation may occur in the holding ponds. Reported achievable effluent concentrations are summarized in Table 8-24. Spent zeolite and spent regenerant is shipped off-site to a hazardous waste facility. This operation reported continuous difficulty with the operation of zeolite for ammonium removal from effluent and has adjusted its water management practices to better control ammonia in effluent prior to treatment.

Table 8-24: Reported Achievable Concentrations from Use of Zeolite Ion Exchange

Parameter	Reported Achievable Concentration (mg-N/L)	Reference
Ammonium (NH_4^+)	7 – 9[51]	Operations Questionnaires

A base metal operation in Ontario piloted zeolite for ammonia removal from effluent but deemed the treatment technology infeasible due to difficulty with regeneration of the zeolite, reduced effectiveness of ammonium ion exchange with regeneration cycles and difficulty managing the spent regenerant. 1

One uranium operation in Saskatchewan is piloting a thermally-treated zeolite to remove ammonia from effluent via ion exchange. Thermally treating the zeolite (subjecting the zeolite to temperatures greater than 400 ºC for several hours) is reported to increase its ability to reject calcium ions, which compete with ammonium ions for exchange sites on the resin and reduce the removal efficiency of the zeolite. Preliminary lab-scale tests with this type of zeolite demonstrated little or no reduction in capacity and removal efficiency with subsequent loading and regeneration cycles. The regenerant proposed to be used is sodium sulfate, which will generate a spent regenerant of ammonia sulfate, which can then be used as a uranium processing chemical at the operation. This may reduce the regenerant management difficulty, and associated costs encountered by other operations. 1

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[51] Bench-scale test data provided by operations suggests that lower ammonia concentrations can be achieved (e.g., < 5 mg/L); however this is unconfirmed in full-scale installation.

Residuals

The regenerant solution used to remove the immobilized targeted ion(s) from the zeolite is the main residual produced by the use of zeolite ion exchange in an effluent treatment process. This solution contains the targeted parameters (e.g., ammonia) at and concentrations which are not suitable for release to the environment. This solution can be managed by:

- Ammonia stripping system to remove ammonia from the spent regenerant via volatilization.
- Further concentration of the solution for use by other industries (i.e. fertilizer).
- Subsequent biological oxidation system.

Zeolite material degrades over time and thus may require replacement over the operational life of the system. The degraded zeolite material can be landfilled for permanent disposal.

Major Equipment

Pre-treatment may be required prior to effluent introduction to zeolite ion exchange columns to control fouling and rapid increase in pressure drop during the treatment cycle, depending on the upstream treatment process. At minimum, treatment for suspended solids would be required.

The major equipment for ion exchange system is as follows:

- Feed and treated effluent pumps, as necessary
- Zeolite ion exchange columns.
- Clinoptilolite zeolite.
- Regenerant chemical totes/tanks and dosing pumps.
- Feed, spent regenerant, and treated effluent tanks, as necessary.

Synergies and Challenges

Zeolite ion exchange can be employed following chemical and physical bulk removal processes as a polishing step for removal of ammonia, independently of other treatment processes, or as a pre-treatment step, to generate a low volume and high concentration stream for treatment by other means.

Challenges associated with zeolite ion exchange include:

- Variations in volume, temperature and increases in feed ammonia are reported as not well tolerated by the zeolite ion exchange process.
- Management and disposal of spent regenerant is site-specific and must be considered carefully; spent regenerant treatment equipment can add significant capital and operating costs.
- Achieving high removal efficiencies may be difficult depending on target parameters and effluent chemistry (presence of competing ions may lower removal efficiencies).

- Removal capacity, and as a result, time between regeneration cycles, is reduced by the presence of other cations in solution.
- Zeolite has been reported to lose exchange capacity with subsequent loading and regeneration cycles.

Relative Prevalence in Industry

This technology is only in full-scale use at one mining operation in Canada. Two operations have reported testing zeolite in pilot-scale applications. Zeolite ion exchange is generally an unfamiliar technology in terms of mine effluent treatment processes.

Costs

Capital Cost

Equipment capital costs are expected to be similar to ion exchange capital costs, as nearly identical equipment is required for the housing of the zeolite media and for process wrap-around. The difference in capital costs will lie in the price of zeolite media versus the price of ion exchange resin, which is generally claimed to be less expensive than selective resins. A vendor quote received for zeolite material placed the cost of zeolite as less than CAD$1.00 per kilogram; however, reference documents have placed the costs much higher, at CAD$15 to CAD$90 per kilogram. Vendor costs have been used in zeolite cost estimates in later sections.

Sustaining Capital and Operating Cost

Sustaining capital expenditure required for zeolite systems is for zeolite media replacement. Operating cost will depend largely on the frequency of regeneration required, as this will dictate the amount of regenerant chemical required on an annual basis. Operating costs are expected to be less than selective ion exchange operating costs when NaCl is utilized as the regenerant, as it is less expensive that those typically required for ion exchange resin regeneration (HCl, H_2SO_4).

Like ion exchange systems, it is expected that zeolite ion exchange systems would be largely automated, requiring several hours of dedicated operator attention per day and monitoring on a continuous basis. Full operator attention is required during regeneration, the frequency of which depends on effluent chemistry. Monthly maintenance may be required for mechanical upkeep, and annual maintenance would be required for thorough system cleaning and equipment replacement as necessary.

8.2.12 *Adsorption*

8.2.12.1 *Zero Valent Iron*

Process Description

Zero valent iron (ZVI) may be used to remove selenium via the reduction and precipitation of oxidized forms of selenium (selenate and selenite) to insoluble elemental selenium and also via co-precipitation of selenite with ferric hydroxide (see Section 8.2.3), according to the following overall reactions:

$$3Fe(s) + SeO_4^{2-} + 8H^+ \leftrightarrow 3Fe^{2+} + Se(s) + 4H_2O$$

$$2Fe(s) + SeO_3^{2-} + 6H^+ \leftrightarrow 2Fe^{2+} + Se(s) + 3H_2O$$

$$Fe^{2+} + \tfrac{1}{4}O_2 + 2OH^- + \tfrac{1}{2}H_2O \leftrightarrow Fe(OH)_3(s)$$

Elemental iron is oxidized to ferrous and ferric iron. Ferrous and ferric iron reduce selenate to selenite and selenite to elemental selenium and/or reduce selenate to selenite and adsorb selenite onto ferric iron precipitates. The process is carried out at slightly acidic pH (pH 4 to 6) to promote the oxidation of ZVI to ferric iron (44).

ZVI may be supplied as granular ZVI, shredded cast iron, steel wool, iron filings, iron powder, or nanoscale iron. The media surface area for reduction-oxidation reaction and adsorption plays an important role in reaction kinetics and efficiency. The selection of media will depend on site-specific factors (e.g., media availability, delivery costs, residuals disposal, etc.) and required selenium removal efficiency.

Upstream solid/liquid separation may be required to remove TSS in order to prevent media clogging.

Downstream solid/liquid separation is required to separate spent ZVI media with entrained elemental selenium from effluent. This is typically accomplished via clarification.

Further downstream treatment is required to remove soluble iron and adjust pH to within discharge limits, for example, by aeration and neutralization and solid/liquid separation to remove iron hydroxide precipitates:

$$Fe^{2+} + \tfrac{1}{4}O_2 + 2OH^- + \tfrac{1}{2}H_2O \leftrightarrow Fe(OH)_3(s)$$

CH2MHill found as much as 100 to 200 mg/L soluble ferrous iron in ZVI effluent. At such high concentrations, downstream treatment to remove soluble iron would be associated with considerable capital and operating costs.

ZVI reduction of selenate and selenite may be catalyzed via the addition of copper or nickel (“catalyzed reduction” or “cementation”); however, this technique has only been demonstrated at bench and pilot scale.

ZVI has been demonstrated in stirred-tank reactor systems, filtration systems (columns), and as permeable reactive barrier (PRB) systems. For all systems, anoxic conditions should be maintained to promote selenium oxyanion reduction. Long retention times are required for all systems.

Good removal efficiencies for selenium (selenate and selenite) can be achieved. Typical achievable concentrations from ZVI adsorption are summarized in Table 8-25.

Table 8-25: Typical Achievable Concentrations from ZVI Adsoprtion

Parameter	Achievable Concentration (mg/L)	Reference
Se	<0.010	(44)(26)

Increases in selenium loading are not well tolerated by ZVI adsorption systems. Equalization of effluent flows and selenium loadings is required for stable operation.

Temperature affects reaction kinetics and required retention time. As with all effluent treatment systems, freezing must be prevented. Depending on climate, systems may be installed indoors with climate control, or outdoors with adequate insulation and heat tracing.

Residuals

Spent ZVI with entrained elemental selenium residuals are produced from solid/liquid separation. Ferric hydroxide sludge is produced from downstream removal of soluble iron. Residuals may require storage under reducing conditions to ensure that selenium is not oxidized and re-released to the environment. Moreover, adsorbed selenium is likely to be more mobile than reduced selenium. Due to the relatively recent adoption of this technology, little is known about the long term stability of residuals and the potential for selenium remobilization.

Major Equipment

- Reagent make-up/storage systems and feed systems for pH adjustment chemicals.
- ZVI handling systems for ZVI media, if required (e.g., for stirred-tank reactor systems).
- Upstream solid/liquid separation equipment, if required.
- Agitated pH adjustment tank, if required (e.g., for filtration vessel systems).
- Agitated ZVI reaction tank(s) or vessel(s).
- Agitated post-pH adjustment tank.
- Aeration blower(s)/compressor(s) and diffuser(s).
- Clarifier/thickener(s) and/or media filter(s).
- Residuals management equipment (e.g., pumps to disposal, mechanical dewatering equipment).

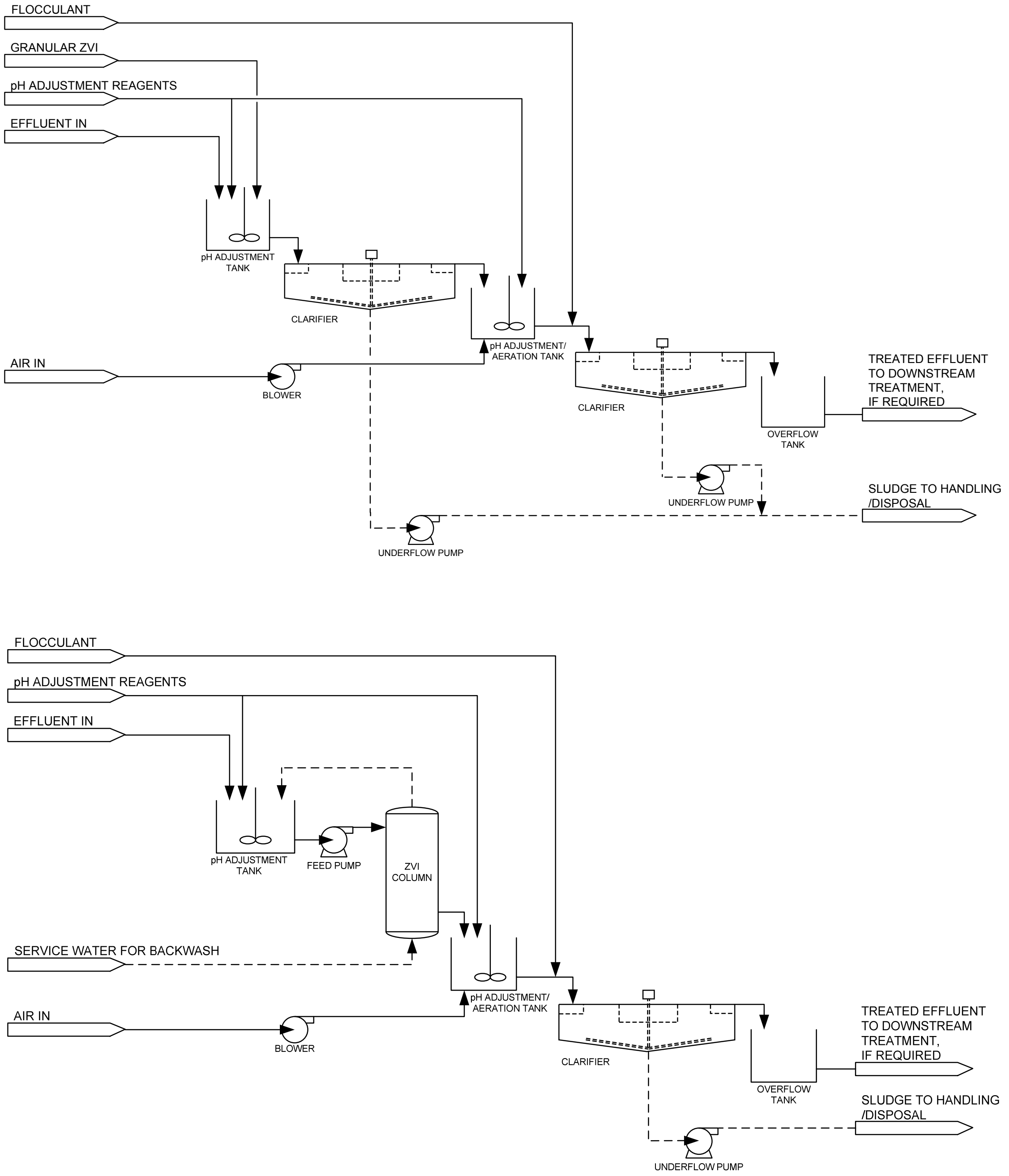

Figure 8-14: Simplified Process Flow Diagrams of ZVI in Stirred-Tank Reactor Configuration (top) and Filtration Vessel Configuration (bottom)

Synergies and Challenges

Synergies with existing hydroxide precipitation processes may be possible to replace downstream treatment for the removal of remove soluble iron and pH adjustment to within discharge limits.

Challenges associated with ZVI adsoprtion include:

- Equalization of flows and/or loadings is required for stable operation of ZVI technology.
- Treatment efficiency is temperature and pH dependent; low temperatures reduce reaction kinetics; upstream pH adjustment to pH 4 to 5 may be required depending on influent pH.
- Upstream solid/liquid separation may be required to remove TSS.
- Downstream treatment (e.g., aeration and hydroxide precipitation) is required to remove iron, adding substantially to capital and operating costs.
- ZVI media is a consumable and requires periodic replacement and handling and disposal of spent media from filtration vessel systems.
- Spent media may require storage in reducing conditions.
- Other contaminants (e.g., carbonate, arsenic, nitrate, phosphate, and sulfate) may compete with selenium oxyanions for reduction and co-precipitation and increase ZVI demand (61).
- Dissolved oxygen may oxidize ZVI and increase ZVI demand.
- Passivation with oxide and scaling/fouling of ZVI media reduces reaction efficiency.
- The process generates relatively large quantities of hydroxide sludge when compared with other selenium removal technologies.

Relative Prevalence in Industry

There are multiple full scale installations for the treatment of coal effluent in the USA (26) and one full scale installation for the treatment of precious metal effluent at a closed mine in the USA. It is understood that ZVI technology was selected for the latter application, in part because existing carbon-in-pulp (CIP) tanks could be retrofitted for the system to minimize capital cost expenditure (65). The system achieves about 0.012 to 0.022 mg/L selenium in treated effluent from an untreated effluent concentration of about 0.100 mg/L. Reverse osmosis treatment is required to reduce selenium concentrations to 0.002 mg/L for discharge.

Few installations have been in operation for long enough to determine long term feasibility and most installations treat flow rates at least one order of magnitude lower than the (sub)sector design flow rates determined in this study. The applicability of this technology may be limited, accordingly.

Costs

Capital

A +100%/-50% capital investment cost curve of total installed costs for greenfield installation of ZVI technology for selenium removal in stirred-tank reactor configuration with steel wool media has been developed in a recent CH2MHill report (26). The estimates are expected to be inflated, as they include upstream straining, clarification, and media filtration, residuals dewatering, standalone utilities, and a control room building, which may not be required for all applications.The equipment is assumed to be installed outdoors with adequate insulation and heat tracing with heated buildings/housings provided for pumps and electrical equipment. For extreme cold climates, installation in climate controlled buildings may be required, which could add to capital costs. Flow equalization infrastructure costs are omitted.

For the base case of 182 m^3/h (800 gpm), a total installed cost of CAD$36,800,000 (USD$35,000,000) was estimated (2012). The ratio of preliminary 2013 Chemical Engineering Plant Cost Index (CEPCI) to 2012 CEPCI is 0.97. Adjusting for this ratio brings the cost to CAD$35,600,000. It should be noted that CH2MHill cost estimates for selenium removal technologies are not on the same accuracy basis as other technology costs estimates given in this report. Based on comparisons between CH2MHill cost estimates and cost estimates provided by vendors for other selenium removal technologies (see Section 8.2.14), CH2MHill capital cost estimates may be inflated by over 200% over base technology costs due to the inclusion of wrap-around equipment and infrastructure which may not be required for all applications.

Operating

A +100%/-50% operating cost curve for technology for selenium removal in stirred-tank reactor configuration with steel wool has been developed by CH2MHill (26). The estimates include reagents, power, ZVI media replacement, cleaning, maintenance, labour, and on-site residue disposal costs (residuals are assumed to be non-hazardous). 1

For the base case of 182 m^3/h (800 gpm), a total operating and maintenance cost of CAD$3.18/$m^3$ treated (USD$3.14/$m^3$) was estimated (2012). It should be noted that CH2MHill cost estimates for selenium removal technologies are not on the same accuracy basis as other technology costs estimates given in this report. Based on comparisons between CH2MHill cost estimates and cost estimates provided by vendors for other selenium removal technologies (see Section 8.2.14), CH2MHill operating cost estimates may be inflated by as much as 200% over base technology costs due to the inclusion of wrap-around equipment and infrastructure which may not be required for all applications.

8.2.13 Active Aerobic Biological Oxidation

Process Description

Aerobic biological oxidation may be used to oxidize ammonia (NH_3/NH_4^+), cyanide, cyanate (OCN^-), and thiocyanate (SCN^-), according to the following generic reactions:

$$CN^- + \frac{1}{2}O_2 \leftrightarrow OCN^-$$

$$OCN^- + 3H_2O \leftrightarrow NH_4^+ + HCO_3^- + OH^-$$

$$SCN^- + 3H_2O + O_2 \leftrightarrow NH_4^+ + CO_2 + SO_4^{2-}$$

$$NH_4^+ + 2O_2 \leftrightarrow NO_3^- + 2H^+ + H_2O$$

The volatile fraction of total suspended solids may also be removed via biological degradation.

SAD cyanide complexes are not readily biodegradable, but may be removed through precipitation and adsorption to a limited extent (16). *Pseudomonas*, *Alcaligenes*, and *Achromobacter*, among others, are responsible for cyanide oxidation.

Biological ammonia oxidation, or nitrification, is a two-step biological process in which ammonia is first oxidized to nitrite and then nitrite is oxidized to nitrate via two distinct groups of autotrophic bacteria, *Nitrosomonas* and *Nitrobacter*, respectively. Phosphate is required as a nutrient for biomass development and may be added as a reagent if insufficient amounts are available in the effluent.

Aerobic biological oxidation can be accomplished in suspended growth (e.g., activated sludge processes, membrane bioreactors, sequencing batch reactors, and aerated lagoons) and attached growth/fixed film processes (e.g., trickling filters, rotating biological contactors, packed-bed reactors, moving bed biofilm reactors, and submerged attached growth reactors). In suspended growth processes, microorganisms are maintained in suspension in the effluent to be treated via mixing. In attached growth processes, microorganisms are attached as biofilms to inert packing material through which the effluent to be treated flows. Integrated fixed film activated sludge (IFAS) systems combine suspended growth and attached growth/fixed film processes.

Fixed film processes are generally more appropriate than suspended growth processes for the treatment of mining effluent as biofilms are less susceptible to variations in contaminant loading (due to variation in flow or quality) and temperature, are more compact, and can have minimal sludge handling requirements.

In rotating biological contactors (RBCs), closely spaced discs that provide large surface area for the establishment of biofilms are partially submerged in effluent and continuously rotated, such that they are alternately exposed to air, which provides oxygen, and effluent, which provides biodegradable matter, to support aerobic biological oxidation. Although RBCs have been employed to treat Canadian mining effluent, moving bed biofilm reactors (MBBRs) are now replacing RBCs as the preferred attached growth aerobic biological oxidation technique. In an MBBR, carriers that provide large surface area for the establishment of biofilms are kept in suspension by aeration.

Aerobic biological oxidation is affected by a number of effluent factors, including, but not limited to, those below:

- Optimal nitrification rates occur in the range of pH 7.0 to 9.0 and, as nitrification reaction consumes alkalinity, alkalinity addition may be required for low alkalinity effluent.
- Optimal nitrification rates occur in the range of 10 to 30 °C. Reaction kinetics decrease with temperature and long retention times or pre-heating may be required for low temperature effluent (i.e., for effluent below 5 °C). If untreated effluent is heated, downstream cooling of treated effluent may also be required; this may be accomplished via heat exchange with the untreated effluent stream to minimize energy input to the overall system.
- Optimal nitrification rates occur with dissolved oxygen > 2 mg/L.
- Metals and other toxic chemicals in mining effluent can inhibit nitrification at relatively low concentrations. Metals removal may be required prior to aerobic biological oxidation.
- Cyanide itself is toxic to nitrifying bacteria. Bulk cyanide oxidation to cyanate via alternative means (e.g., chemical oxidation) may be required as pre-treatment prior to aerobic biological oxidation.
- High concentrations of un-ionized ammonia may also inhibit nitrification.
- Calcium concentration has a significant impact on biofilm structure and biofilm detachment, and therefore, system performance. Higher concentrations of calcium promote biofilms that are thicker, denser, and more stable. At higher calcium concentrations, MBBR systems may be capable of simultaneous nitrification/denitrification as thicker biofilms have more protected anoxic zones. However, the optimal calcium concentration for MBBR performance may be in the range of 50 to 200 mg/L, with negative impacts to performance occurring at higher calcium concentration as biofims become primarily composed of inorganic salts and become more resistant to mechanical detachment/sloughing, and as mass transfer is reduced through thicker biofilms and organism growth rates decline. Thus at higher calcium concentrations, longer retention times may be required to achieve nitrification. (66), (67), (68).
- Ionic strength may inhibit nitrification. A recent Finnish study demonstrated that nitrification is less efficient for pre-concentrated mine effluent; however, it did not distinguish inhibition due to metals from inhibition due to dissolved salts (69). Moreover, there are examples of MBBRs operating on medium to high ionic strength effluents from mining, coal gasification, and flue gas desulfurization (70), (71).

Typical reagents include nutrient (to provide phosphorus and micronutrients), lime, caustic, or soda ash to maintain alkalinity, and anti-foam agent. Ferric iron or aluminum salts may be required as reagents to precipitate residual phosphorus from nutrient addition.

Achievable ammonia, cyanide, cyanate, and thiocyanate concentrations as reported by a vendor of MBBR systems are summarized in Table 8-26.

Table 8-26: Typical Achievable Concentrations from MBBR-based Aerobic Biological Oxidation

Parameter	Achievable Concentration (mg/L)	Reference
NH_3	<2.0 as N	Industry standard design criteria
CN	<8.0	(58)
Cyanate	<1.0 as N	(58)
Thiocyanate	<2.0 as N	(58)

Veolia Water Solutions and Technologies Canada Inc., based in Ontario, specializes in aerobic biological oxidation for the Canadian mining sector with their AnoxKaldnes™ MBBR technology. Headworks BIO, based in British Columbia, also specializes in MBBR technology for the Canadian mining sector.

Residuals

Fixed film processes generate less residuals and have lower sludge management requirements than suspended growth processes. Fixed film processes do not require the recycle of activated sludge. In fixed film processes, excess biomass sloughs off from the biofilm carrier and requires downstream solid/liquid separation (e.g., clarifier, dissolved air flotation) and disposal.

Major Equipment

- Reagent make-up/storage systems (mainly dilution in agitated tanks) and feed apparatus (mainly dosing pumps) for nutrient, pH control, and anti-foam reagents.
- Heating and heat exchange systems for low temperature effluents.
- MBBR tank(s) complete with carriers, carrier retention sieve, aeration grid.
- Aeration blower(s).
- Solid/liquid separation equipment (e.g., clarifier, dissolved air flotation).
- Residuals management equipment (e.g., pumps to disposal, filter press for dewatering).

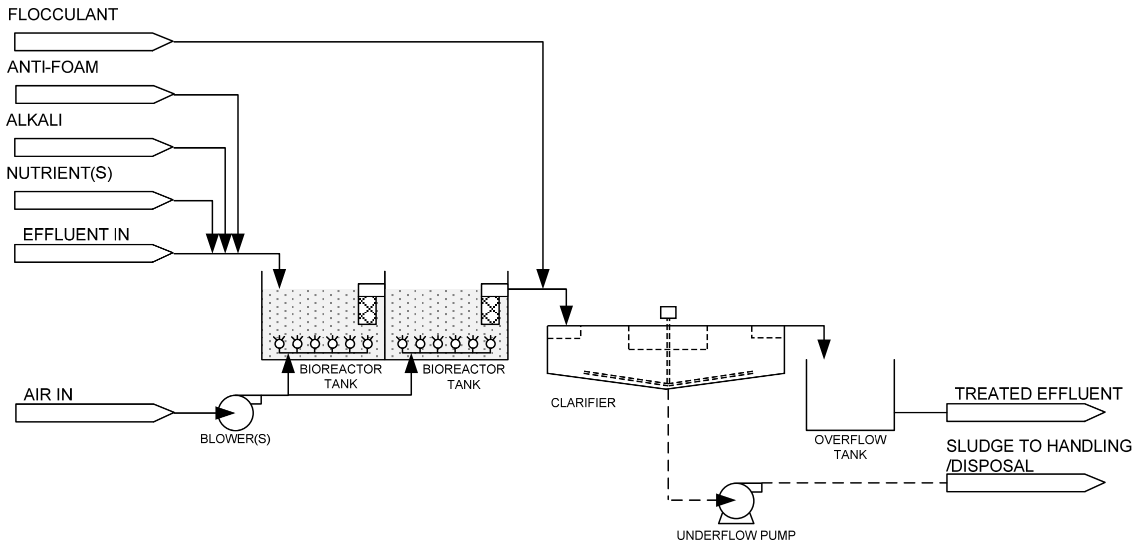

Figure 8-15: Simplified MBBR and Solid/Liquid Separation Process Flow Diagram

Synergies and Challenges

Aerobic biological oxidation can be employed synergistically with metals precipitation processes. Aerobic biological oxidation can be used to remove metal chelating and complexing agents (ammonia and cyanide) and improve metals precipitation downstream. Moreover, aerobic biological oxidation has relatively low operating costs and footprint in comparison to alternative ammonia and cyanide removal processes. Aerobic biological oxidation can also be employed downstream of metals precipitation process, after the bulk of potentially toxic metals have been removed from the effluent.

Aerobic biological oxidation can be employed synergistically with anaerobic biological reduction in order to achieve total nitrogen removal, if required.

Establishment of the biological system can take months and cannot be accomplished with effluent temperature <10 °C. However, once established, the system can withstand temperatures approaching 0 °C. However, nitrification declines as the temperature falls below 10 °C, and below 5 °C nitrification may be unacceptably impeded. This means that systems must be commissioned during warm seasons, or effluent must be heated for commissioning and possibly also operation during cold seasons.

Pre-treatment for grit and large debris removal is required. Post-treatment for residual phosphorus (from nutrient addition) removal may be required.

As shown in the generic chemical reactions for nitrification, nitrate is produced from the aerobic biological oxidation of ammonia. If the resultant nitrate loadings are not acceptable to the receiving body of water, then denitrification may be required. In this case, combined nitrification/denitrification process flow sheets and technologies would be preferred.

Relative Prevalence in Industry

A suspended growth activated sludge process was employed to treat ammonia, cyanide, and thiocyanate at the closed Nickel Plate mine in British Columbia.

An RBC attached growth process for thiocyanate, cyanate, and ammonia removal was employed at a precious metal operation in Quebec. As that system experienced catastrophic mechanical failure (shaft) due to the excessive weight of the RBC from inefficient sloughing off of excess biomass, it was replaced with MBBR technology over a period of 6 years. The system includes pre-heating of effluent and a heat recovery feed effluent/treated effluent heat exchanger, as treatment efficiency is highly sensitive to temperature variation for this application. Calcium carbonate is added to provide alkalinity. Excess phosphorus supplied as nutrient is precipitated with alum (see Section 8.2.3).

An MBBR based aerobic biological treatment plant for ammonia removal from underground mine dewatering effluent is expected to be operational by the end of 2013 at a precious metal operation in Saskatchewan. The system includes pre-heating of effluent to 10 °C.

One precious metal operation in Ontario will pilot an MBBR process for ammonia removal in winter 2013/2014 to evaluate cold weather performance. However, the pilot plant includes pre-heating of effluent for start-up, and if successful, the full scale installation might be implemented on an effluent stream that is warm year-round (directly from milling process) to reduce MBBR size.

Costs

Capital

Capital investment for MBBR technology is low compared to most other attached growth and suspended growth processes. The cost curve information presented in Figure 8-16 was in part provided by vendor questionnaire data, and Veolia and Headworks BIO as part of their vendor questionnaire submissions for the MBBR process.

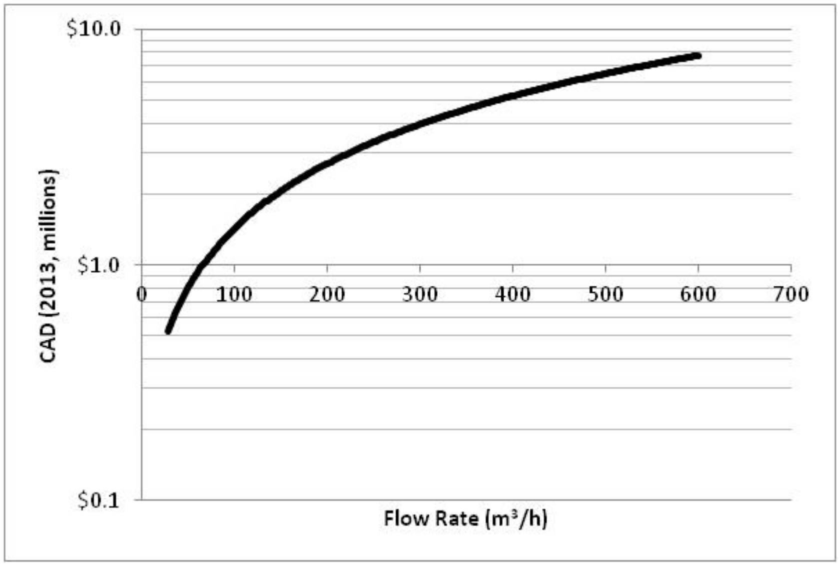

Figure 8-16: Total Installed Costs for MBBR Process

Additional costs for pre-heating (e.g., via natural gas fired boiler or electric heater) and heat recovery (e.g., via heat exchange between effluent and untreated effluent) must be considered. Cost curves for pre-heating and heat exchange technology are not provided here; however, capital costs for pre-heating and heat exchange are estimated for applicable (sub)sectors in Section 9.

Operating

Reagent consumption is proportional to contaminant loading, feed pH, and treated effluent limits. Power consumption for air blowing is proportional to contaminant loading and temperature, which dictates reactor size. Operator attention requirements are low for this process (less than two hours per day), with checking of dissolved oxygen levels, blower function/media agitation, visual inspection for foaming, and reagent refill. Preventative and corrective annual plant maintenance is moderate (approximately 100 hours per year).

Operating costs for the activated sludge system at Nickel Plate Mine in British Columbia were reported to be CAD$7.92/m^3 (CAD$0.03/US gallon) in 1997 CAD (72). However, this figure also included costs for operation of downstream denitrification and high density sludge metals removal processes, as well as dedicated services/utilities.

Operating costs for the MBBR at the aforementioned Quebec precious metal operation is estimated to cost between CAD$0.57/m^3 and CAD$1.14/m^3. However, these figures also include operating costs for air stripping and residual phosphorus removal systems.

Veolia estimates an operating cost of CAD$0.09/m^3 treated including nutrient and anti-foam reagents and power (a power cost of CAD$0.08/kWh is assumed). pH control reagents and power costs for pre-heating have been excluded from this amount. Pre-heating and heat exchange operating costs are estimated for applicable (sub)sectors in Section 9.

8.2.14 Active Anoxic/Anaerobic Biological Reduction

8.2.14.1 Fluidized Bed Reactor

A fluidized bed reactor (FBR) is a completely-mixed attached growth process reactor with plug flow characteristics, utilized for the anaerobic or anoxic biological reduction of oxyanions, including nitrate to nitrogen gas and selenium oxyanions (selenate and selenite) to insoluble elemental selenium, according to the following generic reactions:

$$SeO_4^{2-} + \text{organic carbon} \leftrightarrow SeO_3^{2-}$$

$$SeO_3^{2-} + \text{organic carbon} \leftrightarrow Se(s) + CO_2 + H_2O$$

Organic carbon is utilized by heterotrophic bacteria as an electron donor with selenium oxyanions as electron acceptors. In this process, nitrate is preferentially reduced to nitrogen gas (denitrification) before selenate and selenite are reduced to selenium. *Pseudomonas*, *Micrococcus*, *Achromobacter*, and *Bacillus* among others, are responsible for dentitrification under anoxic conditions. Chlorate is also preferentially reduced to chloride before selenate and selenite are reduced, but chlorate is a less common contaminant in mine effluents.

FBR vessels contain granular solid media that provide large surface area for the establishment of biofilms of naturally occurring heterotrophic facultative bacteria. The granular solid media is typically sand or granular activated carbon (GAC). Untreated effluent and recycled effluent are pumped into the bottom of the FBR in an upwards flow direction at a high enough velocity to fluidize the granular solid media. Fluidization increases the active surface area of the granular solid media. Organic carbon electron donor (e.g. methanol, molasses, MicroCg) and nutrient (e.g., phosphorus and micronutrients) reagent addition is required to support biological function. Excess biomass, including particulate and colloidal Se, is sheared from the media by effluent flow and with biomass separation device. Some effluent is recycled and some treated effluent containing excess biomass, reduced selenium, and some entrained granular media is discharged from the top of the vessel. FBR can be employed as a single stage or as multiple stages in series, depending on the selenium and nitrate loading and required removal efficiency.

Upstream adjustment of effluent pH may be required to counter biological alkalinity generation. Upstream removal of TSS may also be required, depending on loading. Downstream solid/liquid separation is required to remove TSS, which is largely biomass, from the treated effluent. Typically, pond-based settling/sedimentation, clarification, flotation, or media filtration are utilized based on TSS load and treatment requirement. Applications with untreated effluent selenium concentrations exceeding 0.050 mg/L selenium may require more advanced solid/liquid separation technology such as filtration or membrane filtration (particularly microfiltration and ultrafiltration) to achieve treated effluent selenium concentrations below 0.010 mg/L (26), as colloidal forms and fine particles of reduced selenium that are not filterable to 0.1 to 0.4 μm are found in effluents with as little as 0.100 mg/L selenium (73). Such advanced downstream solid/liquid separation technology could add considerably to overall implementation costs. Downstream solid/liquid separation must be performed anoxically to prevent re-oxidation of selenium and re-dissolution into treated effluent.

Finally, effluent treatment may require pH adjustment, aeration and/or residual BOD removal via aerobic biological treatment such as moving bed bioreactors (MBBR) or membrane bioreactors (MBR).

Anoxic biological reduction is affected by a number of effluent factors:

- Optimal reduction/denitrification rates occur in the range of pH 6.5 to 7.5 and, as the biological reduction reactions generate alkalinity and carbon dioxide, upstream adjustment of effluent pH may be required.
- Optimal reduction/denitrification rates occur in the range of 25 to 45 °C. Reaction kinetics decrease with temperature and long retention times or pre-heating to ≥10 °C are required for low temperature effluent (i.e., for effluent below 5 °C). If untreated effluent is heated, downstream cooling of treated effluent may also be required; this may be accomplished via heat exchange with the untreated effluent stream to minimize energy input to the overall system.

Typical reagents include carbon substrate (electron donor), nutrient, sulfuric acid or base to adjust pH, and anti-foam reagents, if required.

Typical Achievable selenium and nitrate are summarized in Table 8-27.

Table 8-27: Typical Achievable Concentrations from FBR-based Anoxic Biological Reduction with Downstream Solid/Liquid Separation

Parameter	Achievable Concentration (mg/L)	Reference
Se	0.005 to 0.020	(44)(26) (74)
NO_3^-	<0.1 as N	(74)
TSS	<30	(74)
COD	<100, depends on electron donor	(74)

Residuals

Excess biomass including particulate and colloidal selenium sloughs off from the granular media and requires downstream solid/liquid separation as discussed above. The biomass is typically non-hazardous (i.e., by toxicity characteristic leaching procedure (TCLP criteria), but should be stored in anaerobic/reducing conditions to ensure that selenium is not oxidized and re-released to the environment. Due to the relatively recent adoption of this technology, little is known about the long term stability of residual biomass and the potential for selenium remobilization. Some coal operations in the Appalachian regions of the U.S.A. have considered storage of biomass under water cover (approximately 1 m depth) with reagent addition to maintain reducing conditions.

Major Equipment/Infrastructure

- Reagent make-up/storage systems (mainly dilution in agitated tanks) and feed apparatus (mainly dosing pumps) for pH control, carbon substrate, nutrient, and anti-foam reagents.
- FBR vessel(s).
- Fluidization/recirculation pump(s).
- Solid/liquid separation equipment (e.g., clarifier, DAF, media filter, UF/MBR).
- Aerobic polishing equipment (e.g., aeration, MBR, MBBR).
- Residuals management equipment (e.g., pumps to disposal, thickener/dissolved air flotation, filter press for dewatering).

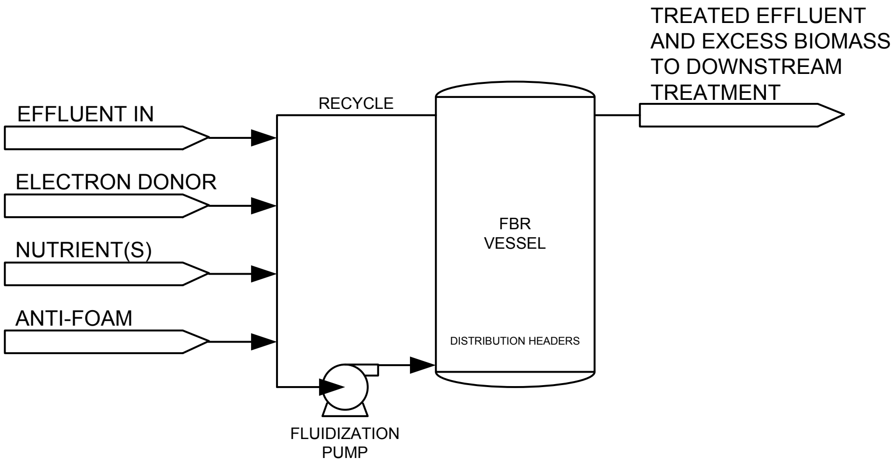

Figure 8-17: Simplified FBR Process Flow Diagram

Synergies and Challenges

As FBRs are completely mixed reactors with plug-flow characteristics and high biomass concentrations, they benefit from high sludge retention times and lower hydraulic retention times, and thus lower installed costs than other anoxic/anaerobic biological reduction technologies. Due to the fluidized nature of the reactors, FBRs are also less sensitive to untreated effluent TSS loading and are less likely to require upstream TSS removal than other anoxic/anaerobic biological reduction technologies.[52] FBRs do not require backwash, unlike filtration-based anoxic/anaerobic biological reduction technologies, meaning that they can operate continuously and have a higher operating factor. FBRs are also less susceptible to flow channelization, short-circuiting, and by-passing than alternative anoxic/anaerobic biological reduction technologies. FBR performance has been shown to be independent of sulfate concentration (61).

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Challenges associated with FBR include:

- Equalization of flows and/or loadings is required for stable operation of FBR technology.
- Effluents with <0.015 to 0.050 mg/L selenium (as selenate) may be too dilute for economical biological treatment (61), where other non-biological treatment technologies may be more appropriate.

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[52] A limit for feed TSS cannot be established, as particle size distribution and specific gravity determine FBR sensitivity to TSS.

- As nitrate is preferentially reduced before selenium oxyanions, high feed nitrate concentrations may prevent selenium removal to the lower range of achievable concentrations. High feed nitrate concentrations may drive retention time requirements and system sizing. For example, one FBR vendor reported that a system with a 15 mg/L total selenium load with high feed nitrate had required greater retention time than a system with a 50 mg/L total selenium load. This issue can be addressed by having a two stage system, where the first stage targets nitrate removal, and the second stage targets selenium removal.
- High feed nitrate concentrations consume proportional amounts of electron donor and nutrients to support biological function, and thus, also increase residual biomass production.
- High feed total dissolved solids (TDS) concentrations may also increase retention time requirements and system sizing.
- Excess nutrient may cause elevated treated effluent phosphorus concentrations that require appropriate downstream management.
- Applications with untreated effluent selenium concentrations exceeding 0.050 mg/L selenium may require more advanced solid/liquid separation technology such as filtration or membrane filtration (particularly microfiltration and ultrafiltration) to achieve treated effluent selenium concentrations below 0.010 mg/L, which could add considerably to overall implementation costs.
- Downstream solid/liquid separation must be performed anoxically to prevent re-oxidation of selenium and re-dissolution into treated effluent.
- Residual biomass typically requires thickening and dewatering prior to disposal, depending on site-specific option for ultimate disposal.

Relative Prevalence in Industry

Envirogen has installed five full scale systems treating base metal effluent and one full scale system treating coal effluent in the USA. Envirogen also has one full scale coal installation in Canada planned for 2014.

Costs

Capital

A +100%/-50% capital investment cost curve of total installed costs for greenfield installation of FBR technology for selenium removal has been developed in a recent CH2MHill report (26). The estimates are expected to be inflated, as they include influent heating, combined anoxic and aerobic biomass gravity thickening and dewatering system, standalone utilities, and control room building, which may not be required for all installations. The equipment is assumed to be installed outdoors with adequate insulation and heat tracing with heated buildings/housings provided for pumps and electrical equipment. For extreme cold climates, complete system installation in climate controlled buildings may be required, which could add to capital costs. Flow equalization infrastructure costs are omitted. For the base case of 182 m^3/h (800 gpm), a total installed cost of CAD$31,600,000 (USD$30,000,000) was estimated (2012). The ratio of preliminary 2013 Chemical Engineering Plant Cost Index (CEPCI) to 2012 CEPCI is 0.97. Adjusting for this ratio brings the cost to CAD$30,500,000. It should be noted that CH2MHill cost estimates for selenium removal technologies are not on the same accuracy basis as other technology costs estimates given in this report.

Envirogen has created cost models for their core treatment components. Based on these models and operating experience with a system treatment mine effluent in eastern U.S.A., Envirogen has provided an estimate for a typical FBR system including: consulting service and permitting assistance, engineering (with the exception of civil engineering, which is highly site-specific), construction management, construction, system commissioning, and operational acceptance testing. The FBR system itself has been assumed to include a self-cleaning filter with 3mm screen for untreated effluent screening for TSS removal, two FBR vessels in series[53], inlet distribution laterals and nozzles, effluent collection piping, fluidization pump skids, instrumentation, process controls (PLC) and SCADA system, manual and automated valves, pH adjustment system, nutrient system, electron donor system, and a submerged ultrafiltration membrane system[54] for treated effluent solid/liquid separation. The equipment is assumed to be installed outdoors with adequate insulation and heat tracing with heated buildings/housings provided for pumps and electrical equipment. For extreme cold climates, installation in climate controlled buildings may be required, which could add to capital costs. Flow equalization infrastructure costs are omitted. Based on the scope of work and FBR system described above, Envirogen estimates the cost for an installed system for a flow rate of 182 m^3/h (800 gpm) system to be CAD$8,000,000 to CAD$13,000,000. The discrepancy between the CH2MHill cost and Envirogen cost is partially accounted for in that CH2MHill have included costs for standalone utilities and electrical service to the plant, feed, effluent, and residuals piping to/from the plant, influent heating, downstream aerobic polishing, and residual biomass thickening and dewatering.

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[53] For the treatment of at least 0.300 mg/L selenium as selenate and up to 50 mg-N/L nitrate, which is thought to be typical of applications in Western Canada.

[54] Since the application exceeds 0.050 mg/L selenium, it is assumed to require more advanced solid/liquid separation technology to achieve treated effluent selenium concentrations below 0.010 mg/L.

Sustaining Capital

Sustaining capital costs are associated with the periodic replacement of granular media. Granular media replacement frequency is a function of untreated effluent quality (scaling and fouling species) and media abrasion due to fluidization. Media replacement due to loss is approximately 1 to 3% of total media volume per year.

Operating

Reagent consumption is proportional to contaminant loading, feed pH, required contaminant removal efficiencies, and selected electron donor. Table 8-28 summarizes indicative delivered electron donor costs. Typically, only one of the tabulated electron donor reagents is utilized and selection is site-specific. Power consumption for pumping is proportional to contaminant loading, which dictates reactor size.

Table 8-28: FBR Electron Donor Reagent Costs (75)

Reagent	Format	Cost (CAD$/L)
Molasses	bulk liquid	$0.39
Methanol	bulk liquid	$0.42
MicroCg	bulk liquid	$0.56

A +100%/-50% operating cost curve for FBR technology for selenium removal has been developed by CH2MHill (26). The estimates include reagents, power, granular media top-up, cleaning, maintenance, labour, and on-site residue disposal costs (residuals are assumed to be non-hazardous). For the base case of 182 m^3/h (800 gpm), a total operating and maintenance cost of CAD$1.59/$m^3$ treated (USD$1.57/$m^3$) was estimated (2012). It should be noted that CH2MHill cost estimates for selenium removal technologies are not on the same accuracy basis as other technology costs estimates given in this report.

Envirogen has provided an operating cost estimate for operations and maintenance for the FBR system described above to be in the range of CAD$0.85/$m^3$ and CAD$1.16/$m^3$, including costs for reagents, power (electrical), and labour (operations, maintenance, and engineering support).

8.2.14.2 ABMet®

ABMet® is a proprietary attached growth process by GE, utilized for the anoxic biological reduction of selenium oxyanions (selenate and selenite) to insoluble elemental selenium. In this process, nitrate is preferentially reduced to nitrogen gas (denitrification) before selenate and selenite are reduced to selenium.

ABMet® is configured as a downflow granular activated carbon (GAC) filter. Due to its high porosity, the GAC media provides large surface area for the establishment of biofilms of naturally occurring heterotrophic facultative bacteria. Electron donor and nutrient reagent addition is required to support biological function. GE provides its own engineered nutrient for ABMet® systems which combines electron donor, nitrogen, phosphorus, and micronutrients. Treated effluent is continuously discharged from the bottom of the vessel. Excess biomass, including particulate and colloidal Se, is periodically sheared from the GAC media by backwashing with treated effluent. Backwash may be performed as little as once per month. During the backwash cycle, flow is reversed through the biofilter, the GAC media is fluidized, and excess biomass and some entrained GAC media are discharged from the top of the vessel. The biomass contains the reduced elemental selenium. The backwash water is allowed to settle with residual biomass reporting to solids handling (typically pond-based settling/sedimentation and subsequent dredging, or thickening and dewatering prior to disposal) and decant water being returned to the process.

Upstream removal of large TSS is required to prevent clogging of GAC media. Upstream adjustment of effluent pH may also be required to counter biological alkalinity generation. Downstream solid/liquid separation, and perhaps dewatering, is required to remove TSS, which is largely biomass, from the backwash stream. Applications with untreated effluent selenium concentrations exceeding 0.050 mg/L selenium may require more advanced solid/liquid separation technology such as filtration or membrane filtration (particularly microfiltration and ultrafiltration) to achieve treated effluent selenium concentrations below 0.010 mg/L (26), as colloidal forms and fine particles of reduced selenium that are not filterable to 0.1 to 0.4 μm are found in effluents with as little as 0.100 mg/L selenium (73). Such advanced downstream solid/liquid separation technology could add considerably to overall implementation costs. Downstream solid/liquid separation must be performed anoxically to prevent re-oxidation of selenium and re-dissolution into treated effluent.

Downstream effluent pH adjustment may be required to counter biological alkalinity generation. Also, downstream aeration of the treated effluent may be required to address toxicity issues associated with low dissolved oxygen concentration and BOD, due to residual electron donor and residual dissolved BOD.

Anoxic biological reduction in a downflow reactor is affected by a number of effluent factors:

- Optimal reduction/denitrification rates occur in the range of pH 6.5 to 7.5 and, as the biological reduction reactions generate alkalinity, upstream adjustment of effluent pH may be required.
- Optimal reduction/denitrification rates occur in the range of 25 to 45 °C. Reaction kinetics decrease with temperature and long retention times or pre-heating to ≥10 °C is recommended for low temperature effluent. Interestingly, GE’s process guarantee for ABMet® sets a lower limit for feed temperature of just 5 °C. One operation with untreated effluent temperatures of 1.5 to 4.0 °C during winter compensates by adding more nutrient to maintain bacterial activity rather than by pre-heating water (19).

Typical reagents include carbon substrate (electron donor), nutrient, and sulfuric acid or base to adjust pH.

Typical achievable selenium and nitrate concentrations are summarized in Table 8-29.

Table 8-29: Typical Achievable Concentrations from ABMet®-based Anoxic Biological Reduction

Parameter	Achievable Concentration (mg/L)	Reference
Se	<0.005	(44)(26)(76)
NO_3^-	<0.1 as N	(76)
TSS	<35	(76)
BOD	<30	(76)

Residuals

Excess biomass including particulate and colloidal selenium sloughs off from the GAC media during backwash and requires downstream solid/liquid separation, and perhaps dewatering, as discussed above. The biomass is non-hazardous. GE states that biomass from every ABMet® installation has passed US toxicity characteristic leaching procedure (TCLP) criteria. However, the biomass should be stored in anaerobic/reducing conditions to ensure that selenium is not oxidized and re-released to the environment. Due to the relatively recent adoption of this technology, little is known about the long term stability of residual biomass and the potential for selenium remobilization. Some coal operations in the Appalachian regions of the U.S.A. have considered storage of biomass under water cover (approximately 1 m depth) with reagent addition to maintain reducing conditions.

Major Equipment/Infrastructure

- GE's engineered nutrient combines electron donor, nitrogen, phosphorus, and micronutrients and allows for a single reagent make-up/storage system (bulk tanks) and feed apparatus (dosing pumps). The nutrient is delivered as a bulk liquid in tanker volumes of approximately 17 m^3, so a bulk reagent storage tank of at least 20 m^3 is recommended. The reagent does not have any special storage nor agitation requirements. Additional reagent make-up/storage systems and feed apparatus may be required if feed and discharge pH control are required.
- Feed and backwash pumps.
- ABMet® biofilter.
- Treated Effluent/Backwash Storage Tank.
- Spent Backwash Storage Tank.
- Decant recirculation pump.
- Solid/liquid separation equipment (e.g., media filter, UF/MBR).
- Residuals management equipment (e.g., pumps to disposal, filter press for dewatering, as required).

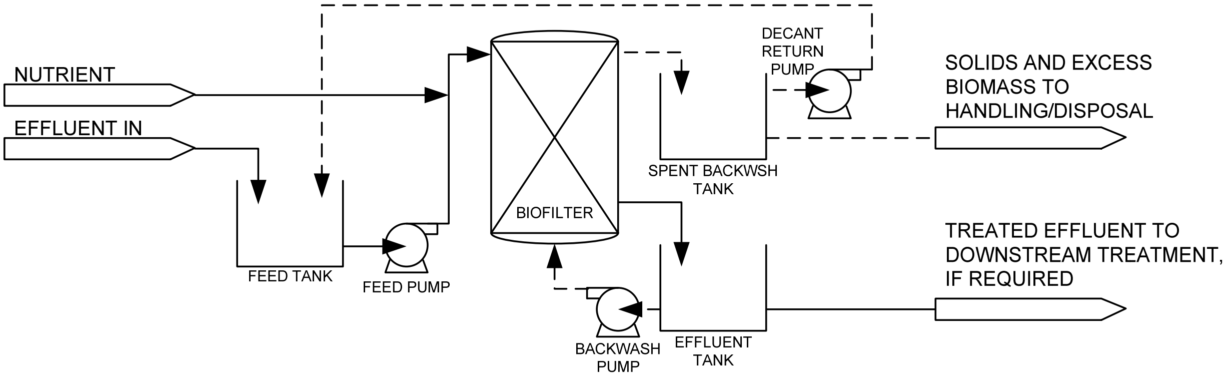

Figure 8-18: Simplified ABMet® Process Flow Diagram

Synergies and Challenges

ABMet® is an established, commercially proven technology with effluent quality assured via process guarantee. ABMet® performance has been shown to be independent of sulfate concentration (61). However, challenges associated with ABMet® include:

- Backwash equipment required, adding to treatment costs.
- Equalization of flows and/or loadings is required for stable operation of ABMet® technology.
- Large footprint requirement due to low hydraulic loading rate and high hydraulic residence time.
- Effluents with <0.015 to 0.050 mg/L selenium (as selenate) may be too dilute for efficient biological treatment (61).
- As nitrate is preferentially reduced before selenium oxyanions, high feed nitrate concentrations may prevent selenium removal to the lower range of achievable concentrations.
- High feed nitrate concentrations consume proportional amounts of electron donor and nutrients to support biological function, and thus, also increase residual biomass production.
- Residual biomass typically requires thickening and dewatering prior to disposal.

Relative Prevalence in Industry

In Canada, there have been one full scale precious metal installation (2004), three pilot scale coal mining demonstrations, and one full scale coal mining installation is scheduled for 2014.

In other jurisdictions, GE has installed many full scale ABMet® systems treating precious metal effluent, metal refinery effluent, flue-gas desulfurization effluent, coal ash landfill leachate, and agricultural runoff. GE has performed two pilot scale base metal demonstrations in the USA.

The range of full-scale ABMet® installation flow rates is 6 to 318 m^3/h (25 to 1,400 US gpm).

Costs

Capital

A +100%/-50% capital investment cost curve of total installed costs for greenfield installation of ABMet® technology for selenium removal has been developed by CH2MHill (26). The estimates are expected to be inflated, as they include influent heating, residual biomass thickening and dewatering, standalone utilities, and control room building, which may not be required for all installations. The equipment is assumed to be installed outdoors with adequate insulation and heat tracing with heated buildings/housings provided for pumps and electrical equipment. For extreme cold climates, complete system installation in climate controlled buildings may be required, which could add to capital costs. Flow equalization infrastructure costs are omitted. For the base case of 182 m^3/h (800 gpm), a total installed cost of CAD$42,100,000 (USD$40,000,000) was estimated (2012). Adjusting for the 2013/2012 CEPCI ratio brings the cost to CAD$40,700,000. It should be noted that CH2MHill cost estimates for selenium removal technologies are not on the same accuracy basis as other technology costs estimates given in this report.

A +30%/-20% capital investment cost curve (77) and an average treatment cost curve (78) of total installed costs for greenfield installation of ABMet® technology for selenium removal have been developed by GE. The estimates include engineering services (including design engineering, construction services, permitting assistance, and commissioning), influent basket strainer, feed tank, ABMet® biofilter with biological support media and seed culture, treated effluent storage tank, feed and backwash pumps, spent backwash tank, spent backwash supernatant tank, spent backwash supernatant return pump, nutrient dosing skid and first-fill of nutrient, air compressor, process valves and instruments, motor control centre, instrumentation, electrical programmed PLC/HMI, civil works, and construction labour. The equipment is assumed to be installed outdoors with adequate insulation and heat tracing. For extreme cold climates, installation in climate controlled buildings may be required, which could add to capital costs. Heated buildings/housings are provided for pumps and electrical equipment. Flow equalization infrastructure costs are omitted. Third party engineering costs are omitted.

For comparison purposes with the CH2MHill estimate, for 182 m^3/h, a total installed cost of CAD$10,300,000 to CAD$15,300,000 was estimated by GE (2013). The discrepancy is partially accounted for in that CH2MHill have included costs for standalone utilities and electrical service to the plant, feed, effluent, and residuals piping to/from the plant, influent heating and pH adjustment, downstream aerobic polishing, and residual biomass thickening and dewatering.

For additional comparative purposes:

- Total installation costs for one plant operating at about 9 m^3/h (40 gpm) to remove selenium from 0.015 to 0.005 mg/L were under CAD$1,500,000 (USD$1,000,000 in 2002) (19). However, the installation made use of some existing tanks. Factoring this cost using the rule of six-tenths to a flow rate of 182 m^3/h generates a total installed cost of CAD$9,000,000 which is considerably closer to the costs estimated by GE than those estimated by CH2MHill.

- Total installation costs for one plant operating at about 17 m^3/h (75 gpm) to remove selenium from 0.500-0.700 to 0.100 mg/L were CAD$4,500,000 (USD$3,000,000 in 2002) (19). Factoring this cost using the rule of six-tenths to a flow rate of 182 m^3/h generates a total installed cost of CAD$18,700,000 which is closer to the costs estimated by GE than those estimated by CH2MHill.

Sustaining Capital

Less than 1% annual GAC media attrition is expected for most operations; 5% GAC media top-up may be required every 5 to 10 years (79).

Operating

Reagent consumption is proportional to contaminant loading, feed pH, and required contaminant removal efficiencies. Power consumption for pumping is proportional to contaminant loading, which dictates reactor size. Operator attention requirements are moderate at about one full-time equivalent (79) for reagent refill, plant walkdown/observation, and instrument cleaning. Annual maintenance requirements are moderate.

A +100%/-50% operating cost curve for ABMet® technology for selenium removal has been developed by CH2MHill (26). The estimates include reagents, power, granular media top-up, cleaning, maintenance, labour, and on-site residue disposal costs (residuals are assumed to be non-hazardous). It should be noted that CH2MHill cost estimates for selenium removal technologies are not on the same accuracy basis as other technology costs estimates given in this report.

For the base case of 182 m^3/h (800 gpm), a total operating and maintenance cost of CAD$1.28/$m^3$ treated (USD$1.26/$m^3$) was estimated (2012). In contrast, GE estimates the operating cost of the ABMet® system to range between CAD$0.03 to CAD$0.14/m^3 treated (USD$0.10 to USD$0.50/1000 US gallons treated) (2013) (79).

Table 8-30: ABMet® Reagent Costs

Reagent	Format	Cost (CAD$/kg)
Nutrient	bulk liquid	$0.37

Per GE, the typical power consumption of the ABMet® system is less than 0.13 kW/m^3 treated (79).

For additional comparative purposes:

- Annual operating costs for one plant operating at about 9 m^3/h (40 gpm) to remove selenium from 0.015 to 0.005 mg/L are approximately CAD$63,000 (USD$60,000) or CAD$0.79/$m^3$ treated (19).
- Annual operating costs for one plant operating at about 17 m^3/h (75 gpm) to remove selenium from 0.500-0.700 to 0.100 mg/L are approximately CAD$263,000 (USD$250,000) or CAD$1.68/$m^3$ treated (19).

8.2.15 Membrane Size/Charge Exclusion

8.2.15.1 Reverse Osmosis

Process Description

Reverse osmosis (RO) removes total dissolved solids (TDS) (including dissolved metals, selenium, phosphorus, chlorides, ammonia and cyanide) by the high pressure application of effluent to selectively permeable membranes that exclude dissolved solids but allow the passage of water molecules. Reverse osmosis membranes exclude dissolved solids by charge and size. The high feed pressure is required to overcome the osmotic pressure that develops across RO membranes, pushing the water molecules through the membrane to generate a low TDS permeate stream. Dissolved solids are retained on the feed side of the membrane and exit the pressure vessels in the high TDS concentration reject stream. Prior to discharge, the permeate requires pH adjustment and potentially re-mineralization (e.g., re-addition of Ca^{2+}, Mg^{2+}, etc.) to meet discharge toxicity requirements.

Reverse osmosis is generally reported as being able to remove over 95% of total dissolved solids from feed effluent, however precise removal efficiency depends on effluent quality and temperature, and will vary for individual parameters in the feed stream (e.g., copper, selenium, ammonia, etc.). As the application of reverse osmosis for treatment of mine effluents prior to discharge is not common at Canadian mining operations, a limited amount of data on removal efficiencies and achievable effluent concentrations exists for full scale operations. For this study, this information has been supplemented by removal efficiencies available in literature.

A base metal operation in Yukon Territory employs reverse osmosis to polish effluent prior to discharge. The process achieves removal efficiencies between 20% to 96% depending on parameter. Lower removal efficiencies are achieved for those parameters with low feed concentrations. Concentrations below 0.05 mg/L are achieved for arsenic, copper, iron, manganese, nickel, selenium, zinc and phosphorus. Concentrations below 0.1 mg/L are achieved for aluminum and ammonia.

Table 8-31: Reported Removal Efficiency from Reverse Osmosis Systems

Parameter	Removal Efficiency	Reference
Al	95 - 99%	(80)
As	As(V) 91 – 99% As(III) 20 – 55%	(80) Operations Questionnaires
Cl	> 98%	In-House Data Operations Questionnaires
Cu	> 95%	(81)
Fe	> 95%	In-House Data Operations Questionnaires
Mn	> 95%	In-House Data Operations Questionnaires
Ni	> 95%	In-House Data Operations Questionnaires
P	>80%	In-House Data Operations Questionnaires
Se	91% - 99%	(26)
Zn	>95%	(80) Operations Questionnaires
NH_4^+	>85%	In-House Data Operations Questionnaires

Reverse osmosis systems operate best with stable feed quality and volumes, and at indoor ambient temperatures, though they can tolerate variations in these parameters. Recovery and permeate volume increase with lower feed dissolved solids and warmer feed temperatures. Conversely, increases in feed dissolved solids result in higher reject volumes requiring management. Cooler feed temperatures require higher pressures to achieve the same removal efficiencies that could be achieved at higher temperature and lower pressures.

As solutes rejected by the RO membranes accumulate on the feed side of the membrane, there is a risk of scale formation as low solubility ions reach their solubility limits. This can be especially problematic when feed solutions contain species that are at or near saturation. Typically this risk is managed by antiscalant dosing into the feed stream and clean-in-place regimes, however if scaling occurs it can reduce recoveries and shorten membrane life.

Residuals

Residuals generated by reverse osmosis are the high TDS reject stream, the spent clean-in-place chemicals and backwash water. The most significant among these is the high TDS reject stream, as it constitutes a large fraction of the residuals requiring management. These residuals streams may be managed by:

- Conventional treatment (e.g., metal or sulfide precipitation), either in a downstream treatment step or by return to the feed of an upstream treatment process, followed by sludge dewatering and disposal in an isolated storage facility.
- Evaporation and crystallization followed by drying to form a solid waste product. The solid wastes must then be stored in an isolated storage facility to prevent their re-dissolution in water.
- Disposal in an isolated storage facility (e.g., the tailings storage facility).

When the high TDS reject is returned to facilities that contain water (e.g., such as a tailings storage facility) for recycle for site use or for treatment and discharge, accumulation of highly soluble ions (e.g., Na^+, Cl^-) can occur. This accumulation can render the water unacceptable for recycle as the high TDS may be incompatible with process requirements or equipment materials of construction. Similarly, TDS accumulation in effluent discharged to the environment could result in failing effluent toxicity tests. The return of high TDS reject to tailings storage facilities can also impact the closure of the tailings facility. Upon closure, the high TDS water will ultimately need to be treated. For these reasons, disposal of high TDS reject in tailings storage facilities is not recommended.

Reject management is a critical consideration in the design of reverse osmosis systems for mine and mill effluent treatment and can add significant capital and operating costs.

Reverse osmosis membranes typically require replacement every 3 to 5 years, generating an additional waste stream that must be managed. Membranes are generally landfilled, in either on-site or off-site landfill facilities.

Major Equipment

Pre-treatment may be required prior to effluent introduction to membranes to control fouling/scaling and to minimize damage to the membranes, depending on whether the RO system is fed by an upstream treatment process, and if so, what that process comprises. Pre-treatment for reverse osmosis typically consists of, at minimum, removal of total suspended solids, and antiscalant addition. pH adjustment may also be necessary, depending on the targeted parameters. These pre-treatment processes may be preceded by bulk removal of targeted parameters (e.g., metals) by conventional treatment processes (e.g., hydroxide precipitation), depending on effluent quality.

Major equipment for RO:

- Bulk TSS removal, if necessary.
- Fine filtration (e.g., media filtration, microfiltration, ultrafiltration, cartridge filters).
- High pressure feed pump.
- Reverse osmosis pressure vessel skids.
- Reverse osmosis membranes.
- Antiscalant dosing system.
- Clean-in-place system.
- Permeate and Reject Storage Tanks, if required.
- Discharge or transfer pumps, if required.

Synergies and Challenges

Reverse osmosis can be employed following chemical and physical bulk removal processes (e.g., hydroxide or sulfide precipitation, ferrous hydroxide co-precipitation and adsorption) as a polishing step to achieve low effluent concentrations. Alternatively, it could be used a pre-treatment step to generate a lower volume and higher concentration stream to reduce the capital cost and removal efficiency of treatment by other means.

At sites where a concentrated brine is required for mine service water due to its anti-freeze properties (e.g., drill water in permafrost or to facilitate ore handling in extreme cold), there may be a potential to re-use the reject stream generated by reverse osmosis; however depending on the use, this could result in unacceptable solute accumulation in site water.

Challenges associated with reverse osmosis include:

- Reject management is site-specific and must be considered carefully.
- Scale formation on membranes due to the supersaturation of solutes rejected by the membrane that accumulate on the feed side. This may be an especially significant issue when considering mining effluents in which low solubility species such as calcium and sulfate (which together form gypsum) are frequently present.
- Reverse osmosis permeate requires pH adjustment and re-mineralization (e.g., alkalinity addition) to comply with effluent pH and toxicity requirements, adding additional reagent costs.
- Permeate recovery is limited by mechanical pressure tolerance of pressure vessels housing the membranes (an issue encountered with high total dissolved solids feeds, may not be a significant issue for typical mine effluents).
- Effluent may require pre-heating for optimal operation, depending on upstream process environment (i.e., indoors/outdoors, season).

- There is a limited amount of full-scale experience with this technology in mine effluent treatment applications though it is a well established technology for other applications (e.g., desalination).
- The high pressure required for effluent delivery to membranes in turn requires high pressure and high energy demand feed pumps.

Relative Prevalence in Industry

This technology has seen limited application for the treatment of mining effluent prior to discharge to the environment, as regulatory discharge limits have not typically necessitated the removal efficiencies associated with reverse osmosis. Further, the technology is considered to be prohibitively expensive in terms of both capital and operating costs by several questionnaire respondents that had engaged in feasibility studies for reverse osmosis effluent treatment. However, this technology is employed for effluent treatment at a base metal operation in Canada, and has been employed for selenium removal at Richmond Hill Mine in South Dakota (19).

Costs

Capital Cost

The bulk of the capital cost data reviewed for reverse osmosis equipment for this study fell between CAD$6,000 - CAD$25,000 per m^3/h of installed capacity (m^3/h of feed basis).The data was taken from in-house cost data, technology review reports, and vendor and operations data reported via questionnaire.

The capital cost for reverse osmosis equipment (including pre-treatment) based on feed flow rate is illustrated in Figure 8-19.

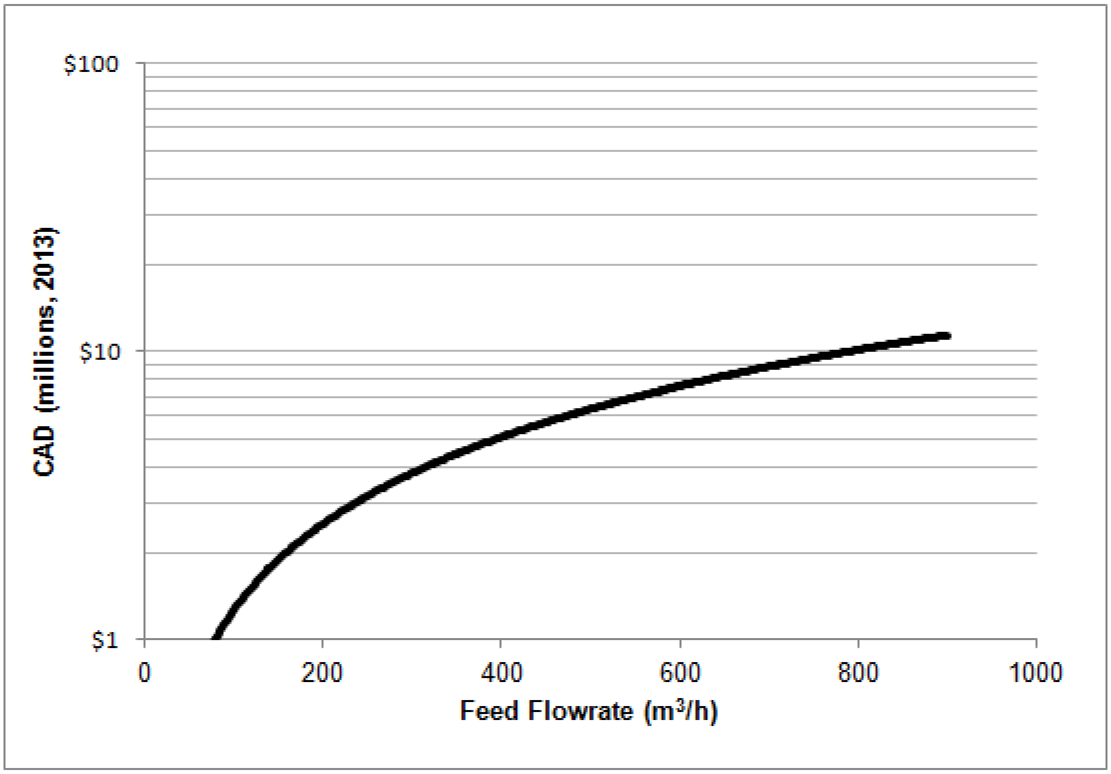

Figure 8-19: Capital Cost of RO Equipment by Feed Flow Rate

1

Sustaining Capital

Sustaining capital expenditure is required for membrane replacement every 2 to 5 years, depending on effluent quality, pre-treatment and maintenance regimes. Cartridge filters in the pre-treatment system will also require placement, typically more frequently than the RO membranes. Reverse osmosis membranes typically cost around CAD$1000 each.

Operating Cost

Consumption of antiscalant and pH adjustment chemicals is proportional to the feed flow rate to RO systems, while consumption of clean-in-place chemicals (HCl, NaOH, EDTA) is dependent on the frequency of cleaning required during operations.

Depending on effluent quality, an RO system could require 2 to 5 kWh of electrical energy per cubic metre treated.

Operator attention requirements are fairly low for this process, as reverse osmosis units are largely automated systems. Operation of RO systems requires some level of monitoring and maintenance each shift, to monitor and maintain chemical supplies and equipment. Full operator attention is required during clean-in-place operations, the frequency of which depends largely on effluent quality.

Monthly maintenance may be required for pump upkeep, chemical replacement, RO membranes and cartridge filter replacement as necessary, and instrumentation calibration. Annual maintenance would be required for thorough system cleaning and equipment replacement as necessary.

Operating costs reviewed for this study for reverse osmosis operation fell between CAD$0.30 – CAD$2.50/m^3 treated.

8.2.15.2 Nanofiltration

Process Description

Nanofiltration (NF) is a membrane process similar to reverse osmosis that removes multivalent dissolved solids (including aluminum, arsenic, copper, iron, lead, manganese, nickel, zinc, radium-226 and selenium) from effluent via the pressurized application of effluent to a charged, selectively permeable membrane that rejects multivalent ions. Unlike reverse osmosis, however, the membrane allows the passage of water and monovalent ions (e.g., sodium, chlorides, cyanide, ammonia, etc.), and the required feed pressure is lower. Nanofiltration membranes exclude multivalent dissolved solids by charge and size. Like RO, NF generates a low TDS permeate stream, and a concentrated, high TDS reject stream on the feed side of the membrane.

Nanofiltration has been proposed as a substitute to reverse osmosis in instances where rejection of multivalent ions (e.g., Cu^{2+}, Ni^{2+}) is more important than rejection of monovalent ions (e.g., Na^+, Cl^-, NH_4^+,CN^-) and where lower removal efficiencies are acceptable. Removal of multivalent metals is frequently the objective for treatment of mining effluents, and so nanofiltration is an interesting option.

Nanofiltration has been reported to remove up to 95% of targeted multivalent ions in effluent, however the precise removal efficiency depends on effluent quality, and will vary for individual parameters in the feed stream (e.g., copper, iron, zinc, etc.) (82). As the application of nanofiltration for treatment of effluent prior to discharge is not typical at Canadian mining operations, little data on removal efficiencies and achievable effluent qualities exist as demonstrated by full-scale operations.

The use of NF at the Bingham Canyon Mine in Utah was reviewed in MEND Report 3.15.1, *Application of Membrane Separation Technology to Mitigation of Mine Effluent and Acidic Drainage* (82). This report found that the nanofiltration process achieved over 97% rejection of measured parameters (Al, Ca, Cu, Fe, Mg, Mn, Zn, SO_4, TDS); however, as the feed stream in this case had very high influent concentrations, the permeate concentrations were above 2 mg/L, which would exceed current *MMER* discharge limits.

An effluent treatment system including NF for the removal of hardness and sulfates as pre-treatment for ion exchange has been installed at a base metal operation in Ontario; however, this plant is not in use at this time and is not needed to meet discharge limits.

Table 8-32: Reported Achievable Concentrations and Removal Efficiency from Nanofiltration △1

Parameter	Removal Efficiency	Reference(s)
Al	> 95%	(83)(82)
As	> 90% As(V) 20 – 90% As(III)	(84)
Cu	> 90%	In-House Data (83)
Fe	> 95%	In-House Data (83)
Pb	> 84%	(85)
Mn	> 95%	(86)
Ni	> 95%	In-House Data (80)
P	n/a**	(26)
Se	> 90%	(44)
Zn	> 95%	(82),(87), (82)

Note: these values are based on concentrations primarily reported in literature based on experiments that utilized a variety of effluents, including those with high metal concentrations. The achievable concentrations will ultimately depend on the feed concentrations and the associated cation or anion as well as pH.
**No permeate qualities were found in the literature.

Like reverse osmosis systems, nanofiltration systems operate best with stable feed quality and volumes, and at indoor ambient temperatures, though they can tolerate variations in these parameters. Recovery and permeate volume increase with lower feed dissolved solids and warmer feed temperatures. Conversely, increases in feed dissolved solids result in higher reject volumes requiring management. Cooler feed temperatures require higher pressures to achieve the same removal efficiencies that could be achieved at higher temperature and lower pressures.

As solutes rejected by the NF membranes accumulate on the feed side of the membrane, there is a risk of scale formation as low solubility ions reach their solubility limits. Typically this risk is managed by antiscalant dosing into the feed stream, however if scaling occurs it can reduce recoveries and shorten membrane life.

Residuals

Residuals generated by nanofiltration are the high TDS reject stream, the spent clean-in-place chemicals and backwash water. The most significant among these is the high TDS reject stream, as it constitutes a large fraction of the residuals requiring management. These residuals streams may be managed by:

- Further brine concentration through RO, evaporation and crystallization followed by drying to form a solid waste product, resulting in significant additional capital and operating cost. The solid wastes must then be stored in an isolated storage facility to prevent their re-dissolution in water.
- Disposal in an isolated storage facility (e.g., the tailings storage facility).
- Conventional treatment (e.g., metal or sulfide precipitation), either in a downstream treatment step or by returning the reject to the feed of an upstream treatment process, followed by sludge dewatering and disposal in an isolated storage facility.

Even though the reject stream will not contain as high a TDS concentration as RO reject reclaim water can still accumulate highly soluble ions (e.g., Na^+, Cl^-) over time. Depending on the rate of recycle this accumulation can render the water unacceptable for reclaim due to incompatibility with process water requirements or equipment materials of construction. Similarly, TDS accumulation in water discharged to the environment could result in failing effluent toxicity tests. The return of high TDS reject to tailings storage facilities can also impact the closure of the tailings facility. Upon closure, the high TDS water will ultimately need to be treated. For these reasons, disposal of high TDS reject in tailings storage facilities is not recommended.

Reject management is a critical consideration in the design of nanofiltration systems for mine and mill effluent treatment and can add significant capital and operating costs.

Membranes for the nanofiltration process are likely to require replacement every 3 to 5 years, generating an additional waste stream that must be managed. Membranes are generally landfilled, in either on-site or off-site landfill facilities.

Major Equipment

Pre-treatment may be required to control fouling/scaling and to minimize damage to the membranes, depending on what treatment comprises the upstream process. Pre-treatment for nanofiltration typically consists of, at minimum, removal of total suspended solids, and antiscalant addition. pH adjustment may also be necessary, depending on the targeted parameters.TSS removal may be preceded by bulk removal of targeted parameters (e.g., metals) by conventional treatment processes (e.g., hydroxide precipitation), depending on the feed quality of water being treated. The summary of major equipment required for reverse osmosis provided in this section covers suspended solids pre-treatment and the reverse osmosis process.

Major equipment for nanofiltration

- Bulk TSS removal, if necessary.
- Fine filtration (e.g., media filtration, microfiltration, ultrafiltration, cartridge filters,).
- Feed pump.
- Nanofiltration pressure vessel skids.
- Nanofiltration membranes.
- Antiscalant dosing system.
- Clean-in-place system.
- Permeate and Reject Storage Tanks, if required.
- Discharge or transfer pumps, if required.

Synergies and Challenges

Nanofiltration can be employed following chemical and physical bulk removal processes (e.g., hydroxide or sulfide precipitation, ferrous hydroxide co-precipitation and adsorption) as a polishing step to achieve low effluent concentrations. It can also be employed prior to additional parameter-specific polishing steps (e.g., selective ion exchange polishing) for pre-treatment to protect and reduce the metal loading to a downstream polishing step. Alternatively, it could be used as a pre-treatment step to generate a lower volume and higher concentration stream to reduce the capital cost and removal efficiency of treatment by other means.

Challenges associated with nanofiltration include:

- Reject management is site-specific and must be considered carefully.
- Scale formation on membranes due to the supersaturation of solutes that are rejected by the membrane and accumulate on the feed side. This may be an especially significant issue when considering mining effluents in which low solubility species such as calcium and sulfate (which together form gypsum) are frequently present.
- Nanofiltration permeate may require pH adjustment and re-mineralization (e.g., alkalinity addition) to comply with *MMER* effluent pH and toxicity requirements, adding additional reagent costs.
- Effluent may require pre-heating for optimal operation, depending on upstream process environment (i.e., indoors/outdoors, season).
- There is a limited amount of full-scale experience with this technology.

Relative Prevalence in Industry

Nanofiltration has seen little application for the treatment of Canadian mining effluent, and is a relatively unfamiliar and untested technology, especially as compared to other effluent polishing steps. Historically, regulatory discharge limits have not necessitated the consideration of this technology to meet effluent quality requirements.

Costs

Capital Cost

Capital cost considerations for nanofiltration technology is comparable to reverse osmosis capital costs. Both technologies require similar membrane housing equipment and wrap-around equipment, and have similar membrane unit costs.

Sustaining Capital

Sustaining capital expenditure is required for membrane placement every 3 to 5 years, depending on feed water quality, pre-treatment and maintenance regimes. Cartridge filters in the pre-treatment system will also require placement, typically more frequently than the NF membranes.

Operating Cost

Consumption of antiscalant and pH adjustment chemicals is proportional to the feed flow rate to NF systems, while consumption of clean-in-place chemicals (HCl, NaOH, EDTA) is dependent on the frequency of cleaning required during operations.

Operator attention requirements are fairly low for this process, as nanofiltration systems are largely automated. Operation of NF systems requires some level of monitoring and maintenance each shift, to monitor and maintain chemical supplies and equipment. Full operator attention is required during clean-in-place operations, the frequency of which depends largely on feed water quality.

Monthly maintenance may be required for pump upkeep, chemical replacement, NF membrane and cartridge filter replacement as necessary, and instrumentation calibration. Annual maintenance would be required for thorough system cleaning and equipment replacement as necessary.

Operating costs for NF are comparable, but slightly less than, RO operating costs due to the reduced pump energy requirements associated with NF membranes.

8.2.16 Passive Treatment

Passive treatment systems require little to no input of reagents, power, operating labour, or maintenance. They rely on naturally occurring processes and ideally, require only infrequent monitoring and maintenance. Passive treatment systems have been applied for removal of contaminants of concern from mining effluent in many mining jurisdictions.

In general, the feasibility and performance of passive systems depends on a number of conditions including climate, availability of land, substrate requirements for biological systems, effluent flow rate, and effluent chemistry. Passive systems are generally very sensitive to temperature and residence time. In many cases, these systems are used for secondary and tertiary treatment rather than primary treatment.

Some of the concerns surrounding these technologies include the availability of good design data and documentation of long term performance, geographical suitability (e.g. land availability, containment), their application to cold Canadian climates, particularly the low temperatures in winter (which impacts both biological activity and chemical processes), and their robustness to variability in effluent flow and quality (e.g., such as due to freshet).

In the sections below, degradation and aeration cascades passive treatment technologies are discussed.

8.2.16.1 Natural Degradation

Natural degradation is the most commonly used technology for the passive removal of ammonia, cyanide, and thiosalts from Canadian mining effluents.

Natural degradation of ammonia primarily occurs through volatilization of un-ionized ammonia gas (NH_3) and biological oxidation. These processes are influenced by pH, temperature, and dissolved oxygen concentration. The equilibrium curve for ammonia is such that at pH ≥ 9 and ambient temperatures of 20 °C (approximate summer temperature), more than 50% of ammonia exists as un-ionized ammonia (NH_3) which has a high vapour pressure and can volatilize into the atmosphere. Higher temperatures, pH, and dissolved oxygen concentrations promote volatilization and aerobic biological oxidation. Large surface area to depth ratios promote un-ionized ammonia volatilization and higher dissolved oxygen contents. The rate of volatilization is also influenced by pond conditions (e.g. turbulence). Natural degradation of ammonia can be used as primary treatment in combination with active treatment seasonally. However, it is impeded by ice/snow cover in winter (which limits NH_3(g) volatilization and O_2 ingress) as well as cold temperatures. Natural degradation is also impeded by the high flows associated with spring freshet, due to shorter retention time. Favourable conditions for natural degradation of ammonia can be found at sites with large storage basins and polishing ponds, which allow for long residence time and seasonal discharge.

Cyanide may be degraded naturally in on-site impoundments (e.g., tailings storage facility, polishing ponds) via various pathways; primarily via volatilization of hydrogen cyanide gas (HCN), but also via hydrolysis, photo-degradation, dissociation of metal cyanide complexes, chemical oxidation, aerobic biological oxidation, and precipitation (16). These processes are influenced by pH, temperature, ultraviolet irradiation, and dissolved oxygen concentration. The dissociation of metal cyanide complexes and volatilization of HCN are thought to be the dominant mechanisms of removal(35). The equilibrium curve for cyanide is such that at pH ≤ 8, most cyanide exists as hydrogen cyanide (HCN) which has a high vapour pressure and can volatilize into the atmosphere. Cyanidation tailings, although normally alkaline, may approach pH 8 through atmospheric carbon dioxide dissolution. Heat and ultraviolet irradiation promote the hydrolysis of metal-cyanide complexes. Higher temperatures and dissolved oxygen concentrations promote chemical oxidation and aerobic biological oxidation. Large surface area to depth ratios promote cyanide volatilization, ultraviolet irradiation, and higher dissolved oxygen contents. Natural degradation of cyanide can be used as primary treatment in combination with active treatment seasonally. However, it is impeded by ice/snow cover in winter (which limits CO_2 ingress, HCN volatilization, and O_2 ingress) as well as cold temperatures. Natural degradation is also impeded by the high flows associated with freshet, due to shorter retention time.

Un-ioniozed Ammonia and hydrogen cyanide volatilize into the atmosphere at low concentrations below thresholds for harm to the environment or human health.

Thiosalts in mining effluents are most frequently controlled through natural degradation to sulfate/sulfuric acid in tailings ponds or holding ponds. An adequate degree of degradation may be achieved with sufficient volume and residence time as well as sufficiently high temperature (degradation rate is higher in warmer waters).

Phosphorus may be synergistically removed in biological natural degradation processes, as it is a nutrient required for aerobic biological oxidation.

In general, seasonal variations in system performance (due to temperature fluctuations and freshet) may be addressed by ensuring adequate storage and residence time is available in order to avoid discharging partially treated effluent.

Table 8-33: Typical Achievable Concentrations from Natural Degradation

Parameter	Achievable Concentration (mg/L)	Reference
NH_3/NH_4^+	<2.0 as N	Demonstrated by water management system performance for various (sub)sectors
CN	<5.0	(16)

8.2.16.2 *Aeration Cascades*

In aeration cascades, effluent is allowed to flow downward by gravity over a series of steps or baffles, in order to increase exposure time and the area to volume ratio of air-water contact. The simplest version is a concrete step structure, where water falls in thin layers from one step to the next (see Figure 8-20). Increasing the number of steps increases the air to water exposure time, and the addition of baffles improves the area to volume ratio by producing turbulence.

Figure 8-20: Aeration Cascade for Oxidation of Coal Effluent (88)

Aeration removes or modifies contaminants via scrubbing (physical removal of dissolved gases/volatile components) and oxidation as described in Section 8.2.5.1. Aside from the removal of CO_2, iron, and manganese, an aeration cascade may also be used at the end of an effluent treatment process to raise dissolved oxygen levels in effluent prior to discharge (e.g., after anaerobic treatment processes).

Suspended solids generated due to oxidation and subsequent precipitation of iron and manganese require downstream solid/liquid separation.

In limited situations, aeration is used as the sole remediation technology for mine waters, but more often is applied in conjunction with other treatment steps. Aeration may be used at various stages in the effluent treatment. When utilized prior to active chemical treatment steps, aeration may reduce the amount of treatment chemical required. Passive cascade aeration is ideal for remote mine sites as it requires little or no power.

Some challenges may include operating problems such as corrosion, slime and algae build-up, as well as operation in cold climates, where the cascade aerator may need to be housed, with adequate ventilation provisions.

9. Cost Estimation of Effluent Treatment Technologies under Consideration as BAT/BATEA

In this section, for each subsector, the model effluent management and treatment system is summarized, technologies that can be applied to the model treatment process to augment system performance are identified, and ultimately, capital and operating cost estimates are presented for each applicable technique to support BATEA selection in comparison to the model base case. Cost estimates presented in this section are summarized as part of the BATEA Selection Summary, in Section 10.

The technologies that were carried forward from preliminary screening for consideration as BATEA were again screened to select the technologies that can augment the (sub)sector model effluent management and treatment systems by improving removal efficiencies and reducing final effluent concentrations of parameters of concern. Technologies that are already included in the (sub)sector model effluent treatment systems were considered non-applicable as their addition is redundant.

Cost values presented in this section are order-of-magnitude (±50%) estimates that have been generated to approximately quantify the incremental capital and operating costs that would be incurred for the installation and operation of the technique at each subsector model site. Costs for the model systems are not included in the incremental costs for augmentative technologies.

To generate these cost estimates, a variety of cost data sources were utilized, including:

- Capital and operating cost data collected via the operations and vendor questionnaires.
- Validated capital and operating cost data collected from operations via review of Revision A and Revision 0 of this report.
- In-house capital and operating cost information.
- Capital and operating cost data specifically collected from vendors in response to commentary received during review of Revision A and Revision 0 of this report.
- Relative contribution of reagents, labour, power, utilities, transportation, sludge management and maintenance to operating costs, reported in the operations questionnaire data.
- Cost data reported in literature.

There were generally less cost data available for those technologies that have had limited application for the treatment of mining effluent. High level technology capital and operating cost information is presented within the technical characterizations of BAT technology (Section 8).

It is important to note the capital and operating costs presented in this section have been developed on an order-of-magnitude basis (±50%) for the sole purpose of this study. These costs are intended to be generally representative of the incremental capital and operating costs that the model site would incur to install and operate the studied technologies, to support the BATEA selection in this study. Accordingly, the level of engineering performed to develop these costs was that which was sufficient to produce approximate order-of-magnitude cost estimates while remaining feasible within the time and budget constraints of the study.

For most effluent treatment technologies, total installed costs were estimated by applying typical factors to equipment costs to incorporate additional direct and indirect costs. Direct cost factors account for shipping and transportation, installation, site preparation and civil works, piping, HVAC, electrical and controls and plant services and utilities costs. Indirect cost factors account for wrap-around engineering, procurement, construction management, temporary construction services, insurance, spares and cold commissioning.

Where total installed costs were developed from equipment costs utilizing typical factors, total installed costs were determined to be roughly 3 times equipment costs for most technologies. However, one uranium operation in Saskatchewan reported during the Revision A / Revision 0 review period that the ratio of total installed costs to equipment costs for a clarifier installation in 2008 was greater than 5 for site-specific reasons possibly related to high materials and labour costs due to the remote location of the operation. Commentary provided by a coal operation during the Revision A / Revision 0 review period indicated ratios of total installed costs to equipment costs as high as 10 for certain technologies; however, follow-up to seek clarification on this comment was unsuccessful.

It is acknowledged that actual site costs could vary significantly from the presented figures, depending on numerous site-specific factors including process factors (e.g., effluent parameters of concern and concentrations, pH, temperature, volume/flow rate) and site factors (e.g., site location, shipping costs, electricity costs, existing effluent management and treatment facilities, existing residuals storage/disposal facilities, site layout, available outdoor footprint, available footprint in process buildings, available utilities, available skilled labour, discharge criteria, etc.). For all technologies, it is assumed that a sufficient space is available for the incorporation of the necessary equipment into the model system. Site layout may impact the distance to supply effluent, electricity and other utilities to treatment processes, as well as the distance to pump treatment residuals to storage/disposal facilities.

Based on commentary received during the review of Revision A / Revision 0 of this report, the development of cost estimates to accommodate of site-specific factors was considered, but ultimately not recommended, as developing alternative model systems and cost estimates would require substantial effort, while potentially not adding much value to the study. To achieve the level of model system definition necessary to estimate costs of site-specific features (e.g., costs to construct residuals storage/disposal facilities where none are available or it is not feasible to use existing facilities), many assumptions would be required (e.g., sludge production and settleability, storage/disposal method, meteorological conditions which may dictate storage facility design, storage facility geometry and materials of construction, sources of materials of constructions, etc.). Hatch and MEND agreed that in establishing these assumptions, there would be a risk that the model system considering site-specific factors would become less representative of actual operations and of less value to BATEA selection. To alleviate this risk would require a comprehensive examination of all site-specific factors and alternative configurations. Such an undertaking would not align well with the scope and schedule of the study, to inform the *MMER* multi-stakeholder consultation process. Site-specific factors that could have a substantial impact on total installed cost and operating cost, but have largely not been considered for the model effluent treatment system and sites include, but are not limited to, the following:

- Effluent characteristics including parameters of concern, concentration, pH, temperature, ionic strength. These characteristics of the effluent can affect the amounts of reagents required, the amount of sludge or waste products generated which require management and storage, or even which treatment technologies may be viable.
- Volume or flow rate of the effluent and the seasonal variability of the flow. This can also be influenced by the amount of seasonal attenuation capacity existing on site or that must be added.
- Site location which can affect materials and equipment transportation costs, reagent shipping costs, and labour costs. Site location may also affect the scheduling of construction and can significantly increase construction costs if construction windows are small or if construction labour needs to be brought to site at a premium, as examples.
- Climatic conditions which can affect the volumes of effluent to be treated, the available treatment and/or discharge window, the effluent pre-treatment required (i.e. preheating), and the design of residuals storage/disposal facilities.
- Source of electricity supply (grid based, generators) and the resultant electricity costs. It should be noted that the addition of treatment equipment at some sites may require the addition of supplementary power generation equipment, adding significant capital and operating cost to the site.
- Existing effluent management and treatment facilities, their age, effectiveness and capacity.
- Existing residuals storage/disposal facilities. Cost of residual disposal may be significantly increased if new storage/disposal cells or facilities are needed, storage capacity must be augmented to handle new volumes of waste, and/or regulatory approvals must be sought for these new facilities.
- Existing site layout. Distances to transport residuals to storage/disposal facilities, either by pipeline or by trucking can affect operating as well as initial capital costs. Site layout may also affect the cost of supplying utilities to the effluent treatment plant.
- Footprint availability. The availability of land on site, or space within existing process buildings, can impact costs in a variety of ways. Additional land may need to be purchased, permitting of land for mining use may need to be sought, additional building may need to be constructed or demolition activities may need to occur.

- Soil qualities and geotechnical characteristics in the area of the mine operations directly impact the cost of construction of any new buildings or structures required for the treatment plant.
- Available service utilities, such as potable water or other special quality water, natural gas, steam, etc.
- Available skilled labour, especially labour familiar with the operation of specialty effluent treatment equipment (i.e., MBBR, RO, etc.). The regional cost differences in labour rates can also affect operating costs and construction costs significantly. For example, one uranium operation in Saskatchewan reported during the Revision A / Revision 0 review period that labour costs have increased three fold in proportion to materials costs from 2008 to 2014. 1
- Test work requirements that can include both bench and pilot testing. These test programs must be conducted before many of the technologies can be implements at full scale, adding additional costs to the estimate and potentially delaying schedule for implementation.
- Local permitting requirements and stakeholder consultation requirements which can significantly affect schedule as well as cost.

9.1 Metals: Base Metal

Refer to Section 6.1 for the complete discussion of the base metal subsector model effluent management and treatment system.

In this model, effluent is equalized prior to hydroxide precipitation and bulk TSS removal via pond-based settling. The effluent is coagulated and flocculated before precipitates and TSS are allowed to settle in the settling pond. The pond system also allows residence time for passive natural degradation of ammonia. Pond decant is pH adjusted with carbon dioxide to meet *MMER* pH limits and/or un-ionized ammonia/toxicity requirements prior to discharge to the environment.

The design flow rate of the model effluent management and treatment system for the base metal subsector is 2,000 m^3/h. The nominal flow rate is 870 m^3/h. See Section 6.1 for more details on these design criteria.

9.1.1 Technologies Applicable for the Augmentation of the Model Effluent Management and Treatment System

The effluent treatment technologies that are considered applicable for augmentation of the base metal subsector model effluent management and treatment system are:

- Sulfide Precipitation.
- Sulfide Precipitation with Proprietary Polymeric Organosulfide Chemicals.
- Solid/Liquid Separation – Clarification, Enhanced Coagulation and Settling, and Filtration.
- Air Stripping.
- Selective Ion Exchange – Synthetic Resins for Metals Polishing.

- Selective Ion Exchange – Zeolite for Ammonia Removal.
- Adsorption – ZVI.
- Active Aerobic Biological Oxidation.
- Active Anoxic/Anaerobic Reduction.
- Reverse Osmosis.
- Nanofiltration.

The concentrations achieved by the model effluent treatment system in the base metal subsector of radium-226 and cyanide are very low, 0.1 Bq/L and 0.05 mg/L, respectively (see Table 6-20). Therefore, barium chloride co-precipitation and cyanide destruction technologies were not considered as BATEA for the base metal subsector.

Oxidation technologies were also ruled out as there is insufficient information on the speciation of iron and manganese to determine if improved removal efficiencies could be attained.

9.1.2 Model Treatment Cost

The range of reported capital costs for base metal effluent management and treatment systems similar to the model, including upgrades and adjusted to 2013 CAD$, is CAD$1,300 to CAD$11,000 per m^3/h installed capacity. For the model effluent management and treatment system with 2000 m^3/h design treatment capacity, this would equate to CAD$2,600,000 to CAD$22,000,000 total installed cost.

The range of reported operating costs for base metal effluent management and treatment systems similar to the model is CAD$0.02 to CAD$0.34/m^3. The majority of operating costs are associated with reagent consumption, operating labour, and maintenance. For the model effluent management and treatment system with 870 m^3/h nominal treatment flow rate, this would equate to CAD$150,000 to CAD$2,600,000 annual operating cost.

9.1.3 Technique CAPEX and OPEX

9.1.3.1 Sulfide Precipitation

Chemical sulfide precipitation technology for metals polishing would be best employed within the base metal subsector model flow sheet after the lime addition pond/tailings storage facility and settling pond(s) where bulk dissolved metals and TSS removal and equalization would occur (see Figure 6-16). It is assumed that overflow from the settling pond(s) would be pumped into the chemical sulfide precipitation system, and effluent from the system would then flow by gravity into the polishing pond(s). Residuals could be disposed of in a dedicated area of the tailings storage facility.

Feed pumps, reagent make-up/storage systems and feed systems for sulfide reagent and any additional reagent (e.g., pH adjustment chemicals, flocculant), agitated reaction tank(s), clarifier/thickener(s), and underflow pump(s) would be required.

The incremental capital and operating cost estimates for a chemical sulfide precipitation system for the base metal subsector model effluent treatment process:

- The incremental total installed cost for the system is estimated to be approximately CAD$11,000,000.
- The incremental operating cost for the system is estimated to be approximately CAD$3,700,000/year to CAD$8,200,000/year depending on feed quality (reagent consumption). This equates to an operating cost of CAD$0.48 to CAD$1.08/m^3 treated.
- Other considerations:
- No operating cost discounts have been applied for value recovery through residuals re-processing.
- Insufficient effluent quality information is available to estimate costs for biogenic sulfide precipitation technology.

9.1.3.2 *Sulfide Precipitation with Proprietary Polymeric Organosulfide Chemicals*

Proprietary polymeric organosulfide precipitation technology for metals polishing would be best employed within the base metal subsector model flow sheet before the settling pond (see Figure 6-16). Bulk dissolved metals and TSS removal and equalization would occur at the upstream lime addition pond/tailings storage facility. The proprietary reagent could be dosed into the settling pond influent within a new agitated reactor tank. The effluent would be pumped to the agitated reactor tank via new pumps. The agitated reactor tank would discharge by gravity to the settling pond(s) where subsequent solid/liquid separation would occur. It is assumed that the incremental generation of sulfide sludge could be accommodated by the pond. Addition of a reagent dosing system would be required. Addition of a bulk reagent tank may also be desirable if the reagent is consumed at a high rate. Otherwise, the reagent could be dosed directly from the tote in which it is supplied by the vendor.

Utilizing the GE rule of thumb of 10 mg/L proprietary reagent per mg/L target metals and the concentrations achieved by the model effluent treatment system in the base metal subsector (Table 6-20), it is estimated that, approximately 40 mg/L dosage of proprietary reagent would be required for this application. At the nominal flow rate of 870 m^3/h and 40 mg/L dosage, a tote of proprietary reagent would be consumed within 2 days. It is assumed that this is an unacceptable tote replacement period, and so a 7 day bulk reagent tank has been included in the capital cost estimate below. None of the proprietary reagents investigated require agitation, so a bulk reagent tank agitator has not been included in the capital cost estimate below. Small progressive cavity pumps would be required. It is assumed that dosing pumps would be installed in redundant, duty/stand-by configuration. Power consumption by the pumps is expected to be minor, and is not included in the operating cost estimate below.

The incremental capital and operating cost estimates for a proprietary polymeric organosulfide sulfide precipitation system for the base metal subsector model effluent treatment process are as follows:

- The incremental equipment cost for the system is estimated to be approximately CAD$370,000.
- The incremental total installed cost for the system is estimated to be approximately CAD$1,100,000.

- The incremental operating cost for the system is estimated to be approximately CAD$2,500,000/year. This equates to an operating cost of CAD$0.33/m^3 treated.

Other considerations:

- The chemicals may be acutely lethal to rainbow trout and *Daphnia magna* at certain residual chemical concentrations in effluent. For example, the rule of thumb dosage of 40 mg/L could potentially lead to residual chemical concentrations in effluent that exceed the rainbow trout LC50 of 8 mg/L for MetClear™ MR2405. It is expected that the majority of the chemical will be retained with precipitated metals in the settling pond(s) rather than reporting to the environment. However, sludge carryover and/or cycling up of residual chemical concentration due to effluent recirculation (e.g., for mill process re-use, for effluent treatment process re-use, or for return of off-spec effluent for re-treatment) may pose risk of non-compliance with toxicity requirements. It is advised to verify that treated effluent complies with toxicity requirements (i.e., residual chemical concentration is below lethality thresholds). It is also advised that treated effluent be discharged rather than recirculated for any purpose such that cycling up of residual chemical concentration is limited.
- Due to the relatively recent adoption of these reagents and the proprietary nature of their formulations, little is known about the long term stability of residuals and the potential for acid generation and metals remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.
- There is a potential for reduction of operating costs due to reductions in flocculant consumption, as the proprietary reagents are polymeric in nature and may offset flocculant demand. However, no discounts have been applied to the operating cost presented here.
- It may be possible to mix proprietary reagent with effluent by means alternative to an agitated reactor tank in order to reduce costs and still achieve good metals removal efficiency; however, this has not been demonstrated to the best of Hatch's knowledge.
- The budgetary quotations provided for the proprietary reagents were for delivery to Northern Ontario. Additional costs will apply for delivery to more remote mining operations. The reagents are not classified as dangerous goods.

9.1.3.3 Clarification

Clarification for bulk TSS removal would be best employed upstream of the series of ponds currently used for lime reaction and TSS removal for the base metal subsector model flow sheet. The model process flow sheet would be modified such that lime and effluent are mixed in an agitated feed tank to permit hydroxide precipitation to occur. A clarifier would be installed after the reactor tank and coagulant and flocculant would be dosed to aid in the removal of TSS.

Overflow from the clarifier would flow by gravity, where possible, to the series of ponds for further clarification and solids removal.

Underflow from the clarifier would be pumped to the Tailings Storage Facility.

It may be possible to dose lime upstream of the clarifier in an in-line arrangement; however, for conservatism in estimating capital and operating costs, a reactor tank is included in the cost estimate.

The addition of a reactor tank and clarifier to the base metal subsector model flow sheet would potentially increase lime efficiency, lower sludge production, and offer a higher degree of control over TSS removal and ultimate effluent quality.

The following equipment additions would be required:

- Lime addition reactor feed pump and tank.
- Clarifier feed pump.
- Clarifier.
- Residuals management equipment (e.g., underflow pumps to disposal, underflow tank, etc.).
- The incremental capital and operating cost estimates for a reactor tank and clarifier addition to the base metal subsector model effluent treatment process are as follows:
- Equipment costs are estimated to be CAD$4,900,000.
- The total installed cost for the system is estimated to be approximately CAD$16,200,000.
- The incremental operating cost for the system is estimated to be approximately CAD$760,000/year. This equates to an operating cost of CAD$0.10/m^3 treated.
- CAPEX costs have been updated in Revision 1 based on additional reference cost information for both equipment and total installed costs. These costs have been used to update the clarification equipment cost curve and to adjust factors used to generate installed costs based on clarification equipment costs.

Other considerations:

- There is a potential for reduction of operating costs due to reductions in reagent consumption, due to the higher reagent efficiency associated with the upgraded lime addition system. However, no discounts have been applied to the operating cost presented here.

9.1.3.4 *Enhanced Coagulation and Settling*

An enhanced coagulation and settling process for bulk TSS removal would be best employed upstream of the series of ponds currently used for lime reaction and TSS removal for the base metal subsector model flow sheet. The model process flow sheet would be modified such that lime and effluent are mixed in an agitated feed tank to permit hydroxide precipitation to occur. An ECS system would be installed after the reactor tank and coagulant and flocculant would be dosed to aid in the removal of TSS.

Overflow from the clarifier would flow by gravity, where possible, to the series of ponds for further clarification and solids removal.

Underflow from the clarifier would be pumped to the Tailings Storage Facility.

It may be possible to dose lime upstream of the clarifier in an in-line arrangement; however, for conservatism in estimating capital and operating costs, a reactor tank is included in the cost estimate.

The addition of a reactor tank and clarifier to the base metal subsector model flow sheet would potentially increase lime efficiency, lower sludge production, and offer a higher degree of control over TSS removal and ultimate effluent quality.

The following equipment additions would be required:

- Lime addition reactor feed pump and tank.
- ECS unit.
- Residuals management equipment (e.g., underflow pump(s), underflow tank, pump(s) to disposal), if required.
- The incremental capital and operating cost estimates for the addition of an ECS system to the base metal subsector model effluent treatment process are as follows: 1
- Equipment costs are estimated to total CAD$3,100,000.
- The total installed cost for the system is estimated to be approximately CAD$9,800,000.
- The incremental operating cost for the system is estimated to be approximately CAD$760,000/year. This equates to an operating cost of CAD$0.10/m^3.

The only enhanced coagulation and settling capital and operating cost information provided via the vendor questionnaire for technologies that passed BAT screening was for Veolia’s proprietary ACTIFLO® system; for this reason, ACTIFLO® costs have been used as representative of ECS technologies for BATEA purposes.

Other considerations:

- There is a potential for reduction of operating costs due to reductions in reagent consumption, due to the higher reagent efficiency associated with the upgraded lime addition system and due to the enhanced coagulation provided by ballast or sludge recycle. However, no discounts have been applied to the operating cost presented here.

9.1.3.5 *Filtration*

Media filtration for TSS removal would be best employed within the base metal subsector model flow sheet as an additional solids removal step downstream of the series of ponds currently used for lime reaction and TSS removal. This step would provide removal of contaminants present as solids in the effluent stream. Backwash from media filtration would be returned to upstream settling pond(s) for solids sedimentation.

The following equipment additions would be required:

- Media filtration vessel feed pump.
- Media filtration vessels.

- Media filtration backwash pump.
- Backwash tank.
- Discharge pump.

The incremental capital and operating cost estimates for the addition of a media filtration system to the base metal subsector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$3,400,000.
- The total installed cost for the system is estimated to be approximately CAD$10,300,000.
- The incremental operating cost for the system is estimated to be approximately CAD$380,000/year. This equates to an operating cost of CAD$0.05/m^3.

9.1.3.6 *Air Stripping*

The concentration of total ammonia achieved by the model effluent treatment system in the base metal subsector is 4 mg-N/L (see Table 6-20). At such a low feed concentration, air stripping technology would not be technically feasible for ammonia removal due to the low concentration driving force for volatilization to a lower achievable limit of 3 mg-N/L, as discussed in Section 8.The air stripping process is best suited to feed total ammonia concentrations in the range of 10 to 100 mg/L.

9.1.3.7 *Selective Ion Exchange*

Selective ion exchange for metals polishing would be best employed within the base metal model effluent flow sheet downstream of the series of ponds currently used for lime reaction and TSS removal. Media filtration for solids removal would be required as pre-treatment for selective ion exchange.

The following equipment additions would be required:

- Media filtration vessel feed pump.
- Media filtration vessels.
- Media filtration backwash pump.
- Ion exchange feed, backwash, treated effluent pump(s).
- Ion exchange columns.
- Regenerant chemical totes/tanks and pumps.
- Tanks (spent regenerant and treated effluent if needed).

The incremental capital and operating cost estimates for the addition of a selective ion exchange system to the base metal subsector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$15,400,000.
- The total installed cost for the system is estimated to be approximately CAD$39,600,000.

- The incremental operating cost for the system is estimated to be approximately CAD$5,000,000/year. This equates to an operating cost of CAD$0.65/m^3.

These costs assume that the spent regenerant is returned to the feed to the upstream effluent treatment process to immobilize the metals as hydroxides and that the sludge will be managed as part of the existing sludge management regime. Backwash from media filtration would be returned to upstream settling pond(s) for solids sedimentation.

Other considerations:

- Spent resin disposal costs have not been considered here. If spent resin must be disposed of off-site, this would add to operating costs.
- Operating costs for ion exchange systems are extremely sensitive to metal loading in feed stream.

9.1.3.8 *Zeolite Ion Exchange*

Based on a review of the values in Table 6-7, it was concluded that total ammonia concentrations in base metal effluents are already lower than the achievable total ammonia concentration from a zeolite ion exchange system. Therefore, capital and operating costs for zeolite ion exchange have not been assessed for the base metal subsector.

9.1.3.9 *Adsorption – Zero Valent Iron*

Zero Valent Iron adsorption technology for selenium removal would be best employed within the base metal subsector model flow sheet after the polishing pond(s) (see Figure 6-16). The lime addition pond/tailings storage facility and settling pond(s) would serve for bulk removal of dissolved metals and TSS and for equalization.

ZVI could also be employed upstream of the lime addition pond/tailings storage facility, depending on upstream equalization capacity and the concentration of competing oxyanions in the effluent (e.g., oxyanions of arsenic and sulfate). Such a configuration could be more economical, as it could eliminate the need for equipment associated with downstream iron precipitation and solid/liquid separation. However, with the limited information available and for the purposes of this study, it is assumed that a complete ZVI system would be installed after the settling pond(s). Residual streams could be thickened and disposed of in a dedicated area of the tailings storage facility where appropriate storage conditions are maintained. It is assumed that the incremental generation of sludge could be accommodated by the existing tailings storage facility.

Assuming a stirred-tank reactor ZVI system would be employed, the following equipment additions would be required:

- Reagent make-up/storage systems and feed systems for pH adjustment chemicals.
- ZVI handling systems for ZVI media.
- Agitated ZVI reaction tank(s).
- Agitated post-pH adjustment tank.
- Aeration blower(s)/compressor(s) and diffuser(s).

- Clarifier/thickener(s) and/or media filter(s).
- Residuals management equipment (e.g., pumps to disposal, mechanical dewatering equipment, if necessary).

A base case total installed cost of CAD$35,600,000 for a stirred-tank reactor ZVI system was estimated by CH2MHill for a flow rate of 182 m^3/h; however, this cost could be inflated over more basic costs by over 200% (see Section 8.2.12.1). An operating cost of CAD$1.70/$m^3$ to CAD$3.18/$m^3$ was estimated for stirred-tank reactor ZVI technology; however, this could be inflated over more basic costs by as much as 200% (see Section 8.2.12.1). Factoring the total installed cost using the rule of six-tenths, the incremental capital and operating cost estimates for a ZVI system for the base metal subsector model effluent treatment process are as follows:

- The total installed cost for the system is estimated to be approximately CAD$63,900,000 to CAD$150,000,000.
- The incremental operating cost for the system is estimated to be approximately CAD$17,700,000/year to CAD$24,300,000/year. This equates to an operating cost of CAD$2.32/$m^3$ treated to CAD$3.18/$m^3$ treated.
- Other considerations:
- Most full-scale installations of this technology treat flow rates two orders of magnitude lower than the base metal subsector design flow rate. The applicability of this technology may be limited, accordingly.
- Few full-scale installations have been in operation for long enough to determine long term feasibility.
- The speciation of the base metal subsector total selenium is unknown and, therefore, the cost impacts of speciation cannot be determined.

Due to the relatively recent adoption of this technology, little is known about the long term stability of residuals and the potential for selenium remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.

9.1.3.10 Active Aerobic Biological Oxidation

The concentration of total ammonia achieved by the model effluent treatment system in the base metal subsector is 4 mg-N/L (see Table 6-20). At such a low feed concentration, active aerobic biological oxidation technology would not be technically feasible for ammonia removal due to a typical lower achievable limit of 2 mg-N/L, as discussed in Section 8.2.13.

9.1.3.11 Active Anoxic/Anaerobic Biological Reduction

FBR or ABMet® technology for selenium removal would be best employed within the base metal subsector model flow sheet after the polishing pond(s) (see Figure 6-16). The lime addition pond/tailings storage facility and settling pond(s) would serve for bulk removal of dissolved metals and TSS and for equalization. Residual streams could be thickened, dewatered, and disposed of in a dedicated area of the tailings storage facility where appropriate storage conditions are maintained. It is assumed that the incremental generation of sludge could be accommodated by the existing tailings storage facility.

The following equipment additions would be required:

- Reagent dosing system(s) for pH adjustment, electron donor, and nutrient.
- Bulk reagent storage tanks for electron donor and nutrient, as they are typically supplied as bulk liquids.
- Influent heat exchange system.
- FBR or ABMet system®.
- Aerobic polishing.
- Solid/liquid separation and/or sludge handling, thickening, and disposal system.

A base case total installed cost of CAD$30,500,000 for an FBR system was estimated by CH2MHill for a flow rate of 182 m^3/h (see 8.2.14.1). An operating cost of CAD$1.59/$m^3$ was estimated by CH2MHill for the same system. Envirogen estimated CAD$8,000,000 to CAD$13,000,000 for an FBR system without influent heat exchange, aerobic polishing, and sludge handling, thickening, and disposal systems, and without standalone utilities and electrical service to the plant, and feed, effluent, and residuals piping to/from the plant. An operating cost of CAD$0.85/$m^3$ to CAD$1.16/$m^3$ was estimated by Envirogen for the same system. Factoring the total installed cost using the rule of six-tenths, the incremental capital and operating cost estimates for an FBR system for the base metal subsector model effluent treatment process are as follows:

- The total installed cost for the system is estimated to be approximately CAD$33,700,000 to CAD$54,800,000 for a basic system integrated into existing systems to CAD$128,600,000 for a standalone system.
- The incremental operating cost for the system is estimated to be approximately CAD$6,500,000/year to CAD$8,800,000/year for a basic system integrated into existing systems to CAD$12,100,000/year for a standalone system. This equates to an operating cost of CAD$0.85/$m^3$ treated to CAD$1.59/$m^3$ treated.

As the base metal subsector model effluent treatment process is fairly rudimentary, the addition of an FBR system would require substantial wrap around and independent sludge handling, thickening, and disposal systems. Therefore, the costs may be closer to the higher end of the ranges presented.

A base case total installed cost of CAD$40,700,000 for an ABMet® system was estimated for a flow rate of 182 m^3/h (see Section 8.2.14.2). An operating cost of CAD$1.28/$m^3$ was estimated by CH2MHill for the same system. Factoring the total installed cost using the rule of six-tenths, the incremental capital and operating cost estimates for an ABMet® system for the base metal subsector model effluent treatment process are as follows:

- The total installed cost for the system is estimated to be approximately CAD$171,000,000.
- The incremental operating cost for the system is estimated to be approximately CAD$9,700,000/year. This equates to an operating cost of CAD$1.28/m^3 treated.

It is important to consider that a total installed cost estimate for the same ABMet® system factored from cost curves developed and provided by GE would be lay between CAD$43,400,000 and CAD$64,400,000, which is less than half the total installed cost estimated by factoring from CH2MHill cost curves and would make the technology economically competitive with FBR technology. However, as the base metal subsector model effluent treatment process is fairly rudimentary, the addition of an ABMet® system would require substantial wrap around and independent sludge handling, thickening, and disposal systems. Therefore, the costs may be closer to the higher end of the range presented.

Other considerations:

- Few full-scale FBR installations have been in operation for long enough to determine long term feasibility.
- The speciation of the base metal subsector total selenium is unknown and, therefore, the cost impacts of speciation cannot be determined. △1

Due to the relatively recent adoption of this technology, little is known about the long term stability of residual biomass and the potential for selenium remobilization under various disposal conditions. If residuals are not stable, significant costs associated with biomass stabilization technology or re-treatment of residual leachate could be incurred. △1

9.1.3.12 Reverse Osmosis

Reverse osmosis for TDS removal would be best employed within the base metal subsector model flow sheet as a polishing stage downstream of the series of ponds currently used for lime reaction and TSS removal. Media filtration for solids removal would also be required as pre-treatment to the RO system.

Permeate from the reverse osmosis system would be discharged to the final monitoring pond in the treatment system for effluent quality monitoring or to the environment, following pH adjustment and/or remineralization, as required. Concentrate could be returned to the upstream lime hydroxide precipitation process. Backwash from media filtration would be returned to upstream settling pond(s) for solids sedimentation.

The following equipment additions would be required:

- Media filtration vessel feed pump.
- Media filtration vessels.
- Media filtration backwash pump.

- Fine filtration (cartridge filters).
- Reverse osmosis feed pumps.
- Reverse osmosis pressure vessel skids, with vessels to house approximately 2,000 membranes.
- Antiscalant storage and dosing system.
- Clean-in-place system.
- pH adjustment system.
- Permeate and Concentrate Storage Tanks, if required.
- Discharge or transfer pumps, if required.

The incremental capital and operating cost estimates for the addition of a reverse osmosis system to the base metal subsector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$28,800,000.
- The total installed cost for the system is estimated to be approximately CAD$103,000,000.
- The incremental operating cost for the system is estimated to be approximately CAD$7,000,000/year. This equates to CAD$0.88/m^3.

CAPEX costs have been updated in Revision 1 based on additional reference cost information for both equipment and total installed costs. These costs have been used to update the RO equipment cost curve and to adjust factors used to generate installed costs based on RO equipment costs.

OPEX costs have been updated in Revision 1 based on information received concerning the experience of operations with respect to the operating and maintenance effort required for RO systems. Operations reported that for successful operation of RO systems, frequent cleaning and diligent operator attention is required. The costs of labour and cleaning chemicals have been increased to reflect these demands.

Other considerations:

- RO concentrate management could be difficult to accommodate in the model effluent treatment system. Concentrate return to an upstream treatment process may incur additional costs to expand equipment capacity, and would result in the cycling up of contaminants that are not removed by lime hydroxide precipitation or natural degradation. Should this become problematic, concentrate management equipment may be required and would add significant capital cost and operating cost. For example, the use of an evaporator/crystallizer to manage brine from the RO process (assuming 70% recovery in the RO) would incur the following additional costs:
    - Equipment costs of around CAD$61,900,000, installed equipment costs of around CAD$191,400,000 and operating costs of around CAD$11,400,000/year.

- The operating cost for the RO system is highly dependent on the site-specific energy cost, and on the required frequency of cleaning cycles, which is dependent on the RO feed quality.
- RO permeate is very low in TDS and alkalinity. Re-mineralization of the permeate stream prior to discharge to the environment may be required to comply with toxicity requirements.

9.1.3.13 Nanofiltration

Nanofiltration would be best employed in the base metal model effluent flow sheet for removal of multivalent dissolved ions downstream of the series of ponds currently used for lime reaction and TSS removal.

Media filtration for solids removal would also be required as pre-treatment to the NF unit. Permeate from the nanofiltration system would be discharged to the final monitoring pond in the pond system for effluent quality monitoring or to the environment, following pH adjustment and/or remineralization, as required. Concentrate could be directed to the upstream lime hydroxide precipitation step. Backwash from media filtration would be returned to upstream settling pond(s) for solids sedimentation.

The following equipment additions would be required:

- Media filtration vessel feed pump.
- Media filtration vessels.
- Media filtration backwash pump.
- Fine filtration (cartridge filters).
- Nanofiltration feed pump.
- Nanofiltration pressure vessel skids.
- Antiscalant dosing system.
- Clean-in-place system.
- pH adjustment system.
- Permeate and Concentrate Storage Tanks, if required.
- Discharge or transfer pumps, if required.

The incremental capital and operating cost estimates for the addition of a nanofiltration system to the base metal subsector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$28,800,000.
- The total installed cost for the system is estimated to be approximately CAD$103,000,000.
- The incremental operating cost for the system is estimated to be approximately CAD$5,400,000/year. This equates to an operating cost of CAD$0.71/$m^3$.

Because nanofiltration and reverse osmosis are very similar, with the exception of operating pressure and membranes, the capital costs for nanofiltration have been assumed to be the same as estimated for reverse osmosis. Nanofiltration operates at lower pressures compared to reverse osmosis, therefore energy consumption for nanofiltration will be less. The energy requirements of nanofiltration have been assumed to be 2/3 of the energy requirements of reverse osmosis.

CAPEX costs have been updated in Revision 1 based on updated RO costs, as NF CAPEX have been assumed to be the same as RO costs.

OPEX costs have been updated in Revision 1 based on information received concerning the experience of operations with respect to the operating and maintenance effort required for RO systems. Operations reported that for successful operation of RO systems, frequent cleaning and diligent operator attention is required. It is assumed similar maintenance and operation demands would apply to nanofiltration membranes as well. The costs of labour and cleaning chemicals have been increased to reflect these demands.

Other considerations:

- NF concentrate management could be difficult to accommodate in the model effluent treatment system. Concentrate return to an upstream treatment process may incur additional costs to expand equipment capacity, and would result in the cycling up of contaminants that are not removed by lime hydroxide precipitation or natural degradation. Should this become problematic, concentrate management equipment may be required and would add significant capital cost and operating cost. For example, the use of an evaporator/crystallizer to manage brine from the NF process (assuming 70% recovery in the NF) would incur the following additional costs:
    - Equipment costs of around CAD$61,900,000, installed equipment costs of around CAD$191,400,000 and operating costs of around CAD$11,400,000/year.
- The operating cost for the NF system is highly dependent on the site-specific energy cost, and on the required frequency of cleaning cycles, which is dependent on the feed quality.
- NF permeate is low in TDS and alkalinity. Re-mineralization of the permeate stream prior to discharge to the environment may be required to comply with toxicity requirements.

9.2 Metals: Precious Metal

9.2.1 Model Effluent Management and Treatment System

Refer to Section 6.2 for the complete discussion of the precious metal subsector model effluent management and treatment system.

In the precious metal subsector model, equalized effluent from the tailings storage facility (post-cyanide destruction) is subject to hydroxide precipitation, iron co-precipitation, and TSS removal via flocculant-assisted clarification. Clarifier overflow is discharged to the environment. Clarifier underflow is disposed of at the tailings storage facility, which provides the residence time required for natural degradation of ammonia and residual cyanide.

The design flow rate of the model effluent management and treatment system for the precious metal subsector is 600 m^3/h. The nominal flow rate is 180 m^3/h.

9.2.1.1 *Technologies Applicable for the Augmentation of the Model Effluent Management and Treatment System*

The technologies that are considered applicable for augmentation of the precious metal subsector model effluent management and treatment system are:

- Sulfide Precipitation.
- Sulfide Precipitation with Proprietary Polymeric Organosulfide Chemicals.
- Solid/Liquid Separation – Filtration.
- Air Stripping.
- Selective Ion Exchange – Synthetic Resins for Metals Polishing.
- Selective Ion Exchange – Zeolite for Ammonia Removal.
- Adsorption – ZVI.
- Active Aerobic Biological Oxidation.
- Active Anoxic/Anaerobic Reduction.
- Reverse Osmosis.
- Nanofiltration.

The concentration of radium-226 achieved by the model effluent treatment system in the precious metal subsector is very low at 0.051 mg Bq/L (Table 6-40), therefore barium chloride co-precipitation was not considered as BATEA for the precious metal subsector.

Oxidation was ruled out as there is insufficient information on speciation of iron and manganese to determine if improved removal efficiencies could be attained.

9.2.2 Model Treatment Cost

The range of reported capital costs for precious metal effluent management and treatment systems similar to the model, including upgrades and adjusted to 2013 CAD$, is CAD$6,000 to CAD$100,000 per m^3/h installed capacity. For the model effluent management and treatment system with 600 m^3/h design treatment capacity, this would equate to CAD$3,700,000 to CAD$60,000,000 total installed cost.

The range of reported operating costs for precious metal effluent management and treatment systems similar to the model is CAD$0.34 to CAD$3.18/m^3. The majority of operating costs are associated with reagent consumption, operating labour, and maintenance. For the model effluent management and treatment system with 180 m^3/h nominal treatment flow rate, this would equate to CAD$530,000 to CAD$5,000,000 annual operating cost.

9.2.3 Technique CAPEX and OPEX

9.2.3.1 Sulfide Precipitation

Chemical sulfide precipitation technology for metals polishing would be best employed within the precious metal subsector model flow sheet after the overflow tank, while bulk dissolved metals and TSS removal and equalization would occur in upstream processes (see Figure 6-31). The overflow pump(s) would deliver effluent to the chemical sulfide precipitation system, and effluent from the system would flow by gravity into the monitoring/settling pond(s). Residuals could be disposed of in a dedicated area of the tailings storage facility.

Reagent make-up/storage systems and feed systems for sulfide reagent and any additional reagent (e.g., pH adjustment chemicals, flocculant), agitated reaction tank(s), clarifier/thickener(s), and underflow pumps would be required.

The incremental capital and operating cost estimates for a chemical sulfide precipitation system for the precious metal subsector model effluent treatment process are as follows:

- The incremental total installed cost for the system is estimated to be approximately CAD$4,600,000.
- The incremental operating cost for the system is estimated to be approximately CAD$1,500,000 to CAD$2,500,000 per year depending on reagent dosage. This equates to an operating cost of CAD$0.97 to CAD$1.57/m^3 treated.
- Other considerations:
- No operating cost discounts have been applied for value recovery through residuals re-processing.
- Insufficient effluent quality information is available to estimate costs for biogenic sulfide precipitation technology.

9.2.3.2 *Sulfide Precipitation with Proprietary Polymeric Organosulfide Chemicals*

Proprietary polymeric organosulfide precipitation technology for metals polishing would be best employed within the precious metal subsector model flow sheet within the hydroxide precipitation stage (see Figure 6-31). The proprietary reagent could be dosed in-line into the feed to the hydroxide precipitation clarifier. Adequate mixing of proprietary reagent and effluent is essential, but such an approach has been demonstrated in the treatment of Canadian mining effluent. This would allow sufficient retention time in the upstream reactor tank(s) for metal hydroxide precipitates to form, such that the sulfide reagent would not compete with the hydroxide reagent (lime) for metals. Such a treatment system is considered suitable for lower strength effluents (total metals concentration <100 mg/L). However, testwork would be required to verify this assertion. It is assumed that the incremental generation of sulfide sludge could be accommodated by the existing clarifier, underflow equipment, and tailings storage facility. Addition of a reagent dosing system would be required. Addition of a bulk reagent tank may also be desirable if the reagent is consumed at a high rate. Otherwise, the reagent could be dosed directly from the tote in which it is supplied by the vendor.

Utilizing the GE rule of thumb of 10 mg/L proprietary reagent per mg/L target metals and the concentrations achieved by the model effluent treatment system in the precious metal subsector (Table 6-40), it is estimated that, approximately 25 mg/L dosage of proprietary reagent would be required for this application. At the nominal flow rate of 180 m^3/h and 25 mg/L dosage, a tote of proprietary reagent would be consumed within 10 days. It is assumed that this is an acceptable tote replacement period, so no bulk reagent tank has been included in the capital cost estimate below.

Small progressive cavity pumps would be required. It is assumed that dosing pumps would be installed in redundant, duty/stand-by configuration. Power consumption by the pumps is expected to be minor, and is not included in the operating cost estimate below.

The incremental capital and operating cost estimates for a proprietary polymeric organosulfide sulfide precipitation system for the precious metal subsector model effluent treatment process are as follows:

- The incremental equipment cost for the system is estimated to be approximately CAD$10,000.
- The incremental total installed cost for the system is estimated to be approximately CAD$29,000.
- The incremental operating cost for the system is estimated to be approximately CAD$310,000/year. This equates to an operating cost of CAD$0.20/$m^3$ treated.

Other considerations:

- The chemicals may be acutely lethal to rainbow trout and *Daphnia magna* at certain residual chemical concentrations in effluent. For example, the rule of thumb dosage of 25 mg/L could potentially lead to residual chemical concentrations in effluent that exceed the rainbow trout LC50 of 8 mg/L for MetClear™ MR2405. It is expected that the majority of the chemical will be retained with precipitated metals in the clarifier (directed to the TSF via underflow equipment) rather than reporting to the environment. However, sludge carryover and/or cycling up of residual chemical concentration due to effluent recirculation (e.g., for mill process re-use, for effluent treatment process re-use, or for return of off-spec effluent for re-treatment) may pose risk of non-compliance with toxicity requirements. It is advised to verify that treated effluent complies with toxicity requirements (i.e., residual chemical concentration is below lethality thresholds). It is also advised that treated effluent be discharged rather than recirculated for any purpose such that cycling up of residual chemical concentration is limited.

- Due to the relatively recent adoption of these reagents and the proprietary nature of their formulations, little is known about the long term stability of residuals and the potential for acid generation and metals remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.
- There is a potential for reduction of operating costs due to reductions in flocculant consumption, as the proprietary reagents are polymeric in nature and may offset flocculant demand. However, no discounts have been applied to the operating cost presented here.
- The budgetary quotations provided for the proprietary reagents were for delivery to Northern Ontario. Additional costs will apply for delivery to more remote mining operations. The reagents are not classified as dangerous goods.

9.2.3.3 Filtration

Media filtration for TSS removal would be best employed within the precious metal subsector model flow sheet following the clarifier overflow tank. The overflow from the clarifier would be fed to the media filter to reduce TSS. The effluent would be pumped to the monitoring/settling ponds prior to discharge to the environment. Backwash from media filtration would be returned to the clarifier for solids sedimentation.

The following equipment additions would be required:

- Media filtration vessels.
- Media Filtration backwash pump.

The incremental capital and operating cost estimates for the addition a of a media filtration system to the precious metal subsector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$840,000.
- The total installed cost for the system is estimated to be approximately CAD$2,600,000.
- The incremental operating cost for the system is estimated to be approximately CAD$78,400/year. This equates to an operating cost of CAD$0.05/m^3 treated.

9.2.3.4 *Air Stripping*

The concentration of total ammonia achieved by the model effluent treatment system in the precious metal subsector is 12 mg-N/L (see Table 6-40). At such a low feed concentration, air stripping technology would be expected to be only marginally economic for ammonia removal.

If used, air stripping technology for the removal of ammonia would be best employed within the precious metal subsector model flow sheet after the clarifier overflow tank (see Figure 6-31). This would allow time for the hydrolysis of cyanate created by cyanide destruction to ammonia to occur in the tailings storage facility and would also limit the solids loading to the tower. As well, the partial softening achieved by hydroxide precipitation may reduce scale formation in the tower.

Alternatively, air stripping for ammonia removal could be implemented upstream of the low density sludge hydroxide precipitation tank in Figure 6-31. In this configuration, removing ammonia before the precipitation stage may improve metal removal efficiencies, since ammonia can interfere with hydroxide precipitation. For the purposes of this study, it is assumed that air stripping is an added technology for ammonia removal only and not intended to improve metals removal. Therefore, the proposed installation location of the air stripper is downstream of the clarifier.

To apply air stripping in the precious metal model flow sheet downstream of the clarifier, an agitator would be added to the clarifier overflow tank, converting it to a pH adjustment tank. The existing lime make-up, storage, and distribution system could be utilized for pH adjustment, provided that there is sufficient capacity within the system and that the use of lime would not lead to unmanageable scale formation within the stripping tower. Depending on the number and height of the stripping tower(s) required, it may be feasible to utilize the clarifier overflow pump(s) to feed the air stripping tower(s). If the clarifier overflow pumps are not suitable, additional air stripper feed pumps would be required. In addition to the air stripping tower(s), additional clearwell(s), blower(s), and forwarding pump(s) would be required. A new post-pH adjustment system would be required, such as a carbon dioxide storage and injection system for the monitoring/polishing pond(s).

As ammonia is a year-round issue in precious metal mining, air and/or effluent heat exchange systems would also be required for operations with year round effluent discharge in order to achieve acceptable ammonia removal efficiencies within reasonable equipment sizing. Stripping towers and associated equipment would be sized for the greatest ammonia load, which typically occurs in summer when conditions promote the natural degradation of cyanide and cyanate.

The incremental capital and operating cost estimates for an ammonia stripping system for the precious metal subsector model effluent treatment process are as follows:

- The capital cost for the air stripping system is estimated to be approximately CAD$9,000,000.
- The total installed cost for the air stripping system is estimated to be CAD$25,800,000.

- The operating cost for the air stripping system is estimated to be approximately CAD$840,000/year and is largely associated with power costs for pumps and fans/blowers. This equates to an operating cost of CAD$0.53/m^3 treated.
- Other considerations:
- Based on a November 2013 budgetary quotation by Branch Environmental Corp., approximately 9 towers each of 12 m height and 3.6 m diameter would be required to meet the model flow sheet ammonia requirements. Assuming 5 m clearance around each tower which would allow for ancillary equipment, at least 300 m2 of space would be required for the air stripping system depending on how equipment is arranged.
- Most precious metal operations experience cold winters and moderately warm summers. For those operations with year-round treatment and discharge, pre-heating of air and/or effluent would likely be required for a good portion of the year, leading to high energy costs. High level estimates show that air and effluent pre-heating could almost double operating costs.

9.2.3.5 *Selective Ion Exchange*

Selective ion exchange for metals polishing would be best employed within the precious metal subsector model flow sheet downstream of the clarifier overflow tank. Media filtration for solids removal would be required as pre-treatment for selective ion exchange. Treated effluent from the ion exchange system would then be conveyed to the polishing/monitoring pond(s) prior to discharge to the environment. Spent regenerant would be returned to the upstream lime hydroxide precipitation process. Backwash from media filtration would be returned to the clarifier for solids sedimentation.

The following equipment additions would be required:

- Media filtration vessels.
- Media filtration backwash pump.
- Ion exchange feed, backwash, treated effluent pump(s).
- Ion exchange columns.
- Regenerant chemical totes/tanks and dosing pumps.
- Tanks (spent regenerant and treated effluent if needed).
- The incremental capital and operating cost estimates for the addition of a selective ion exchange system to the precious metal subsector model effluent treatment process are as follows:
- Equipment costs are estimated to total CAD$4,400,000.
- The total installed cost for the system is estimated to be approximately CAD$7,800,000.
- The incremental operating cost for the system is estimated to be approximately CAD$1,000,000/year. This equates to an operating cost of CAD$0.65/m^3 treated.

- These costs assume that the spent regenerant is returned to the feed to the upstream effluent treatment process to immobilize the metals as hydroxides, and that the sludge will be managed as part of the existing sludge management regime.

Other considerations:

- Spent resin disposal costs have not been considered here. If spent resin must be disposed of off-site, this would add to operating costs.
- Operating costs for ion exchange systems are extremely sensitive to metal loading in feed stream.

9.2.3.6 *Zeolite Ion Exchange*

Zeolite ion exchange for ammonia removal would be applied to the precious metal model effluent flow sheet downstream of the clarifier overflow tank and upstream of the monitoring/polishing ponds. Media filtration for solids removal would also be required upstream of the zeolite ion exchange system as pre-treatment. Backwash from media filtration would be returned to the clarifier to settle out solids. Spent regenerant is assumed to be treated by an air stripping system, installed with zeolite ion exchange process.

The following equipment additions would be required:

- Media filtration vessels.
- Media filtration backwash pump.
- Ion exchange feed, backwash, treated effluent pump(s).
- Ion exchange columns.
- Regenerant chemical totes/tanks and dosing pumps.
- Tanks (spent regenerant and treated effluent if needed).
- Air stripping system for spent regenerant treatment.
- The incremental capital and operating cost estimates for the addition of a zeolite ion exchange system to the precious metal subsector model effluent treatment process are as follows: 1
- Equipment costs are estimated to total CAD$6,100,000.
- The total installed cost for the system is estimated to be approximately CAD$16,300,000.
- The incremental operating cost for the system is estimated to be approximately CAD$940,000/year. This equates to an operating cost of CAD$0.60/m^3 treated.

Capital cost and operating cost information is not readily available for zeolite ion exchange systems due to the limited number of full-scale installations. For the purpose of this estimate, it is assumed that the capital cost for a zeolite exchange system is equivalent to selective ion exchange for metals removal, with the exception of the price of the zeolite media, which is less expensive than selective ion exchange resin.

Spent regenerant from the zeolite system will require further management. An allowance is included in the cost estimate for installation of an air stripping system for final ammonia management.

9.2.3.7 *Adsorption – Zero Valent Iron*

Zero Valent Iron adsorption technology for selenium removal would be best employed within the precious metal subsector model flow sheet after the clarifier overflow tank (see Figure 6-31). The upstream processes would serve for bulk removal of dissolved metals and TSS and equalization. However, ZVI could also be employed upstream of the reactor tank(s), depending on the concentration of competing oxyanions (e.g., oxyanions of arsenic and sulfate). Such a configuration could be more economical, as it could eliminate the need for equipment associated with downstream iron precipitation and solid/liquid separation. However, with the limited information available and for the purposes of this study, it is assumed that a complete ZVI system would be installed after the clarifier overflow tank. Residual streams could be disposed of in a dedicated area of the tailings storage facility where appropriate storage conditions are maintained. It is assumed that the incremental generation of sludge could be accommodated by the existing tailings storage facility.

Assuming a stirred-tank reactor ZVI system would be employed, the following equipment additions would be required:

- Reagent make-up/storage systems and feed systems for pH adjustment chemicals.
- ZVI handling systems for ZVI media.
- Agitated ZVI reaction tank(s).
- Agitated post-pH adjustment tank.
- Aeration blower(s)/compressor(s) and diffuser(s).
- Clarifier/thickener(s) and/or media filter(s).
- Residuals management equipment (e.g., pumps to disposal, mechanical dewatering equipment).

A base case total installed cost of CAD$35,600,000 for a stirred-tank reactor ZVI system was estimated by CH2MHill for a flow rate of 182 m^3/h; however, this cost could be inflated over more basic costs by over 200% (see 8.2.12.1). An operating cost of CAD$3.18/$m^3$ was estimated for stirred-tank reactor ZVI technology; however, this could be inflated over more basic costs by as much as 200% (see 8.2.12.1). Factoring the total installed cost using the rule of six-tenths, the incremental capital and operating cost estimates for a ZVI system for the precious metal subsector model effluent treatment process are as follows:

- The total installed cost for the system is estimated to be approximately CAD$31,000,000 to CAD$72,800,000.
- The incremental operating cost for the system is estimated to be approximately CAD$3,700,000/year to CAD$5,000,000/year. This equates to an operating cost of CAD$2.32/$m^3$ treated to CAD$3.18/$m^3$ treated.

Other considerations:

- Most full-scale installations of this technology treat flow rates one order of magnitude lower than the precious metal subsector design flow rate. The applicability of this technology may be limited, accordingly.
- Few full-scale installations have been in operation for long enough to determine long term feasibility.
- The speciation of the precious metal subsector total selenium is unknown and, therefore, the cost impacts of speciation cannot be determined.
- Due to the relatively recent adoption of this technology, little is known about the long term stability of residuals and the potential for selenium remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.

9.2.3.8 *Active Aerobic Biological Oxidation*

MBBR technology for the removal of ammonia would be best employed within the precious metal subsector model flow sheet after the hydroxide precipitation clarifier overflow tank (see Figure 6-31). This would allow time for the hydrolysis of cyanate created by cyanide destruction to ammonia to occur in the tailings storage facility and would also limit the solids loading to the MBBR.

It is assumed that the overflow pump(s) could deliver effluent to the MBBR system and that treated effluent from the MBBR system could flow by gravity to the monitoring/settling pond(s). The existing lime make-up, storage, and distribution system could be utilized for pH control, provided that there is sufficient capacity within the system. It is assumed that a heat exchange system would be used for start-up either where warm weather effluent temperatures are insufficient for start-up or where a quicker start-up is required, as well as during prolonged operation at low effluent temperatures (i.e., <5 °C). Pre-heating (natural gas boiler / electric heater) and heat recovery (treated effluent/untreated effluent heat exchanger) systems have been sized assuming that a temperature rise of 5 °C is required year round, which is considered to be conservative. It is assumed that biomass residuals can be stored in a dedicated area of the tailings storage facility.

The incremental capital and operating cost estimates for an MBBR system including pre-heating and heat recovery for the precious metal subsector model effluent treatment process are as follows:

- The capital cost for the MBBR system is estimated to be approximately CAD$7,400,000.
- The total installed cost for the MBBR system is estimated to be CAD$19,600,000.
- The operating cost for the MBBR system is estimated to be approximately CAD$950,000/year. This equates to an operating cost of CAD$0.60/m^3 treated.

CAPEX and OPEX costs have been updated in Revision 1 to include costs for pre-heating and heat-recovery.

9.2.3.9 *Active Anoxic/Anaerobic Biological Reduction*

FBR or ABMet® technology for selenium removal would be best employed within the precious metal subsector model flow sheet after the clarifier overflow tank (see Figure 6-31). The upstream TSF and processes would serve for bulk removal of dissolved metals and TSS and equalization. Residual streams could report to the clarifier for thickening and co-disposal with hydroxide precipitation and iron co-precipitation residuals. It is assumed that the incremental generation of sludge could be accommodated by the existing clarifier, underflow equipment, and tailings storage facility.

The following equipment additions would be required:

- Reagent dosing system(s) for pH adjustment, electron donor, and nutrient.
- Bulk reagent storage tanks for electron donor and nutrient, as they are typically supplied as bulk liquids.
- Influent heat exchange system.
- FBR or ABMet system®.
- Aerobic polishing.

A base case total installed cost of CAD$30,500,000 for an FBR system was estimated by CH2MHill for a flow rate of 182 m^3/h (see Section 8.2.14.1). An operating cost of CAD$1.59/m^3 was estimated by CH2MHill for the same system. Envirogen estimated CAD$8,000,000 to CAD$13,000,000 for an FBR system without influent heat exchange, aerobic polishing, and sludge handling, thickening, and disposal systems, and without standalone utilities and electrical service to the plant, and feed, effluent, and residuals piping to/from the plant. An operating cost of CAD$0.85/m^3 to CAD$1.16/m^3 was estimated by Envirogen for the same system. Factoring the total installed cost using the rule of six-tenths, the incremental capital and operating cost estimates for an FBR system for the precious metal subsector model effluent treatment process are as follows: △1

- The total installed cost for the system is estimated to be approximately CAD$16,400,000 to CAD$26,600,000 for a basic system integrated into existing systems to CAD$62,400,000 for a standalone system.
- The incremental operating cost for the system is estimated to be approximately CAD$1,300,000/year to CAD$1,800,000/year for a basic system integrated into existing systems to CAD$2,500,000/year for a standalone system. This equates to an operating cost of CAD$0.85/m^3 treated to CAD$1.59/m^3 treated.

As the precious metal subsector model effluent treatment process is moderately advanced, the addition of an FBR system would not necessarily require substantial wrap around and independent sludge handling, thickening, and disposal systems. Therefore, the costs may be closer to the lower end of the ranges presented. △1

A base case total installed cost of CAD$40,700,000 for an ABMet® system was estimated by CH2MHill for a flow rate of 182 m^3/h. An operating cost of CAD$1.28/$m^3$ was estimated for the same system. Factoring the total installed cost using the rule of six-tenths, the incremental capital and operating cost estimates for an ABMet® system for the precious metal subsector model effluent treatment process are as follows:

- The total installed cost for the system is estimated to be approximately CAD$83,300,000.
- The incremental operating cost for the system is estimated to be approximately CAD$2,000,000/year. This equates to an operating cost of CAD$1.28/$m^3$ treated.

It is important to consider that a total installed cost estimate for the same ABMet® system factored from cost curves developed and provided by GE would be lay between CAD$21,100,000 and CAD$31,300,000, which is less than half the total installed cost estimated by factoring from CH2MHill cost curves and would make the technology economically competitive with FBR technology. Again, since the system would not necessarily need substantial wrap around and independent sludge handling, thickening, and disposal equipment, the total installed costs may be in the lower range of costs.

Other considerations:

- Few full-scale FBR installations have been in operation for long enough to determine long term feasibility.
- The speciation of the precious metal subsector total selenium is unknown and, therefore, the cost impacts of speciation cannot be determined.
- Due to the relatively recent adoption of this technology, little is known about the long term stability of residual biomass and the potential for selenium remobilization under various disposal conditions. If residuals are not stable, significant costs associated with biomass stabilization technology or re-treatment of residual leachate could be incurred.

9.2.3.10 Reverse Osmosis

Reverse osmosis for TDS removal would be best employed within the precious metal model effluent flow sheet as a polishing stage downstream of the clarifier overflow tank. Media filtration would be required as pre-treatment for the reverse osmosis system.

Permeate from the reverse osmosis system would be discharged to the monitoring/settling pond for monitoring or to the environment, following pH adjustment and/or remineralization, as required. Concentrate could be returned to the upstream lime hydroxide precipitation process. Backwash from media filtration could be returned to the clarifier for solids sedimentation.

The following equipment additions would be required:

- Media filtration vessel feed pump.
- Media filtration vessels.
- Media filtration backwash pump.
- Fine filtration (cartridge filters).

- Reverse osmosis feed pump.
- Reverse osmosis pressure vessel skids, with vessels to house approximately 600 membranes.
- Antiscalant dosing system.
- Clean-in-place system.
- pH adjustment system.
- Permeate and Concentrate Storage Tanks, if required.
- Discharge or transfer pumps, if required.

The incremental capital and operating cost estimates for the addition of a reverse osmosis system to the precious metal subsector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$8,500,000.
- The total installed cost for the system is estimated to be approximately CAD$30,300,000.
- The incremental operating cost for the system is estimated to be approximately CAD$1,500,000/year. This equates to an operating cost of CAD$0.95/$m^3$.

CAPEX costs have been updated in Revision 1 based on additional reference cost information for both equipment and total installed costs. These costs have been used to update the RO equipment cost curve and to adjust factors used to generate installed costs based on RO equipment costs.

OPEX costs have been updated in Revision 1 based on information received concerning the experience of operations with respect to the operating and maintenance effort required for RO systems. Operations reported that for successful operation of RO systems, frequent cleaning and diligent operator attention is required. The costs of labour and cleaning chemicals have been increased to reflect these demands.

Other considerations:

- RO concentrate management could be difficult to accommodate in the model effluent treatment system. RO concentrate return to an upstream treatment process may incur additional costs to expand equipment capacity, and would result in the cycling up of contaminants that are not removed by lime hydroxide precipitation or natural degradation. Should this become problematic, concentrate management equipment may be required and would add significant capital cost and operating cost. For example, the use of an evaporator/crystallizer to manage brine from the RO process (assuming 70% recovery in the RO) would incur the following additional costs:
    - Equipment costs of around CAD$18,000,000, installed equipment costs of around CAD$60,000,000 and operating costs of around CAD$2,500,000/year.
- The operating cost for the RO system is highly dependent on the site-specific energy cost, and on the required frequency of cleaning cycles, which is dependent on the RO feed quality.

- RO permeate is very low in TDS and alkalinity. Re-mineralization of the permeate stream prior to discharge to the environment may be required to comply with toxicity requirements.

9.2.3.11 Nanofiltration

Nanofiltration would be best employed in the precious metal model effluent flow sheet for the removal of multivalent dissolved ions downstream of the clarifier overflow tank. Media filtration for solids removal would also be required as pre-treatment to the NF system.

Permeate would be discharged to the polishing/monitoring pond or to the environment, following pH adjustment and/or remineralization, as required. Concentrate would be directed to the upstream lime hydroxide precipitation step. Backwash from media filtration could be returned to the clarifier for solids sedimentation.

The following equipment additions would be required:

- Media filtration vessel feed pump.
- Media filtration vessels.
- Media filtration backwash pump.
- Fine filtration (cartridge filters).
- Nanofiltration feed pump.
- Nanofiltration pressure vessel skids.
- Antiscalant dosing system.
- Clean-in-place system.
- pH adjustment system.
- Permeate and Concentrate Storage Tanks, if required.
- Discharge or transfer pumps, if required.

The incremental capital and operating cost estimates for the addition of a nanofiltration system to the precious metal subsector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$8,500,000.
- The total installed cost for the system is estimated to be approximately CAD$30,300,000.
- The incremental operating cost for the system is estimated to be approximately CAD$1,200,000/year. This equates to an operating cost of CAD$0.79/m^3.

Because nanofiltration and reverse osmosis are very similar, with the exception of operating pressure and membranes, the capital costs for nanofiltration have been assumed to be the same as estimated for reverse osmosis. Nanofiltration operates at lower pressures compared to reverse osmosis, therefore energy consumption for nanofiltration will be less. The energy requirements of nanofiltration have been assumed to be 2/3 of the energy requirements of reverse osmosis.

CAPEX costs have been updated in Revision 1 based on updated RO costs, as NF CAPEX have been assumed to be the same as RO costs.

OPEX costs have been updated in Revision 1 based on information received concerning the experience of operations with respect to the operating and maintenance effort required for RO systems. Operations reported that for successful operation of RO systems, frequent cleaning and diligent operator attention is required. It is assumed similar maintenance and operation demands would apply to nanofiltration membranes as well. The costs of labour and cleaning chemicals have been increased to reflect these demands.

Other considerations:

- NF concentrate management could be difficult to accommodate in the model effluent treatment system. NF concentrate return to an upstream treatment process may incur additional costs to expand equipment capacity, and would result in the cycling up of contaminants that are not removed by lime hydroxide precipitation or natural degradation. Should this become problematic, concentrate management equipment may be required and would add significant capital cost and operating cost. For example, the use of an evaporator/crystallizer to manage brine from the NF process (assuming 70% recovery in the NF) would incur the following additional costs:
    - Equipment costs of around CAD$18,000,000, installed equipment costs of around CAD$60,000,000 and operating costs of around CAD$2,500,000/year.
- The operating cost for the NF system is highly dependent on the site-specific energy cost, and on the required frequency of cleaning cycles, which is dependent on the feed quality.
- NF permeate is low in TDS and alkalinity. Re-mineralization of the permeate stream prior to discharge to the environment may be required to comply with toxicity requirements.

9.3 Metals: Iron Ore

9.3.1 Model Effluent Management and Treatment System

Refer to Section 6.3 for the complete discussion of the iron ore subsector model effluent management and treatment system.

In the iron ore subsector model, bulk TSS is removed from effluent via pond-based settling and polishing, which may be assisted by addition of flocculant. These ponds provide the residence time required for natural degradation of ammonia.

The design flow rate of the model effluent management and treatment system for iron ore is 7,000 m^3/h. The nominal flow rate is 3,900 m^3/h.

9.3.1.1 Technologies Applicable for the Augmentation of the Model Effluent Management and Treatment System

The technologies that are considered applicable for augmentation of the iron ore subsector model effluent management and treatment system are:

- Hydroxide Precipitation.
- Sulfide Precipitation.

- Sulfide Precipitation with Proprietary Polymeric Organosulfide Chemicals.
- Solid/Liquid Separation – Clarification, Enhanced Coagulation and Settling, and Filtration.
- Air Stripping.
- Active Aerobic Biological Oxidation.
- Reverse Osmosis.
- Nanofiltration.
- Selective Ion Exchange – Synthetic Resins for Metals Polishing.
- Selective Ion Exchange – Zeolite for Ammonia Removal.

The radium-226 concentration achieved by the model effluent treatment system in the iron ore subsector is very low at 0.016 Bq/L (Table 6-57). Further, cyanide concentrations are not available for the iron ore subsector and are expected to be irrelevant. Therefore, barium chloride co-precipitation and cyanide destruction technologies were not considered for the iron ore subsector.

Oxidation was not considered since there is insufficient information on speciation of iron and manganese to determine if improved removal efficiencies could be attained.

Ferric iron or aluminum salt co-precipitation was not considered as the arsenic and selenium concentrations achieved by the model effluent treatment systems are below their achievable concentrations through this technique.

- To be conservative, as no operations target selenium for removal and thus the concentrations achieved by the model effluent treatment system are not necessarily attributable to the treatment process, the 95th percentile for the entire subsector (<0.005 mg/L) has been used to represent the concentration achieved by the iron ore subsector model effluent treatment system (see 6.3.4). Due to the low total selenium concentration, selenium removal technologies were not considered to be augmentative for the iron ore subsector. In Revision 0 of this report, selenium removal technologies were not considered for the iron ore subsector as there is was no concentration data available; the findings of the report have not changed with regard to consideration of selenium removal technologies for the iron ore subsector.

9.3.2 *Model Treatment Cost*

The range of reported capital costs for iron ore effluent management and treatment systems similar to the model, including upgrades and adjusted to 2013 CAD$, is CAD$370 to CAD$830 per m^3/h installed capacity. For the model effluent management and treatment system with 7,000 m^3/h design treatment capacity, this would equate to CAD$2,600,000 to CAD$5,800,000 total installed cost.

The range of reported operating costs for iron ore effluent management and treatment systems similar to the model is CAD$0.01 to 0.03/$m^3$. The majority of operating costs are associated with reagent consumption and operating labour. For the model effluent management and treatment system with 3,900 m^3/h nominal treatment flow rate, this would equate to CAD$340,000 to CAD$1,000,000 annual operating cost.

9.3.3 *Technique CAPEX and OPEX*

9.3.3.1 Hydroxide Precipitation

Based on a review of the concentrations achieved by the model effluent treatment system for the iron ore subsector values in Table 6-57, it was concluded that hydroxide precipitation could be employed within the iron ore subsector model flow sheet for aluminum and iron removal only. All of the other metals concentrations are below the concentrations that are achievable through hydroxide precipitation.

As discussed in Section 6.3, aluminum and iron are likely associated with TSS, therefore improved TSS removal may also reduce aluminum and iron concentrations. The dissolved fraction of aluminum and iron available to be precipitated as metal hydroxides is unknown. It is also possible that iron is present as ferrous iron and that aeration could improve iron removal; however, the fraction of iron present as ferrous and ferric iron is unknown.

It is assumed that the hydroxide precipitation reaction will be conducted in a 30 minute retention time agitated reactor tank(s). Subsequent solid/liquid separation would be by pond-based settling for solid/liquid separation within the existing settling pond(s) and polishing pond(s) system. Hydroxide precipitation would be best employed within the iron ore subsector model flow sheet before the settling pond (see Figure 6-34), assuming upstream flow equalization, or before the polishing pond, if no upstream flow equalization is available. New transfer pump(s) are required to deliver effluent to the agitated reactor tanks. It is assumed that treated effluent flows by gravity from the agitated reactor tank(s) to the settling pond(s)/polishing pond(s). It is assumed that the incremental generation of hydroxide sludge can be accommodated by the existing settling pond(s) and polishing pond(s).

Lime-based hydroxide precipitation is assumed. Lime make-up, storage, and dosing systems including lime silo, slaker, agitated slurry tank, recirculation pumps and loop, and dosing valves are required.

The incremental capital and operating cost estimates for the hydroxide precipitation system described above for the iron ore subsector model effluent treatment process are as follows:

- The total installed cost for the system is estimated to be approximately CAD$3,900,000.
- The incremental operating cost for the system is estimated to be approximately CAD$1,700,000/year including reagents, power, operating labour, and maintenance. This equates to an operating cost of CAD$0.05/m^3 treated.

CAPEX and OPEX costs in Revision 1 have been updated to reflect updates to the model effluent treatment system design and nominal flow rates (see Section 9.3.1).

9.3.3.2 Sulfide Precipitation

Based on a review of the concentrations achieved by the model effluent treatment system for the iron ore subsector values in Table 6-57, it is possible that sulfide precipitation could be employed within the iron ore subsector model flow sheet for iron removal and very marginal zinc removal. All of the other metals are below the achievable concentrations through sulfide precipitation.

As discussed in Section 6.3, iron is likely associated with TSS and improvements in TSS removal might yield improvements in iron removal. It's also possible that iron is present as ferrous iron and that aeration could improve iron removal. The dissolved fraction of ferrous iron available to be precipitated via sulfide precipitation is unknown. However, this technique is not considered to be economic for the removal of iron, especially at the very high design and nominal treatment capacities required for the iron ore subsector.

9.3.3.3 *Sulfide Precipitation with Proprietary Polymeric Organosulfide Chemicals*

Proprietary polymeric organosulfide precipitation technology for metals polishing would be best employed within the iron ore subsector model flow sheet before the polishing pond(s) (Figure 6-34). Bulk TSS removal and equalization would occur at the upstream settling pond(s).The proprietary reagent could be dosed along with flocculant into the pond influent within a new agitated reactor tank. The agitated reactor tank would discharge by gravity to the settling pond(s) where subsequent solid/liquid separation would occur. It is assumed that the incremental generation of sulfide sludge could be accommodated within the settling pond. Addition of a reagent dosing system would be required. Addition of a bulk reagent tank may also be desirable if the reagent is consumed at a high rate. Otherwise, the reagent could be dosed directly from the tote in which it is supplied by the vendor.

Utilizing the GE rule of thumb of 10 mg/L proprietary reagent per mg/L target metals and the concentrations achieved by the model effluent treatment system in the iron ore subsector (Table 6-57), it is estimated that, approximately 65 mg/L dosage of proprietary reagent would be required for this application. At the nominal flow rate of 3,900 m^3/h and 65 mg/L dosage, a tote of proprietary reagent would be consumed within 4 hours. At such a high consumption, this technique is considered to be uneconomic; annual reagent costs alone would exceed CAD$16,400,000 (or CAD$0.48/m^3 treated).

CAPEX and OPEX costs in Revision 1 have been updated to reflect updates to the model effluent treatment system design and nominal flow rates (see Section 9.3.1).

9.3.3.4 *Clarification*

Clarification would be best employed for bulk TSS removal within the iron ore subsector model flow sheet upstream of the settling pond. Flocculant would be dosed into the clarifier rather than into the settling and polishing ponds. Overflow from the clarifier would report to the model pond system, which would then serve as polishing ponds for further removal of TSS and for monitoring of effluent quality. Underflow from the clarifier would report to the Tailings Storage Facility.

The following equipment additions would be required:

- Clarifier feed pump.
- Clarifier.
- Residuals management equipment (e.g., pumps to disposal, underflow tank, etc.).

The incremental capital and operating cost estimates for the addition of a clarification system to the iron ore subsector model effluent treatment process are as follows:

- Equipment costs are estimated to be CAD$15,270,600.

- The total installed cost for the system is estimated to be approximately CAD$50,600,000.
- The incremental operating cost for the system is estimated to be approximately CAD$3,400,000/year. This equates to an operating cost of CAD$0.10/m^3.

CAPEX costs have been updated in Revision 1 based on additional reference cost information for both equipment and total installed costs. These costs have been used to update the clarification equipment cost curve and to adjust factors used to generate installed costs based on clarification equipment costs. Costs in Revision 1 have been also updated to reflect updates to the model effluent treatment system design and nominal flow rates (see Section 9.3.1).

9.3.3.5 *Enhanced Coagulation and Settling*

An enhanced coagulation and settling process for bulk TSS removal would be best employed within the iron ore subsector model flow sheet upstream of the ponds currently used for TSS removal. Flocculant would be dosed into the feed to the ECS system rather than into the ponds. Overflow from the ECS unit would report to the model pond system, which would then serve as polishing ponds for further removal of TSS and allow monitoring of effluent quality. Underflow from the ECS unit would report to the Tailings Storage Facility.

The following equipment additions would be required:

- ECS unit.
- Reagent make-up/storage systems and feed systems for flocculant/polymer.
- Residuals management equipment (e.g., underflow pump(s), underflow tank, pump(s) to disposal), if required.
- The incremental capital and operating cost estimates for the addition of an ECS system to the iron ore subsector model effluent treatment process are as follows:
- Equipment costs are estimated to total CAD$7,000,000.
- The total installed cost for the system is estimated to be approximately CAD$22,100,000.
- The incremental operating cost for the system is estimated to be approximately CAD$3,400,000/year. This equates to an operating cost of CAD$0.10/m^3.

The only enhanced coagulation and settling capital and operating cost information provided via the vendor questionnaire for technologies that passed BAT screening was for Veolia's proprietary ACTIFLO® system; for this reason, ACTIFLO® costs have been used as representative of ECS technologies for BATEA purposes.

CAPEX and OPEX costs in Revision 1 have been updated to reflect updates to the model effluent treatment system design and nominal flow rates (see Section 9.3.1).

Other considerations:

- It is assumed that sufficient space is available for the incorporation of the necessary equipment into the model system.
- Operating cost estimated has assumed that reagent costs do not change with the installation of this system; however, it is expected that some reduction in reagent requirements would be experienced due to the enhanced coagulation provided by ballast or sludge recycle.

9.3.3.6 Filtration

Media filtration for TSS removal would be best employed within the iron ore subsector model effluent system upstream of the ponds currently in use for suspended solids removal via settling. The TSS concentration achieved by the model effluent treatment system in the iron ore subsector (Table 6-57) is < 62 mg/L even after pond-based solid/liquid separation, therefore bulk removal of TSS prior to filtration would be required prior to media filtration.

A clarifier system would be installed in addition to the media filtration system to provide bulk TSS removal. Overflow from the clarifier would report to the media filtration vessels. Underflow from the clarifier would report to the Tailings Storage Facility. Backwash from media filtration could be returned to an upstream pond for sedimentation of solids.

The following equipment additions would be required:

- Clarifier feed pump.
- Clarifier.
- Residuals management equipment (e.g., pumps to disposal, mechanical dewatering equipment if not disposed of in-pond).
- Media filtration vessel feed pump.
- Media filtration vessels.
- Media filtration backwash pump.
- Discharge pump.

The incremental capital and operating cost estimates for the addition of a media filtration system to the iron ore subsector model effluent treatment process are as follows: △1

- Equipment costs are estimated to total CAD$27,600,000.
- The total installed cost for the system is estimated to be approximately CAD$84,500,000.
- The incremental operating cost for the system is estimated to be approximately CAD$5,100,000/year. This equates to an operating cost of CAD$0.15/m^3.

CAPEX and OPEX costs in Revision 1 have been updated to reflect updates to the model effluent treatment system design and nominal flow rates (see Section 9.3.1). △1

9.3.3.7 *Air Stripping*

The concentration of total ammonia achieved by the model effluent treatment system in the iron ore metal subsector is 7.76 mg-N/L (see Table 6-57). At such a low feed concentration, air stripping technology would not be technically feasible for ammonia removal due to the low concentration driving force for volatilization to a lower achievable limit of 3 mg-N/L, as discussed in Section 7. The air stripping process is best suited to feed total ammonia concentrations in the range of 10 to 100 mg/L.

9.3.3.8 *Selective Ion Exchange*

Based on a review of the concentrations achieved by the model effluent treatment system in the iron ore metal subsector (see Table 6-57) , it was concluded that selective ion exchange could be employed within the iron ore subsector model flow sheet for the removal aluminum, iron, and possibly other trace metals.

To install a selective ion exchange system, a system for bulk removal of TSS would also need to be installed, including a clarifier and media filtration (this system may also reduce the concentrations of iron and aluminum present in effluent as suspended solids).

Given that the installed cost for bulk TSS removal via clarification and filtration alone is estimated to be greater than CAD$84,500,000, the addition of a selective ion exchange system is not considered to be economic for the removal of metals in the iron ore, especially at the very high design and nominal treatment capacities experienced for this subsector.

9.3.3.9 *Active Aerobic Biological Oxidation*

The concentration of total ammonia achieved by the model effluent treatment system in the iron ore metal subsector is 7.76 mg-N/L (see Table 6-57). At such a low feed concentration, active aerobic biological oxidation technology would not be economically feasible for ammonia removal due to a typical lower achievable limit of 2 mg-N/L, as discussed in Section 8.2.13.

9.3.3.10 *Reverse Osmosis*

Based on a review of the concentrations achieved by the model effluent treatment system in the iron ore metal subsector (see Table 6-57), it was concluded that reverse osmosis could be employed within the iron ore subsector model flow sheet for removal of total dissolved solids, which could include removal of metals and ammonia. To install an RO system, a system for bulk removal of TSS would also need to be installed.

Given that the installed cost for bulk TSS removal via clarification and filtration alone is estimated to be greater than CAD$84,500,000, the addition of an RO system is not considered to be economic for the removal of metals in the iron ore, especially at the high design and nominal treatment capacities experienced for this subsector.

9.3.3.11 *Nanofiltration*

Based on a review of the concentrations achieved by the model effluent treatment system in the iron ore metal subsector (see Table 6-57), it was concluded that nanofiltration could be employed within the iron ore subsector model flow sheet for removal of multivalent charged dissolved solids. To install a NF system, a system for bulk removal of TSS would also need to be installed.

Given that the installed cost for bulk TSS removal via clarification and filtration alone is estimated to be greater than CAD$84,500,000, the addition of a nanofiltration system is not considered to be economic for the removal of metals in the iron ore, especially at the very high design and nominal treatment capacities experienced for this subsector.

9.4 Metals: Uranium

9.4.1 Model Effluent Management and Treatment System

Refer to Section 6.4 for the complete discussion of the uranium mining subsector model effluent management and treatment system.

In the uranium subsector model, effluent is equalized prior to treatment. Effluent treatment for the model uranium mining operation includes two stages of treatment, which is necessary in order to target parameters that are removed at significantly different pH values. The first treatment stage is precipitation of metals (e.g., nickel) as metal hydroxides at elevated pH. The second stage of treatment is a low pH metals precipitation/co-precipitation stage targeting metals such as molybdenum, selenium, and radium. Between the two stages is a conventional clarification step followed by media filtration for suspended solids removal.

The design flow rate of the model effluent management and treatment system for uranium mining is 500 m^3/h. The nominal flow rate for the model treatment system for uranium mining is 350 m^3/h.

9.4.1.1 Technologies Applicable for the Augmentation of the Model Effluent Management and Treatment System

The technologies that are considered applicable for augmentation of the uranium model effluent management and treatment system are:

- Sulfide Precipitation.
- Sulfide Precipitation with Proprietary Polymeric Organosulfide Chemicals.
- Air Stripping.
- Aerobic Biological Oxidation.
- Reverse Osmosis.
- Nanofiltration.
- Selective Ion Exchange – Synthetic Resins for Metals Polishing.
- Selective Ion Exchange – Zeolite for Ammonia Removal.
- Anoxic/Anaerobic Biological Reduction.
- Adsorption – ZVI.

Cyanide destruction technologies were not considered as BATEA for the uranium subsector as cyanide is not included in *MMER* monitoring and reporting for uranium mine and mill operations. On this basis, it is assumed that cyanide is not a concern at uranium operations and these technologies are not applicable to the uranium subsector.

Oxidation was not considered since there is insufficient information on speciation of iron and manganese to determine if improved removal efficiencies could be attained.

9.4.2 Model Treatment Cost

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The range of reported capital costs for uranium effluent management and treatment systems similar to the model, including upgrades and adjusted to 2013 CAD$, is CAD$130,000 to 400,000 per m^3/h installed capacity. For the model effluent management and treatment system with 500 m^3/h design treatment capacity, this would equate to CAD$65,000,000 to 200,000,000 total installed cost.

The range of reported operating costs for uranium effluent management and treatment systems similar to the model is CAD$3.30/$m^3$ to CAD$5.90/$m^3$. The majority of operating costs are associated with reagent consumption, operating labour, and maintenance. For the model effluent management and treatment system with 350 m^3/h nominal treatment flow rate, this would equate to CAD$10,000,000 to CAD$18,000,000 annual operating cost.

Note that the model treatment CAPEX and OPEX values have been updated from the Revision A / Revision 0 report based on additional information received from operations in the uranium subsector.

9.4.3 Technique CAPEX and OPEX

9.4.3.1 Sulfide Precipitation

Chemical sulfide precipitation technology for metals polishing would be best employed within the uranium subsector model flow sheet after the low pH media filter(s). Bulk dissolved metals and TSS removal and equalization would occur in upstream processes (see Figure 6-48). It is assumed that filtrate from the low pH media filter(s) would flow under pressure into the chemical sulfide precipitation system, and effluent from the system would then flow by gravity into the monitoring/polishing pond(s). Residuals could be disposed of in a dedicated area of the tailings storage facility.

Feed pumps, reagent make-up/storage systems and feed systems for sulfide reagent and any additional reagent (e.g., pH adjustment chemicals, flocculant), agitated reaction tank(s), clarifier/thickener(s), and underflow pump(s) would be required.

The incremental capital and operating cost estimates for a chemical sulfide precipitation system for the uranium subsector model effluent treatment process are as follows:

- The incremental total installed cost for the system is estimated to be approximately CAD$4,100,000.
- The incremental operating cost for the system is estimated to be approximately CAD$2,000,000 to CAD$3,800,000/year depending on reagent dosage. This equates to an operating cost of CAD$0.64/$m^3$ to CAD$1.24/$m^3$ treated.
- Other considerations:
- No operating cost discounts have been applied for value recovery through residuals re-processing.

- Insufficient effluent quality information is available to estimate costs for biogenic sulfide precipitation technology.

9.4.3.2 Sulfide Precipitation with Proprietary Polymeric Organosulfide Chemicals

Proprietary polymeric organosulfide precipitation technology for metals polishing would be best employed within the uranium subsector model flow sheet within the low pH stage (Figure 6-48). The proprietary reagent could be dosed in-line into the feed to the low pH clarifier. Adequate mixing of proprietary reagent and effluent is essential, but such an approach has been demonstrated in the treatment of Canadian mining effluent. This would allow sufficient retention time in the upstream reactor tank(s) for metal co-precipitates to form, such that the sulfide reagent would not compete with ferric iron for metals. Such a treatment system is considered suitable for lower strength effluents (total metals concentration <100 mg/L). However, testwork would be required to verify this assertion. It is assumed that the incremental generation of sulfide sludge could be accommodated by the existing clarifier, underflow equipment, and tailings storage facility. Addition of a reagent dosing system would be required. Addition of a bulk reagent tank may also be desirable if the reagent is consumed at a high rate. Otherwise, the reagent could be dosed directly from the tote in which it is supplied by the vendor.

Utilizing the GE rule of thumb of 10 mg/L proprietary reagent per mg/L target metals and the concentrations achieved by the model effluent treatment system in the uranium subsector (Table 6-77), it is estimated that, approximately 20 mg/L dosage of proprietary reagent would be required for this application. At the nominal flow rate of 350 m^3/h and 20 mg/L dosage, a tote of proprietary reagent would be consumed within 7 days. It is assumed that this is an acceptable tote replacement period, so no bulk reagent tank has been included in the capital cost estimate below.

At the same dosing rate describe above, small progressive cavity pumps would be required. It is assumed that dosing pumps would be installed in redundant, duty/stand-by configuration. Power consumption by the pumps is expected to be minor, and is not included in the operating cost estimate below.

The incremental capital and operating cost estimates for a proprietary polymeric organosulfide sulfide precipitation system for the uranium subsector model effluent treatment process are as follows:

- The incremental equipment cost for the system is estimated to be approximately CAD$10,000.
- The incremental total installed cost for the system is estimated to be approximately CAD$29,000.
- The incremental operating cost for the system is estimated to be approximately CAD$470,000/year. This equates to an operating cost of CAD$0.15/$m^3$ treated.

Other considerations:

- The chemicals may be acutely lethal to rainbow trout and *Daphnia magna* at certain residual chemical concentrations in effluent. For example, the rule of thumb dosage of 20 mg/L could potentially lead to residual chemical concentrations in effluent that exceed the rainbow trout LC_{50} of 8 mg/L for MetClear™ MR2405. It is expected that the majority of the chemical will be retained with precipitated metals in the clarifier (directed to the TSF via underflow equipment) rather than reporting to the environment. However, sludge carryover and/or cycling up of residual chemical concentration due to effluent recirculation (e.g., for mill process re-use, for effluent treatment process re-use, or for return of off-spec effluent for re-treatment) may pose risk of non-compliance with toxicity requirements. It is advised to verify that treated effluent complies with toxicity requirements (i.e., residual chemical concentration is below lethality thresholds). It is also advised that treated effluent be discharged rather than recirculated for any purpose such that cycling up of residual chemical concentration is limited.
- Due to the relatively recent adoption of these reagents and the proprietary nature of their formulations, little is known about the long term stability of residuals and the potential for acid generation and metals remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.
- There is a potential for reduction of operating costs due to reductions in flocculant consumption, as the proprietary reagents are polymeric in nature and may offset flocculant demand. However, no discounts have been applied to the operating cost presented here.
- The budgetary quotations provided for the proprietary reagents were for delivery to Northern Ontario. Additional costs will apply for delivery to northern Saskatchewan uranium mining operations. The reagents are not classified as dangerous goods.

9.4.3.3 *Air Stripping*

Air stripping technology for the removal of ammonia would be best employed within the uranium subsector model flow sheet after the high pH media filter(s) (see Figure 6-48). Alternatively, air stripping for ammonia removal could be implemented prior to hydroxide precipitation (i.e., prior to the high pH reactors) in order to achieve better metals removal efficiencies by first removing ammonia which can interfere with hydroxide precipitation. However, for the purposes of this study, it is assumed that air stripping is an added technology for ammonia removal only and not intended to improve metals removal.

A new pH adjustment agitated reactor tank would be required. The existing lime make-up, storage, and distribution system could be utilized for pH adjustment, provided that it has sufficient capacity and that the use of lime would not lead to unmanageable scale formation within the stripping tower. New feed pump(s) would be required. The addition of a system including stripping tower, clearwell, blower, and forwarding pump would be required. As ammonia is a year-round issue due to ammonia use in uranium processing, air and/or heat exchange systems would also be required for operations with year round effluent discharge in order to achieve acceptable ammonia removal efficiencies within reasonable equipment sizing. No downstream pH adjustment would be required, as the effluent next flows to the low pH phase of treatment.

The incremental capital and operating cost estimates for an ammonia stripping system for the uranium subsector model effluent treatment process are as follows:

- The capital cost for the air stripping system is estimated to be approximately CAD$8,100,000.
- The total installed cost for the air stripping system is estimated to be CAD$23,100,000.
- The operating cost for the air stripping system is estimated to be approximately CAD$1,380,000/year and is largely associated with power costs for pumps and fans/blowers. This equates to an operating cost of CAD$0.45/m^3 treated.

Other considerations:

- Based on a November 2013 budgetary quotation by Branch Environmental Corp., approximately 8 towers each of 12 m tall, 3.6 m diameter towers would be required to meet the model flow sheet ammonia requirements. Assuming 5 m clearance around each tower which would allow for ancillary equipment, at least 300 m2 of space would be required for the air stripping system depending on how equipment is arranged.
- Northern Saskatchewan, where all active uranium mining operations are situated, experiences very cold winters and only moderately warm summers. For those operations with year-round treatment and discharge, pre-heating of air and/or effluent would likely be required for a significant portion of the year, leading to high energy costs. High level estimates show that air and effluent pre-heating could almost double operating costs.

9.4.3.4 Selective Ion Exchange

Selective ion exchange for metals polishing would be best employed within the uranium model effluent treatment process downstream of the final filtration step. Treated effluent from the selective ion exchange system would then be conveyed to the polishing/monitoring pond(s) prior to discharge to the environment.

The following equipment additions would be required:

- Ion exchange feed, backwash, treated effluent pump(s).
- Ion exchange columns.
- Regenerant chemical totes/tanks and dosing pumps.
- Tanks (spent regenerant and treated effluent if needed).

The incremental capital and operating cost estimates for the addition of a selective ion exchange system to the uranium subsector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$3,000,000.
- The total installed cost for the system is estimated to be approximately CAD$7,800,000.
- The incremental operating cost for the system is estimated to be approximately CAD$1,800,000/year. This equates to an operating cost of CAD$0.60/m^3 treated.

These costs assume that the spent regenerant is returned to the feed to the upstream effluent treatment process to immobilize the metals as hydroxides, and that the sludge will be managed as part of the existing sludge management regime.

Other considerations:

- Spent resin disposal costs have not been considered here. If spent resin must be disposed of off-site, this would add to operating costs.
- Operating costs for ion exchange systems are extremely sensitive to metal loading in feed stream.

9.4.3.5 *Zeolite Ion Exchange*

Zeolite ion exchange could be applied to the uranium model effluent treatment process for ammonia removal downstream of the final filtration step.

The following equipment additions would be required:

- Ion exchange feed, backwash, treated effluent pump(s).
- Ion exchange columns.
- Regenerant chemical totes/tanks and dosing pumps.
- Tanks (spent regenerant and treated effluent if needed).
- Air stripping system for spent regenerant treatment.

Capital cost and operating cost information is not readily available for zeolite ion exchange systems due to the limited number of full-scale installations. For the purpose of this estimate, it is assumed that the capital cost for a zeolite exchange system is equivalent to selective ion exchange for metals removal, with the exception of the price of the zeolite media, which is less expensive than selective ion exchange resin.

Spent regenerant from the zeolite system will require further management. An allowance is included in the cost estimate for installation of an air stripping system for final ammonia management.

The incremental capital and operating cost estimates for a zeolite ion exchange system for the uranium subsector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$4,800,000.
- The total installed cost for the system is estimated to be approximately CAD$12,700,000.
- The incremental operating cost for the system is estimated to be approximately CAD$1,800,000/year. This equates to an operating cost of CAD$0.60/$m^3$ treated.

9.4.3.6 *Adsorption – Zero Valent Iron*

Zero Valent Iron adsorption technology for selenium removal would be best employed downstream of the uranium subsector model flow sheet (see Figure 6-48) after the low pH media filter(s). The existing high pH and low pH circuits would serve for bulk removal of dissolved metals and Ra-226, and existing media filtration would serve as upstream removal of TSS. The upstream processes combined would provide equalization. It is assumed that filtrate from the low pH media filter(s) would flow under pressure into the ZVI system, and effluent from the system would then flow by gravity into the monitoring/polishing pond(s). However, ZVI could also be employed upstream of the high pH reactor tank(s), depending on the concentration of competing oxyanions (e.g., oxyanions of arsenic and sulfate). Such a configuration could be more economical, as it could eliminate the need for equipment associated with downstream iron precipitation and solid/liquid separation. However, with the limited information available and for the purposes of this study, it is assumed that a complete ZVI system would be installed after the low pH media filter(s). Residual streams could be disposed of in a dedicated area of the tailings storage facility where appropriate storage conditions are maintained. It is assumed that the incremental generation of sludge could be accommodated by the existing tailings storage facility.

Assuming a stirred-tank reactor ZVI system would be employed, the following equipment additions would be required:

- Reagent make-up/storage systems and feed systems for pH adjustment chemicals.
- ZVI handling systems for ZVI media.
- Agitated ZVI reaction tank(s).
- Agitated post-pH adjustment tank.
- Aeration blower(s)/compressor(s) and diffuser(s).
- Clarifier/thickener(s) and/or media filter(s).
- Residuals management equipment (e.g., pumps to disposal, mechanical dewatering equipment).

A base case total installed cost of CAD$35,600,000 for a stirred-tank reactor ZVI system was estimated by CH2MHill for a flow rate of 182 m^3/h; however, this cost could be inflated over more basic costs by over 200% (see 8.2.12.1). An operating cost of CAD$3.18/m^3 was estimated for stirred-tank reactor ZVI technology; however, this could be inflated over more basic costs by as much as 200% (see 8.2.12.1). Factoring the total installed cost using the rule of six-tenths, the incremental capital and operating cost estimates for a ZVI system for the uranium subsector model effluent treatment process are as follows:

- The total installed cost for the system is estimated to be approximately CAD$27,800,000 to CAD$65,300,000.
- The incremental operating cost for the system is estimated to be approximately CAD$7,100,000/year to CAD$9,800,000/year. This equates to an operating cost of CAD$2.32/m^3 treated to CAD$3.18/m^3 treated.

Other considerations:

- Most full-scale installations of this technology treat flow rates one order of magnitude lower than the uranium subsector design flow rate. The applicability of this technology may be limited, accordingly.
- Few full-scale installations have been in operation for long enough to determine long term feasibility.
- The speciation of the uranium subsector total selenium is unknown and, therefore, the cost impacts of speciation cannot be determined.

Due to the relatively recent adoption of this technology, little is known about the long term stability of residuals and the potential for selenium remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.

9.4.3.7 *Active Aerobic Biological Oxidation*

MBBR technology for the removal of ammonia would be best employed within the uranium subsector model flow sheet after the low pH media filter(s) (see Figure 6-48). The existing high pH and low pH circuits would serve for bulk removal of dissolved metals and Ra-226, and existing media filtration would serve as upstream removal of TSS. The upstream processes combined would provide equalization.

It is assumed that filtrate from the low pH media filter(s) would flow under pressure into the MBBR system, and effluent from the system would then flow by gravity into the monitoring/polishing pond(s). The existing lime reagent make-up, storage, and distribution system could be utilized for pH control, provided that there is sufficient capacity within the system.

It is assumed that an electric heat exchange system would be used for start-up either where warm weather effluent temperatures are insufficient for start-up or where a quicker start-up is required, as well as during prolonged operation at low effluent temperatures (i.e., <5 °C). Pre-heating (natural gas boiler / electric heater) and heat recovery (treated effluent/untreated effluent heat exchanger) systems have been sized assuming that a temperature rise of 5 °C is required year round, which is considered to be conservative.

It is assumed that biomass residuals can be stored in a dedicated area of the tailings storage facility.

The incremental capital and operating cost estimates for an MBBR system including pre-heating and heat recovery for the uranium subsector model effluent treatment process are as follows:

- The capital cost for the MBBR system is estimated to be approximately CAD$6,300,000.
- The total installed cost for the MBBR system is estimated to be CAD$15,900,000.
- The operating cost for the MBBR system is estimated to be approximately CAD$1,400,000/year. This equates to an operating cost of CAD$0.45/m^3 treated.

CAPEX and OPEX costs have been updated in Revision 1 to include costs for pre-heating and heat-recovery.

9.4.3.8 *Active Anoxic/Anaerobic Biological Reduction*

FBR or ABMet® technology would be best employed for selenium removal downstream of the uranium subsector model flow sheet (see Figure 6-48) after the low pH media filter(s). The existing high pH and low pH circuits would serve for bulk removal of dissolved metals and Ra-226, and existing media filtration would serve as upstream removal of TSS. The upstream processes combined would provide equalization. It is assumed that filtrate from the low pH media filter(s) would flow under pressure into the FBR or ABMet® system, and effluent from the system would then flow by gravity into the monitoring/polishing pond(s). Residual streams could report to the high pH clarifier for thickening and co-disposal with hydroxide precipitation and iron co-precipitation residuals. It is assumed that the incremental generation of sludge could be accommodated by the existing clarifier, underflow equipment and tailings storage facility.

The following equipment additions would be required:

- Reagent dosing system(s) for pH adjustment, electron donor, and nutrient.
- Bulk reagent storage tanks for electron donor and nutrient, as they are typically supplied as bulk liquids.
- Influent heat exchange system.
- FBR or ABMet system®.
- Aerobic polishing.

A base case total installed cost of CAD$30,500,000 for an FBR system was estimated by CH2MHill for a flow rate of 182 m^3/h. An operating cost of CAD$1.59/$m^3$ was estimated by CH2MHill for the same system. Envirogen estimated CAD$8,000,000 to CAD$13,000,000 for an FBR system without influent heat exchange, aerobic polishing, and sludge handling, thickening, and disposal systems, and without standalone utilities and electrical service to the plant, and feed, effluent, and residuals piping to/from the plant. An operating cost of CAD$0.85/$m^3$ to CAD$1.16/$m^3$ was estimated by Envirogen for the same system. Factoring the total installed cost using the rule of six-tenths, the incremental capital and operating cost estimates for an FBR system for the uranium subsector model effluent treatment process are as follows: 1

- The total installed cost for the system is estimated to be approximately CAD$16,400,000 to CAD$26,600,000 for a basic system integrated into existing systems to CAD$56,000,000 for a standalone system.
- The incremental operating cost for the system is estimated to be approximately CAD$1,300,000/year to CAD$1,800,000/year for a basic system integrated into existing systems to CAD$6,900,000/year for a standalone system. This equates to an operating cost of CAD$0.85/$m^3$ treated CAD$1.59/$m^3$ treated.

As the uranium subsector model effluent treatment process is well advanced, the addition of an FBR system would not necessarily require substantial wrap around and independent sludge handling, thickening, and disposal systems. Therefore, the costs may be closer to the lower end of the ranges presented.

A base case total installed cost of CAD$40,700,000 for an ABMet® system was estimated by CH2MHill for a flow rate of 182 m^3/h. An operating cost of CAD$1.28/$m^3$ was estimated for ABMet® technology. Factoring the total installed cost using the rule of six-tenths, the incremental capital and operating cost estimates for an ABMet® system for the uranium subsector model effluent treatment process are as follows:

- The total installed cost for the system is estimated to be approximately CAD$74,600,000.
- The incremental operating cost for the system is estimated to be approximately CAD$3,900,000/year. This equates to an operating cost of CAD$1.28/$m^3$ treated.

It is important to consider that a total installed cost estimate for the same ABMet® system factored from cost curves developed and provided by GE would be lay between CAD$19,000,000 and CAD$28,000,000, which is less than half the total installed cost estimated by factoring from CH2MHill cost curves and would make the technology economically competitive with FBR technology. Again, since the system would not necessarily need substantial wrap around and independent sludge handling, thickening, and disposal equipment, the total installed costs may be in the lower range of costs.

Other considerations:

- Few full-scale FBR installations have been in operation for long enough to determine long term feasibility.
- The speciation of the uranium subsector total selenium is unknown and, therefore, the cost impacts of speciation cannot be determined.
- Due to the relatively recent adoption of this technology, little is known about the long term stability of residual biomass and the potential for selenium remobilization under various disposal conditions. If residuals are not stable, significant costs associated with biomass stabilization technology or re-treatment of residual leachate could be incurred.

9.4.3.9 Reverse Osmosis

Reverse osmosis for TDS removal would be best employed within the uranium subsector model effluent flow sheet after the final filtration step for effluent polishing. Permeate would be discharged to the monitoring/settling pond for monitoring or to the environment, following pH adjustment and/or remineralization, as required. Concentrate could be returned to the upstream lime hydroxide precipitation processes.

The following equipment additions would be required:

- Fine filtration (cartridge filters).
- Reverse osmosis feed pump.
- Reverse osmosis pressure vessel skids, with vessels to house approximately 500 membranes.

- Antiscalant dosing system.
- Clean-in-place system.
- pH adjustment system.
- Permeate and Concentrate Storage Tanks, if required.
- Discharge or transfer pumps, if required.

The incremental capital and operating cost estimates for a reverse osmosis system for the uranium subsector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$6,400,000.
- The total installed cost for the system is estimated to be approximately CAD$22,800,000.
- The incremental operating cost for the system is estimated to be approximately CAD$2,700,000/year. This equates to an operating cost of CAD$0.86/$m^3$.

CAPEX costs have been updated in Revision 1 based on additional reference cost information for both equipment and total installed costs. These costs have been used to update the RO equipment cost curve and to adjust factors used to generate installed costs based on RO equipment costs.

OPEX costs have been updated in Revision 1 based on information received concerning the experience of operations with respect to the operating and maintenance effort required for RO systems. Operations reported that for successful operation of RO systems, frequent cleaning and diligent operator attention is required. The costs of labour and cleaning chemicals have been increased to reflect these demands.

Other considerations:

- An estimate for the installation of a reverse osmosis process at a uranium operation in Northern Saskatchewan that was in a location separate to the main effluent treatment system totaled CAD$75,000,000 for a system with a treatment flow rate of approximately 360 m^3/h. This system included pre-treatment equipment (e.g., precipitation, clarification and filtration steps) and some wrap-around infrastructure (e.g., roads, piping). This estimate is not expected to be representatitve of an installed cost for the installation of the RO to the model effluent treatment system, as the model effluent treatment system is considered sufficient pre-treatment prior to RO and would be expected to be co-located with the model effluent treatment plant. Rather, this cost is an example of an installed cost estimate for a system with more substantial wrap-around requirements than would be expected for the model effluent treatment system.
- RO concentrate management could be difficult to accommodate in the model effluent treatment system. Although, RO concentrate return to the upstream (“conventional”) treatment process is possible, this may incur additional costs to expand equipment capacity, and would result in the cycling up of contaminants that are not removed by lime hydroxide precipitation or natural degradation. Should this become problematic, concentrate management equipment may be required and would add significant capital cost and operating cost. For example, the use of an evaporator/crystallizer to manage

brine from the RO process (assuming 70% recovery in the RO) would incur the following additional costs:

  - Equipment costs of around CAD$16,000,000, installed equipment costs of around CAD$50,000,000 and operating costs of around CAD$4,600,000/year.

- The operating cost for the RO system is highly dependent on the site-specific energy cost, and on the required frequency of cleaning cycles, which is dependent on the RO feed quality.
- RO permeate is very low in TDS and alkalinity. Re-mineralization of the permeate stream prior to discharge to the environment may be required to comply with toxicity requirements.

9.4.3.10 Nanofiltration

Nanofiltration would be best employed in the uranium model effluent flow sheet for removal of multivalent dissolved ions downstream of the final filtration step. Permeate would be discharged to the monitoring/polishing pond or to the environment, following pH adjustment and/or remineralization, as required. Concentrate would be directed to the upstream lime hydroxide precipitation step.

The following equipment additions would be required:

- Fine filtration (cartridge filters).
- Nanofiltration feed pump.
- Nanofiltration pressure vessel skids.
- Antiscalant dosing system.
- Clean-in-place system.
- pH adjustment system.
- Permeate and Concentrate Storage Tanks, if required.
- Discharge or transfer pumps, if required.

The incremental capital and operating cost estimates for a nanofiltration system for the uranium subsector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$6,400,000.
- The total installed cost for the system is estimated to be approximately CAD$22,800,000.
- The incremental operating cost for the system is estimated to be approximately CAD$2,100,000/year. This equates to an operating cost of CAD$0.70/$m^3$.

Because nanofiltration and reverse osmosis are very similar, with the exception of operating pressure and membranes, the capital costs for nanofiltration have been assumed to be the same as estimated for reverse osmosis. Nanofiltration operates at lower pressures compared to reverse osmosis, therefore energy consumption for nanofiltration will be less. The energy requirements of nanofiltration have been assumed to be 2/3 of the energy requirements of reverse osmosis.

CAPEX costs have been updated in Revision 1 based on updated RO costs, as NF CAPEX have been assumed to be the same as RO costs.

- OPEX costs have been updated in Revision 1 based on information received concerning the experience of operations with respect to the operating and maintenance effort required for RO systems. Operations reported that for successful operation of RO systems, frequent cleaning and diligent operator attention is required. It is assumed similar maintenance and operation demands would apply to nanofiltration membranes as well. The costs of labour and cleaning chemicals have been increased to reflect these demands.

Other considerations:

- NF concentrate management could be difficult to accommodate in the model effluent treatment system. NF concentrate return to an upstream treatment process may incur additional costs to expand equipment capacity, and would result in the cycling up of contaminants that are not removed by lime hydroxide precipitation or natural degradation. Should this become problematic, concentrate management equipment may be required and would add significant capital cost and operating cost. For example, the use of an evaporator/crystallizer to manage brine from the NF process (assuming 70% recovery in the NF) would incur the following additional costs:
    - Equipment costs of around CAD$16,000,000, installed equipment costs of around CAD$50,000,000 and operating costs of around CAD$4,600,000/year.
- The operating cost for the NF system is highly dependent on the site-specific energy cost, and on the required frequency of cleaning cycles, which is dependent on the feed quality.
- NF permeate is low in TDS and alkalinity. Re-mineralization of the permeate stream prior to discharge to the environment may be required to comply with toxicity requirements.

9.5 Diamond

9.5.1 Model Effluent Management and Treatment System

Refer to Section 6.5 for the complete discussion of the diamond sector model effluent management and treatment system.

In the diamond sector model, effluent is equalized prior to treatment and bulk TSS is removed via pond-based settling. The ponds also allow time for natural degradation of ammonia and phosphorus. The effluent is coagulated (e.g., with ferric sulfate or aluminum sulfate). If required, to adjust effluent pH/alkalinity and/or precipitate dissolved metals (e.g., reagent addition requires iron hydroxide or aluminum hydroxide precipitation), hydroxide reagent (e.g., lime, sodium hydroxide) may be added on a contingency basis. Coagulated TSS and precipitates are then allowed to settle, aided by flocculant, in a clarifier. Clarifier overflow is then polished by media filtration before being pH adjusted with sulfuric acid to meet un-ionized ammonia/toxicity limits prior to discharge to the environment. Clarifier underflow is co-disposed with tailings.

The design flow rate of the model effluent management and treatment system for diamond mining is 3,000 m^3/h. The nominal flow rate for diamond mining model treatment is 2,000 m^3/h.

9.5.1.1 *Technologies Applicable for the Augmentation of the Model Effluent Management and Treatment System*

The technologies that are considered applicable for augmentation of the diamond model effluent management and treatment system are:

- Air Stripping.
- Selective Ion Exchange – Zeolite for Ammonia Removal.
- Aerobic Biological Oxidation.
- Reverse Osmosis.
- Nanofiltration.

Ferric iron or aluminum salt co-precipitation, reacidification, solid/liquid separation, enhanced coagulation and settling, and natural degradation are considered to be redundant to the model flow sheet.

Radium-226 and cyanide concentrations are not available for the diamond sector and are not expected to be relevant. Therefore, barium chloride co-precipitation and cyanide destruction technologies were not evaluated for the diamond sector.

Augmentative technologies that removal metals, such as hydroxide precipitation, sulfide precipitation, metal oxidation, selective ion exchange – synthetic resins for metals polishing, zero valent iron adsorption for selenium removal, and active anoxic/anaerobic biological reduction for selenium removal were not evaluated as metals are not proposed *MMER* parameters for the diamond sector.

9.5.2 *Model Treatment Cost*

Two active operations reported via the operations questionnaire capital costs and operating costs associated with effluent treatment for systems similar to the model effluent management and treatment system. For these operations, the range of reported total capital cost including upgrades adjusted to 2013 CAD$ is CAD$18,600 to CAD$48,800 per m^3/h installed capacity. For the model effluent management and treatment system with 3,000 m^3/h design treatment capacity, this would equate to CAD$55,700,000 to CAD$146,500,000 total installed cost.

The same operations reported operating costs ranging from CAD$0.02 to CAD$0.20/m^3. The majority of operating costs are associated with reagent consumption and operating labour. For the model effluent management and treatment system with 2,000 m^3/h nominal treatment flow rate, this would equate to CAD$352,000 to 3,500,000 annual operating cost.

9.5.3 Technique CAPEX and OPEX

9.5.3.1 Air Stripping

The concentration of total ammonia achieved by the model effluent treatment system in the diamond sector is 2.35 mg-N/L (see Table 6-90). At such a low feed concentration, air stripping technology would not be technically feasible for ammonia removal due to the low concentration driving force for volatilization to a lower achievable limit of 3 mg-N/L, as discussed in Section 8.2.10.The air stripping process is best suited to feed total ammonia concentrations in the range of 10 to 100 mg/L.

9.5.3.2 Zeolite Ion Exchange

The concentration of total ammonia achieved by the model effluent treatment system in the diamond sector is 2.35 mg-N/L (see Table 6-90). Based on this, it was concluded that total ammonia concentrations in diamond effluents are already lower than the achievable total ammonia concentration from a zeolite ion exchange system. Therefore, capital and operating costs for zeolite ion exchange have not been assessed for the diamond sector.

9.5.3.3 Active Aerobic Biological Oxidation

The concentration of total ammonia achieved by the model effluent treatment system in the diamond sector is 2.35 mg-N/L (see Table 6-90). At such a low feed concentration, active aerobic biological oxidation technology would not be technically feasible for ammonia removal due to a typical lower achievable limit of 2 mg-N/L, as discussed in Section 8.2.13.

9.5.3.4 Reverse Osmosis

Reverse osmosis for TDS removal would be best employed within the diamond sector model effluent flow sheet downstream of the filtration step. Permeate from the RO unit would then be fed into the pH adjustment tank, to neutralize the permeate prior to discharge to the polishing pond. Permeate remineralization may be required prior to discharge to the environment.

The following equipment additions would be required:

- Fine filtration (cartridge filters).
- Reverse osmosis feed pump.
- Reverse osmosis pressure vessel skids, with vessels to house approximately 3,000 membranes.
- Antiscalant dosing system.
- Clean-in-place system.
- pH adjustment system.
- Permeate and Concentrate Storage Tanks, if required.
- Discharge or transfer pumps, if required.

The incremental capital and operating cost estimates for the addition of a reverse osmosis system for the diamond sector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$38,100,000.

- The total installed cost for the system is estimated to be approximately CAD$136,400,000.
- The incremental operating cost for the system is estimated to be approximately CAD$13,900,000/year. This equates to an operating cost of CAD$0.80/$m^3$.
- CAPEX costs have been updated in Revision 1 based on additional reference cost information for both equipment and total installed costs. These costs have been used to update the RO equipment cost curve and to adjust factors used to generate installed costs based on RO equipment costs.
- OPEX costs have been updated in Revision 1 based on information received concerning the experience of operations with respect to the operating and maintenance effort required for RO systems. Operations reported that for successful operation of RO systems, frequent cleaning and diligent operator attention is required. The costs of labour and cleaning chemicals have been increased to reflect these demands.

Other considerations:

- RO concentrate management would be difficult to accommodate in the model effluent treatment system. RO concentrate return to a site water management facility may incur additional costs to expand equipment capacity, and would result in the cycling up of contaminants. Should this become problematic, concentrate management equipment may be required and would add significant capital cost and operating cost. For example, the use of an evaporator/crystallizer to manage brine from the RO process (assuming 70% recovery in the RO) would incur the following additional costs:
    - Equipment costs of around CAD$93,000,000, installed equipment costs of around CAD$290,000,000 and operating costs of around CAD$26,000,000/year.
- The operating cost for the RO system is highly dependent on the site-specific energy cost, and on the required frequency of cleaning cycles, which is dependent on the RO feed quality.
- RO permeate is very low in TDS and alkalinity. Re-mineralization of the permeate stream prior to discharge to the environment may be required to comply with toxicity requirements.

9.5.3.5 *Nanofiltration*

Nanofiltration would be best employed in the diamond model effluent flow sheet for removal of multivalent dissolved ions downstream of the filtration step. Permeate from the NF unit would then be fed into the pH adjustment tank, to neutralize the permeate prior to discharge to the polishing pond. Permeate remineralization may be required prior to discharge to the environment.

The following equipment additions would be required:

- Fine filtration (cartridge filters).
- Nanofiltration feed pump.
- Nanofiltration pressure vessel skids.

- Antiscalant dosing system.
- Clean-in-place system.
- pH adjustment system.
- Permeate and Concentrate Storage Tanks, if required.
- Discharge or transfer pumps, if required.

The incremental capital and operating cost estimates for the addition of a nanofiltration system for the diamond sector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$38,100,000.
- The total installed cost for the system is estimated to be approximately CAD$136,400,000.
- The incremental operating cost for the system is estimated to be approximately CAD$11,000,000/year. This equates to an operating cost of CAD$0.63/m^3.

Because nanofiltration and reverse osmosis are very similar, with the exception of operating pressure and membranes, the capital costs for nanofiltration have been assumed to be the same as estimated for reverse osmosis. Nanofiltration operates at lower pressures compared to reverse osmosis, therefore energy consumption for nanofiltration will be less. The energy requirements of nanofiltration have been assumed to be 2/3 of the energy requirements of reverse osmosis.

CAPEX costs have been updated in Revision 1 based on updated RO costs, as NF CAPEX have been assumed to be the same as RO costs.

OPEX costs have been updated in Revision 1 based on information received concerning the experience of operations with respect to the operating and maintenance effort required for RO systems. Operations reported that for successful operation of RO systems, frequent cleaning and diligent operator attention is required. It is assumed similar maintenance and operation demands would apply to nanofiltration membranes as well. The costs of labour and cleaning chemicals have been increased to reflect these demands.

Other considerations:

- NF concentrate management would be difficult to accommodate in the model effluent treatment system. NF concentrate return to a site water management facility may incur additional costs to expand equipment capacity, and would result in the cycling up of contaminants. Should this become problematic, concentrate management equipment may be required and would add significant capital cost and operating cost. For example, the use of an evaporator/crystallizer to manage brine from the NF process (assuming 70% recovery in the NF) would incur the following additional costs:
    - Equipment costs of around CAD$93,000,000, installed equipment costs of around CAD$290,000,000 and operating costs of around CAD$26,000,000/year.

- The operating cost for the NF system is highly dependent on the site-specific energy cost, and on the required frequency of cleaning cycles, which is dependent on the NF feed quality.
- NF permeate is low in TDS and alkalinity. Re-mineralization of the permeate stream prior to discharge to the environment may be required to comply with toxicity requirements.

9.6 Coal

9.6.1 Model Effluent Management and Treatment System

Refer to Section 6.6 for the complete discussion of the coal sector model effluent management and treatment system.

In the coal sector model, bulk TSS is removed from effluent via pond-based settling and polishing which may be assisted by addition of flocculant. The ponds also allow time for passive natural degradation of ammonia.

The design flow rate of the model effluent management and treatment system is 3,000 m^3/h. and the nominal flow rate is 1,000 m^3/h.

9.6.1.1 Technologies Applicable for the Augmentation of the Model Effluent Management and Treatment System

The technologies that are considered applicable for augmentation of the coal model effluent management and treatment system are:

- Hydroxide Precipitation.
- Sulfide Precipitation.
- Sulfide Precipitation with Proprietary Polymeric Organosulfide Chemicals.
- Ferric Iron Co-Precipitation.
- Solid/Liquid Separation – Clarification, Enhanced Coagulation and Settling, and Filtration.
- Reverse Osmosis.
- Nanofiltration.
- Selective Ion Exchange – Synthetic Resins for Metals Polishing.
- Active Anoxic/Anaerobic Reduction.
- Adsorption – ZVI.

Radium-226 and cyanide concentrations are not available for the coal sector and are not expected to be relevant, therefore barium chloride co-precipitation and cyanide destruction technologies were not considered as BATEA for the coal sector.

Oxidation was not considered as there is insufficient information on speciation of iron and manganese to determine if improved removal efficiencies could be attained.

Air stripping, active aerobic biological oxidation, reacidification, and zeolite ion exchange were not considered as the concentration of total ammonia achieved by the model effluent treatment system in the coal sector is very low at <0.37 mg-N/L (Table 6-98).

9.6.2 *Model Treatment Cost*

Insufficient information was provided by operations questionnaire respondents to report total capital and operating costs for the coal sector model treatment system. Of the operations that did provide cost information, most quoted a total capital cost of less than CAD$5,000,000 and a total annual operating cost of less than CAD$100,000.

9.6.3 *Technique CAPEX and OPEX*

9.6.3.1 *Hydroxide Precipitation*

Based on a review of Table 6-98, of all metals, marginal removal could be achieved only for iron (from <0.82 mg/L to 0.1 mg/L) and aluminum (from <0.90 mg/L to 0.5 mg/L) using hydroxide precipitation. The concentrations of all other metals achieved by the model effluent treatment system in the coal sector are below their achievable concentrations through hydroxide precipitation. Similar to the iron ore subsector, it is possible that iron and aluminum are associated with TSS, therefore improved TSS removal may also reduce iron and aluminum concentrations. The dissolved fraction of aluminum and iron available to be precipitated as metal hydroxides is unknown. It is also possible that iron is present as ferrous iron and that aeration could improve iron removal; however, the fraction of iron present as ferrous and ferric iron is unknown.

It is assumed that the hydroxide precipitation reaction will be conducted in a 30 minute retention time agitated reactor tank(s). Subsequent solid/liquid separation would be by pond-based settling for solid/liquid separation within the existing settling pond(s) and polishing pond(s) system. Hydroxide precipitation would be best employed within the coal sector model flow sheet upstream of the settling pond(s) (see Figure 6-71), assuming upstream flow equalization, or upstream the polishing pond (s) if no upstream flow equalization is available. New transfer pump(s) are required to deliver effluent to the agitated reactor tanks. It is assumed that treated effluent flows by gravity from the agitated reactor tank(s) to the settling pond(s)/polishing pond(s). It is assumed that the incremental generation of hydroxide sludge can be accommodated by the existing settling pond(s) and polishing pond(s).

Lime-based hydroxide precipitation is assumed. Lime make-up, storage, and dosing systems including lime silo, slaker, agitated slurry tank, recirculation pumps and loop, and dosing valves are required.

The incremental capital and operating cost estimates for the hydroxide precipitation system described above for the coal sector model effluent treatment process are as follows:

- The total installed cost for the system is estimated to be approximately CAD$2,600,000.
- The incremental operating cost for the system is estimated to be approximately CAD$400,000/year including reagents, power, operating labour, and maintenance. This equates to an operating cost of CAD$0.05/m^3 treated.

9.6.3.2 *Sulfide Precipitation*

Based on a review of Table 6-98, of all metals, marginal removal could be achieved only for iron (from <0.82 mg/L to 0.3 mg/L) and manganese (from <0.13 mg/L to 0.05 mg/L). Near order of magnitude removal could be achieved for selenium (from <0.38 mg/L to 0.05 mg/L).

In any case, utilization of sulfide precipitation for the removal of iron, manganese, and/or selenium would be a highly atypical application of sulfide precipitation technology.

The concentrations of all other metals achieved by the model effluent treatment system in the coal sector are below their achievable concentrations through sulfide precipitation. It is possible that iron and manganese are associated with TSS, therefore improved TSS removal may also reduce iron and manganese concentrations. The dissolved fraction of iron and manganese available to be precipitated as metal sulfides is unknown. It is also possible that iron is present as ferrous iron and manganese is present as manganous, and that aeration could improve the removal of both metals; however, the fraction of iron present as ferrous and ferric iron and the fraction of manganese present as manganous are unknown.

This technique is not considered to be typical nor economic for the removal of iron, manganese, and/or selenium for the coal sector.

9.6.3.3 *Sulfide Precipitation with Proprietary Polymeric Organosulfide Chemicals*

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Proprietary polymeric organosulfide precipitation technology for metals polishing would be best employed within the coal model effluent treatment system flow sheet upstream of the polishing pond(s) (see Figure 6-71). Bulk TSS removal and equalization would occur at the upstream settling pond(s).

The proprietary reagent could be dosed into the polishing pond(s) influent within a new agitated reactor tank. The effluent would be pumped to the agitated reactor tank via new pumps. The agitated reactor tank would discharge by gravity to the polishing pond(s) where subsequent solid/liquid separation would occur.

It is assumed that the incremental generation of sulfide sludge could be accommodated by the pond. Addition of a reagent dosing system would be required. Addition of a bulk reagent tank may also be desirable if the reagent is consumed at a high rate. Otherwise, the reagent could be dosed directly from the tote in which it is supplied by the vendor.

Utilizing the GE rule of thumb of 10 mg/L proprietary reagent per mg/L target metals and the concentrations achieved by the model effluent treatment system in the coal sector (Table 6-98), it is estimated that, approximately 25 mg/L dosage of proprietary reagent would be required for this application. At the nominal flow rate of 1,000 m^3/h and 25 mg/L dosage, a tote of proprietary reagent would be consumed within 2 days. It is assumed that this is an unacceptable tote replacement period, and so a 7 day bulk reagent tank has been included in the capital cost estimate below.

None of the proprietary reagents investigated require agitation, so a bulk reagent tank agitator has not been included in the capital cost estimate below. Small progressive cavity pumps would be required. It is assumed that dosing pumps would be installed in redundant, duty/stand-by configuration. Power consumption by the pumps is expected to be minor, and is not included in the operating cost estimate below.

The incremental capital and operating cost estimates for a proprietary polymeric organosulfide sulfide precipitation system for the coal sector model effluent treatment process are as follows:

- The incremental equipment cost for the system is estimated to be approximately CAD$400,000.
- The incremental total installed cost for the system is estimated to be approximately CAD$1,100,000.
- The incremental operating cost for the system is estimated to be approximately CAD$1,800,000/year. This equates to an operating cost of CAD$0.21/$m^3$ treated.

Other considerations:

- The chemicals may be acutely lethal to rainbow trout and *Daphnia magna* at certain residual chemical concentrations in effluent. For example, the rule of thumb dosage of 25 mg/L could potentially lead to residual chemical concentrations in effluent that exceed the rainbow trout LC50 of 8 mg/L for MetClear™ MR2405. It is expected that the majority of the chemical will be retained with precipitated metals in the settling pond(s) rather than reporting to the environment. However, sludge carryover and/or cycling up of residual chemical concentration due to effluent recirculation (e.g., for mill process re-use, for effluent treatment process re-use, or for return of off-spec effluent for re-treatment) may pose risk of non-compliance with toxicity requirements. It is advised to verify that treated effluent complies with toxicity requirements (i.e., residual chemical concentration is below lethality thresholds). It is also advised that treated effluent be discharged rather than recirculated for any purpose such that cycling up of residual chemical concentration is limited.
- Due to the relatively recent adoption of these reagents and the proprietary nature of their formulations, little is known about the long term stability of residuals and the potential for acid generation and metals remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.
- There is a potential for reduction of operating costs due to reductions in flocculant consumption, as the proprietary reagents are polymeric in nature and may offset flocculant demand. However, no discounts have been applied to the operating cost presented here.
- It may be possible to mix proprietary reagent with effluent by means alternative to an agitated reactor tank in order to reduce costs and still achieve good metals removal efficiency; however, this has not been demonstrated to the best of Hatch's knowledge.
- The budgetary quotations provided for the proprietary reagents were for delivery to Northern Ontario. Additional costs will apply for delivery to more remote mining operations. The reagents are not classified as dangerous goods.

9.6.3.4 *Ferric Iron Co-Precipitation*

In Revision 0, it was concluded that ferric iron or aluminum salt co-precipitation would not improve effluent quality for the coal sector. However, based on a review of the updated concentrations achieved by the model effluent treatment system in the coal sector (Table 6-98), selenium exceeds its achievable concentration through ferric iron co-precipitation (0.090 mg/L) at <0.38 mg/L.

Ferric iron co-precipitation technology for selenium removal would be best employed within the coal sector model effluent treatment system flow sheet after the polishing pond(s) (see Figure 6-71). The settling pond(s) and polishing pond(s) would serve for bulk removal of TSS and equalization. Residual streams could be thickened and disposed of in a dedicated area of the settling pond(s) where appropriate storage conditions are maintained. It is assumed that the incremental generation of sludge could be accommodated by the existing settling pond(s).

Assuming a stirred-tank reactor system would be employed, the following equipment additions would be required:

- Reagent make-up/storage systems and feed systems for pH adjustment chemicals and ferric iron salt.
- Agitated reaction tank(s).
- Agitated post-pH adjustment tank.
- Clarifier/thickener(s) and/or media filter(s).
- Residuals management equipment (e.g., pumps to disposal, mechanical dewatering equipment).

A base case total installed cost of CAD$10,900,000 for a stirred-tank reactor system was estimated by CH2MHill for a flow rate of 182 m^3/h; however, this cost could be inflated over more basic costs by over 200% (see 8.2.3). An operating cost of CAD$2.78/$m^3$ was estimated for stirred-tank reactor system; however, this could be inflated over more basic costs by as much as 200% or as high as CAD$3.28/$m^3$ to CAD$3.53/$m^3$ (see 8.2.3). Factoring the total installed cost using the rule of six-tenths, the incremental capital and operating cost estimates for a ferric iron co-precipitation system for the coal sector model effluent treatment process are as follows:

- The total installed cost for the system is estimated to be approximately CAD$58,600,000 to CAD$72,700,000.
- The incremental operating cost for the system is estimated to be approximately CAD$24,300,000/year to CAD$30,900,000/year. This equates to an operating cost of CAD$2.78/$m^3$ treated to CAD$3.53/$m^3$ treated.

Other considerations:

- The United States Environmental Protection Agency (USEPA) conducted a pilot study of ferric iron co-precipitation of selenium at Kennecott Utah Copper Corporation's Garfield Wetlands-Kessler Springs site which demonstrated that although the technology was effective in reducing selenium concentrations (though not to the regulatory discharge concentration of 0.005 mg/L), it would not be economically feasible to use at a large scale.
- The speciation of the coal sector total selenium is unknown and, therefore, the cost impacts of speciation cannot be determined.
- TCLP testing during the aforementioned Garfield Wetlands-Kessler Springs pilot study indicated the residuals to be hazardous waste (54). Little is known about the long term stability of residuals and the potential for selenium remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.

9.6.3.5 *Clarification*

Clarification for bulk TSS removal would be best employed within the coal sector model flow sheet upstream of the series of ponds currently used for bulk TSS removal. Overflow from the clarifier would report to settling ponds for monitoring and polishing. Underflow from the clarifier would be pumped to the Tailings Storage Facility.

The following equipment additions would be required:

- Clarifier feed pump.
- Clarifier.
- Clarifier overflow pump.
- Residuals management equipment (e.g., pumps to disposal, mechanical dewatering equipment if not disposed of in-pond).

The incremental capital and operating cost estimates for the addition of a clarifier to the coal sector model effluent treatment process are as follows:

- Equipment costs are estimated to be CAD$6,500,000.
- The total installed cost for the system is estimated to be approximately CAD$21,500,000.
- The incremental operating cost for the system is estimated to be approximately CAD$880,000/year. This equates to an operating cost of CAD$0.10/m^3 treated.

CAPEX costs have been updated in Revision 1 based on additional reference cost information for both equipment and total installed costs. These costs have been used to update the clarification equipment cost curve and to adjust factors used to generate installed costs based on clarification equipment costs.

Other considerations:

- It is assumed that sufficient space is available for the incorporation of the necessary equipment into the model system.

9.6.3.6 *Enhanced Coagulation and Settling*

An enhanced coagulation and settling process for bulk TSS removal would be best employed within the coal sector model flow sheet upstream of the series of ponds currently used for bulk TSS removal. With the installation of the enhanced coagulation and settling system, flocculant would be dosed into the feed to the ECS unit rather than into the ponds. Overflow from the ECS unit would report to the model pond system, which would then serve as polishing ponds for further removal of TSS and allow monitoring of effluent quality. Underflow from the ECS would be pumped to the Tailings Storage Facility.

The following equipment additions would be required:

- ECS unit.
- Reagent make-up/storage systems and feed systems for flocculant/polymer.
- Residuals management equipment (e.g., underflow pump(s), underflow tank, pump(s) to disposal, etc.), if required.

The incremental capital and operating cost estimates for the addition of an ECS system to the coal sector model effluent treatment process are as follows: 1

- Equipment costs are estimated to total CAD$3,400,000.
- The total installed cost for the system is estimated to be approximately CAD$10,700,000.
- The incremental operating cost for the system is estimated to be approximately CAD$880,000/year. This equates to an operating cost of CAD$0.10/m^3.

The only enhanced coagulation and settling capital and operating cost information provided via the vendor questionnaire for technologies that passed BAT screening was for Veolia’s proprietary ACTIFLO® system; for this reason, ACTIFLO® costs have been used as representative of ECS technologies for BATEA purposes.

Other considerations:

- It is assumed that sufficient space is available for the incorporation of the necessary equipment into the model system.
- Operating cost estimated has assumed that reagent costs do not change with the installation of this system; however, it is expected that some reduction in reagent requirements would be experienced due to the enhanced coagulation provided by ballast or sludge recycle.
- One coal operation commented during the review period for the Draft MEND BATEA Study Report that they estimated total installed costs and operating costs for the ECS system above to be 2.5 to 3 times higher, and 5 times higher, respectively, than estimated by Hatch at the time (Revision A / Revision 0). However, follow-up to seek clarification on this comment was unsuccessful. 1

9.6.3.7 *Filtration*

Media filtration for bulk TSS removal would be best employed within the coal sector model flow sheet upstream of the series of ponds currently used for bulk TSS removal. The TSS value after pond-based solid/liquid separation is expected to be <77 mg/L. Therefore bulk removal of TSS prior to filtration would be required prior to media filtration. A clarifier system would thus be installed as well for bulk TSS removal. Underflow from the clarifier would be pumped to the Tailings Storage Facility. Backwash from media filtration would be returned to upstream settling pond(s) for solids sedimentation. The following equipment additions would be required:

- Clarifier feed pump.
- Clarifier.
- Residuals management equipment (e.g., pumps to disposal, mechanical dewatering equipment if not disposed of in-pond).
- Media filtration vessel feed pump.
- Media filtration vessels.
- Media filtration backwash pump.
- Discharge pump.

The incremental capital and operating cost estimates for the addition of a media filtration system, including clarification, to the coal sector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$11,600,000.
- The total installed cost for the system is estimated to be approximately CAD$35,600,000.
- The incremental operating cost for the system is estimated to be approximately CAD$1,300,000/year. This equates to an operating cost of CAD$0.15/m^3.

CAPEX costs have been updated in Revision 1 based on additional reference cost information for both equipment and total installed costs. These costs have been used to update the clarification equipment cost curve and to adjust factors used to generate installed costs based on clarification equipment costs. As discussed above, clarification costs are included in filtration costs.

9.6.3.8 *Selective Ion Exchange*

Selective ion exchange for dissolved metals removal could be employed within the coal sector model flow sheet downstream of the series of ponds currently used for bulk TSS removal. For the addition of selective ion exchange to the coal flow sheet, a bulk removal step for TSS would also be required as pre-treatment, as the TSS concentration achieved by the model effluent treatment system in the coal sector is <77 mg/L..

This bulk removal step would include a clarifier and media filter(s) to prepare the effluent for feed into the ion exchange columns. The ponds in the system could then serve as monitoring and polishing ponds. Underflow from the clarifier would be pumped to the Tailings Storage

Facility. Backwash from media filtration would be returned to an upstream pond for sedimentation of solids

The following equipment additions would be required:

- Clarifier feed pump.
- Clarifier reactor.
- Clarifier overflow pump.
- Residuals management equipment (e.g., pumps to disposal, mechanical dewatering equipment if not disposed of in-pond).
- Media filtration vessel feed pump.
- Media filtration media vessels.
- Media filtration backwash pump.
- Ion exchange feed, backwash, treated effluent pump(s).
- Ion exchange columns.
- Regenerant chemical totes/tanks and dosing pumps.
- Tanks (spent regenerant and treated effluent if needed).

The incremental capital and operating cost estimates for the addition of a selective ion exchange system, including clarification and media filtration, to the coal sector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$29,600,000.
- The total installed cost for the system is estimated to be approximately CAD$76,400,000.
- The incremental operating cost for the system is estimated to be approximately CAD$7,400,000/year. This equates to an operating cost of CAD$0.85/m^3.

CAPEX costs have been updated in Revision 1 based on additional reference cost information for both equipment and total installed costs. These costs have been used to update the clarification equipment cost curve and to adjust factors used to generate installed costs based on clarification equipment costs. As discussed above, clarification costs are included in selective ion exchange costs.

Other considerations:

- Regenerant disposal cannot be easily accomplished in this flow sheet. This regenerant would have to be further treated to remove contaminants.
- Spent resin disposal costs have not been considered here. If spent resin must be disposed of off-site, this would add to operating costs.
- Operating costs for ion exchange systems are extremely sensitive to metal loading in feed stream.

- One coal operation commented during the review period for the Draft MEND BATEA Study Report that they estimated equipment costs, total installed costs, and operating costs for the ion exchange system above to be 3 times higher, 10 times higher, and 5 times higher, respectively, than estimated by Hatch at the time (Revision A / Revision 0). However, follow-up to seek clarification on this comment was unsuccessful.

9.6.3.9 *Adsorption – Zero Valent Iron*

Zero Valent Iron adsorption technology for selenium removal would be best employed within the coal sector model flow sheet after the polishing pond (see Figure). The settling pond(s) and polishing pond(s) would serve for bulk removal of TSS and equalization. Residual streams could be thickened and disposed of in a dedicated area of the settling pond(s) where appropriate storage conditions are maintained. It is assumed that the incremental generation of sludge could be accommodated by the existing settling pond(s).

Assuming a stirred-tank reactor system would be employed, the following equipment additions would be required:

- Reagent make-up/storage systems and feed systems for pH adjustment chemicals.
- ZVI handling systems for ZVI media.
- Agitated ZVI reaction tank(s).
- Agitated post-pH adjustment tank.
- Aeration blower(s)/compressor(s) and diffuser(s).
- Clarifier/thickener(s) and/or media filter(s).
- Residuals management equipment (e.g., pumps to disposal, mechanical dewatering equipment).

A base case total installed cost of CAD$35,600,000 for a stirred-tank reactor ZVI system was estimated by CH2MHill for a flow rate of 182 m^3/h; however, this cost could be inflated over more basic costs by over 200% (see Section 8.2.12.1). An operating cost of CAD$3.18/$m^3$ was estimated for stirred-tank reactor ZVI technology; however, this could be inflated over more basic costs by as much as 200% (see Section 8.2.12.1). Factoring the total installed cost using the rule of six-tenths, the incremental capital and operating cost estimates for a ZVI system for the coal sector model effluent treatment process are as follows:

- The total installed cost for the system is estimated to be approximately CAD$81,400,000 to CAD$191,200,000.
- The incremental operating cost for the system is estimated to be approximately CAD$20,300,000/year to CAD$27,900,000/year. This equates to an operating cost of CAD$2.32/$m^3$ treated to CAD$3.18/$m^3$ treated.

Other considerations:

- Most full-scale installations of this technology treat flow rates two orders of magnitude lower than the coal sector design flow rate. The applicability of this technology may be limited, accordingly.

- Few full-scale installations have been in operation for long enough to determine long term feasibility.
- The speciation of the coal sector total selenium is unknown and, therefore, the cost impacts of speciation cannot be determined.

Due to the relatively recent adoption of this technology, little is known about the long term stability of residuals and the potential for selenium remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.

9.6.3.10 *Active Anoxic/Anaerobic Biological Reduction*

FBR or ABMet® technology for selenium removal would be best employed within the coal sector model flow sheet after the polishing pond(s) (see Figure). The settling pond(s) and polishing pond(s) would serve for bulk removal of TSS and equalization. Residual streams could be thickened and disposed of in a dedicated area of the settling pond(s) where appropriate storage conditions are maintained. It is assumed that the incremental generation of sludge could be accommodated by the existing settling pond(s).

The following equipment additions would be required:

- Reagent dosing system(s) for pH adjustment, electron donor, and nutrient.
- Bulk reagent storage tanks for electron donor and nutrient, as they are typically supplied as bulk liquids.
- Influent heat exchange system.
- FBR or ABMet system®.
- Aerobic polishing.
- Solid/liquid separation and/or sludge handling, thickening, and disposal system.

A base case total installed cost of CAD$30,500,000 for an FBR system was estimated by CH2MHill for a flow rate of 182 m^3/h. An operating cost of CAD$1.59/$m^3$ was estimated by CH2MHill for the same system. Envirogen estimated CAD$8,000,000 to CAD$13,000,000 for an FBR system without influent heat exchange, aerobic polishing, and sludge handling, thickening, and disposal systems, and without standalone utilities and electrical service to the plant, and feed, effluent, and residuals piping to/from the plant. An operating cost of CAD$0.85/$m^3$ to CAD$1.16/$m^3$ was estimated by Envirogen for the same system. Factoring the total installed cost using the rule of six-tenths, the incremental capital and operating cost estimates for an FBR system for the coal sector model effluent treatment process are as follows:

- The total installed cost for the system is estimated to be approximately CAD$43,000,000 to CAD$70,000,000 for a basic system integrated into existing systems to CAD$164,000,000 for a standalone system.

- The incremental operating cost for the system is estimated to be approximately CAD$7,400,000/year to CAD$10,200,000/year for a basic system integrated into existing systems to CAD$14,000,000/year for a standalone system. This equates to an operating cost of CAD$0.85/$m^3$ treated to CAD$1.59/$m^3$ treated.

As the coal sector model effluent treatment process is fairly rudimentary, the addition of an FBR system would require substantial wrap around and independent sludge handling, thickening, and disposal systems. Therefore, the capital and operating costs may be closer to the higher end of the ranges presented.

A base case total installed cost of CAD$40,700,000 for an ABMet® system was estimated by CH2MHill for a flow rate of 182 m^3/h. An operating cost of CAD$1.28/$m^3$ was estimated by CH2MHill for the same system. Factoring the total installed cost using the rule of six-tenths, the incremental capital and operating cost estimates for an ABMet® system for the coal sector model effluent treatment process are as follows:

- The total installed cost for the system is estimated to be approximately CAD$218,700,000.
- The incremental operating cost for the system is estimated to be approximately CAD$11,200,000/year. This equates to an operating cost of CAD$1.28/$m^3$ treated.

It is important to consider that a total installed cost estimate for the same ABMet® system factored from cost curves developed and provided by GE would be lay between CAD$55,400,000 and CAD$82,100,000, which is less than half the total installed cost estimated by factoring from CH2MHill cost curves and would make the technology economically competitive with FBR technology. However, as the coal sector model effluent treatment process is fairly rudimentary, the addition of an ABMet® system would require substantial wrap around and independent sludge handling, thickening, and disposal systems. Therefore, the capital and operating costs may be closer to the higher end of the ranges presented.

Other considerations:

- Few full-scale FBR installations have been in operation for long enough to determine long term feasibility.
- Active anoxic/anaerobic biological reduction (FBR/ABMet®) applications with untreated effluent selenium concentrations exceeding 0.050 mg/L, such as for the coal sector model with a concentration achieved of 0.38 mg/L total selenium, may require more advanced solid/liquid separation technology such as filtration or membrane filtration (particularly microfiltration and ultrafiltration) to achieve treated effluent selenium concentrations below 0.010 mg/L (26), as colloidal forms and fine particles of reduced selenium that are not filterable to 0.1 to 0.4 µm are found in effluents with as little as 0.100 mg/L selenium (73). Such advanced downstream solid/liquid separation technology could add considerably to overall implementation costs. As such, the coal sector capital and operating costs for FBR and ABMet® are likely to be on the higher end of the ranges presented above.
- The speciation of the coal sector total selenium is unknown and, therefore, the cost impacts of speciation cannot be determined.

- Due to the relatively recent adoption of this technology, little is known about the long term stability of residual biomass and the potential for selenium remobilization under various disposal conditions. If residuals are not stable, significant costs associated with biomass stabilization technology or re-treatment of residual leachate could be incurred. One coal operation commented during the review period for the Draft MEND BATEA Study Report that they estimated total installed costs and operating costs for the FBR and ABMet® systems above to be 2.5 times higher and up to 2 times higher, respectively, than estimated by CH2MHill. However, follow-up to seek clarification on this comment was unsuccessful. 1

9.6.3.11 Reverse Osmosis

Reverse osmosis for dissolved metals removal could be employed within the coal sector model flow sheet following to the series of ponds currently used for bulk TSS removal. For the addition of RO to the coal flow sheet after the pond system, a bulk removal step for TSS would also be required prior to the RO as the TSS concentration achieved by the model effluent treatment system in the coal sector is <77 mg/L.

This bulk removal step would include a clarifier, and media filter to prepare the effluent for feed into the RO unit. Permeate from the system would be discharged to the pond system for effluent quality monitoring or to the environment after remineralization, as necessary. Underflow from the clarifier would be pumped to the Tailings Storage Facility. Backwash from media filtration would be returned to upstream settling pond(s) for solids sedimentation.

The following equipment additions would be required:

- Clarifier feed pump.
- Clarifier reactor.
- Clarifier overflow pump.
- Residuals management equipment (e.g., pumps to disposal, mechanical dewatering equipment if not disposed of in-pond).
- Media filtration vessel feed pump.
- Media filtration media vessels.
- Media filtration backwash pump.
- Fine filtration (cartridge filters).
- Reverse osmosis feed pump.
- Reverse osmosis pressure vessel skids with vessels to house approximately 3,000 membranes.
- Antiscalant dosing system.
- Clean-in-place system.
- pH adjustment system.
- Permeate and Concentrate Storage Tanks, if required.

- Discharge or transfer pumps, if required.

The incremental capital and operating cost estimates for the addition of a reverse osmosis system to the coal sector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$49,500,000.
- The total installed cost for the system is estimated to be approximately CAD$177,300,000.
- The incremental operating cost for the system is estimated to be approximately CAD$8,400,000/year. This equates to an operating cost of CAD$0.96/m^3.

CAPEX costs have been updated in Revision 1 based on additional reference cost information for both equipment and total installed costs. These costs have been used to update the clarification equipment cost curve and RO equipment cost curve and to adjust factors used to generate installed costs based on clarification and RO equipment costs. As discussed above, clarification costs are included in selective ion exchange costs.

OPEX costs have been updated in Revision 1 based on information received concerning the experience of operations with respect to the operating and maintenance effort required for RO systems. Operations reported that for successful operation of RO systems, frequent cleaning and diligent operator attention is required. The costs of labour and cleaning chemicals have been increased to reflect these demands.

Other considerations:

- RO concentrate management would be difficult to accomplish within the existing effluent treatment model flow sheet. RO concentrate return to a site water management facility may incur additional costs to expand equipment capacity, and would result in the cycling up of contaminants, which is typically undesirable. Concentrate management equipment would likely be required and would add significant capital cost and operating cost. For example, the use of an evaporator/crystallizer to manage brine from the RO process (assuming 70% recovery in the RO) would incur the following additional costs:
    - Equipment costs of around CAD$185,700,000, installed equipment costs of around CAD$287,100,000 and operating costs of around CAD$13,100,000/year.
- The operating cost for the RO system is highly dependent on the site-specific energy cost, and on the required frequency of cleaning cycles, which is dependent on the RO feed quality.
- RO permeate is very low in TDS and alkalinity. Re-mineralization of the permeate stream prior to discharge to the environment may be required to comply with toxicity requirements.
- One coal operation commented during the review period for the Draft MEND BATEA Study Report that they estimated equipment costs, total installed costs, and operating costs for the reverse osmosis system above to be 2 times higher, 4 times higher, and 10 times higher, respectively, than estimated by Hatch at the time (Revision A / Revision 0). However, follow-up to seek clarification on this comment was unsuccessful.

9.6.3.12 Nanofiltration

Nanofiltration would be best employed in the coal sector model effluent flow sheet for removal of multivalent dissolved ions model flow sheet following the series of ponds currently used for bulk TSS removal.

For the addition of NF to the coal flow sheet after the pond system, a bulk removal step for TSS would also be required prior to the NF as the TSS concentration achieved by the model effluent treatment system in the coal sector is <77 mg/L.

This bulk removal step would include a clarifier, and media filter to prepare the effluent for feed into the NF unit. Permeate from the nanofiltration system would be discharged to the pond system for effluent quality monitoring or to the environment after remineralization, as necessary. Underflow from the clarifier would be pumped to the Tailings Storage Facility. Backwash from media filtration would be returned to upstream settling pond(s) for solids sedimentation.

The following equipment additions would be required:

- Clarifier feed pump.
- Clarifier reactor.
- Clarifier overflow pump.
- Residuals management equipment (e.g., pumps to disposal, mechanical dewatering equipment if not disposed of in-pond).
- Media filtration vessel feed pump.
- Media filtration media vessels.
- Media filtration backwash pump.
- Fine filtration (cartridge filters).
- Nanofiltration feed pump.
- Nanofiltration pressure vessel skids.
- Antiscalant dosing system.
- Clean-in-place system.
- pH adjustment system.
- Permeate and Concentrate Storage Tanks, if required.
- Discharge or transfer pumps, if required.

The incremental capital and operating cost estimates for the addition of a nanofiltration system to the coal sector model effluent treatment process are as follows:

- Equipment costs are estimated to total CAD$49,500,000.
- The total installed cost for the system is estimated to be approximately CAD$177,300,000.

- The incremental operating cost for the system is estimated to be approximately CAD$6,900,000/year. This equates to an operating cost of CAD$0.79/m^3.

Because nanofiltration and reverse osmosis are very similar, with the exception of operating pressure and membranes, the capital costs for nanofiltration have been assumed to be the same as estimated for reverse osmosis. Nanofiltration operates at lower pressures compared to reverse osmosis, therefore energy consumption for nanofiltration will be less. The energy requirements of nanofiltration have been assumed to be 2/3 of the energy requirements of reverse osmosis.

CAPEX costs have been updated in Revision 1 based on updated RO costs, as NF CAPEX have been assumed to be the same as RO costs. 1

OPEX costs have been updated in Revision 1 based on information received concerning the experience of operations with respect to the operating and maintenance effort required for RO systems. Operations reported that for successful operation of RO systems, frequent cleaning and diligent operator attention is required. It is assumed similar maintenance and operation demands would apply to nanofiltration membranes as well. The costs of labour and cleaning chemicals have been increased to reflect these demands. 1

Other considerations:

- NF concentrate management would be very difficult to accomplish with the existing effluent treatment system. NF concentrate return to a site water management facility would result in the cycling up of contaminants. Should this become problematic, concentrate management equipment may be required and would add significant capital cost and operating cost. For example, the use of an evaporator/crystallizer to manage brine from the NF process (assuming 70% recovery in the NF) would incur the following additional costs: 1
    - Equipment costs of around CAD$185,700,000, installed equipment costs of around CAD$287,100,000 and operating costs of around CAD$13,100,000/year.
- The operating cost for the NF system is highly dependent on the site-specific energy cost, and on the required frequency of cleaning cycles, which is dependent on the NF feed quality.
- NF permeate is low in TDS and alkalinity. Re-mineralization of the permeate stream prior to discharge to the environment may be required to comply with toxicity requirements.

10. BATEA Selection

This section summarizes information on the effluent concentrations, operating cost, capital cost, process reliability/robustness, and pertinent risks or opportunities for the model effluent management and treatment systems and applied BAT. The information is summarized in each (sub)sector in the form of a "BATEA Selection Table" from information presented in Sections 6, 8, and 9.

Then, for each (sub)sector, utilizing best professional judgement to assess the summarized information, the best available technology/ies economically achievable for the removal of current and proposed *MMER* parameters is/are selected in comparison to the model flow sheet ("base case"). The BATEA evaluation was based on a series of comparisons weighing the cost/benefit of the various BAT technologies:

- Effluent concentrations achievable by the BAT technology were compared against the performance of the (sub)sector model flow sheets to determine the magnitude of reductions in concentration, if any.
- Capital cost and operating cost of the BAT technology was compared against the reported model flow sheet capital and operating cost and the resultant percentage increase in cost noted as either a minor, moderate, or major increase.
- Capital cost of the BAT technology was also compared against the reported range of previous capital investments for upgrades and retrofits to existing (sub)sector effluent treatment systems and the cost noted as either within the range or exceeding the range.

These selections include a discussion of the rationale for the selection of the technology, applicability across the mine subsector, and the sensitivity of the BATEA selection to factors such as concentration variations, volume variations, climatic effects, etc.

BATEA Selection Considerations △1

It is important to note that BATEA selection is not universal for each (sub)sector due to site-specific considerations. The BATEA selection is bounded by strict criteria for BAT (e.g., technology/technique has been demonstrated at full scale on mining effluent and under representative climate conditions) and in the context of the model operation with an existing effluent management and treatment system (defined as the model effluent ttreatment system) for the selected nominal and design treatment capacities.

This approach to BATEA selection was established to enable BATEA selection in a manner that allowed the study to be feasible within time constraints and remain within the scope specified by MEND. Some examples of other factors and considerations that may be significant for site-specific selection of BATEA are as follows:

- Selected BATEA are upgrades or retrofits to existing equipment for which capital has already been expended and therefore associated with sustaining costs rather than initial capital costs. This affects the consideration of what is economically achievable. BATEA selected for greenfield operations may be different than that selected for existing model operations. Selection of BATEA for greenfield operations was not the focus of this study; however, some suggestions for greenfield operations are made. Technologies/ screened out as BAT and not selected as BATEA in this report could, in fact, prove to be BATEA for some site-specific applications.

- The focus of BATEA selection was for operations subject to *MMER*, the majority of which are operations that are currently in production; as such, less consideration was given to the specific factors associated with the operation of effluent treatment systems at closed operations and BATEA selection largely does not address the comparative treatment requirements of closed sites versus active/operational sites.
- The focus of BATEA selection was on water management practices and effluent treatment technologies for the control of effluent quality. Other approaches for the control of an operation's environmental impact that could impact effluent quality were not considered in BATEA selection (e.g., waste minimization, reagent substitution, etc.). These approaches may be appropriate as part of a broader water quality control regime on a site-specific basis.
- Incremental capital and operating costs for the installation and operation of augmentative technologies were considered relative to previous effluent treatment capital and operating cost expenditures and not within the broader economic framework of overall mine operation costs. This consideration would be valuable in site-specific BATEA selection.
- The BATEA selected are technologies applicable to control of mine effluent quality. Best practice for operation and control of these technologies are highlighted where they are critical to BATEA selection, but comprehensive detailed best practices for the operation, control and maintenance of each BATEA are beyond the scope of the study. Best practices for each BATEA should be employed to optimize technology performance.
- Site-specific variations in effluent treatment systems (e.g., effluent treatment technologies utilized, untreated effluent concentration and speciation, treatment flow rate volumes) could impact site-specific BATEA selection by impacting technology viability and cost estimates, as follows:
    - Site-specific effluent treatment technologies can impact those technologies that would be considered augmentative, thus impacting the BAT that could be considered in BATEA selection. For example, for a base metal operation utilizing reactor-based lime hydroxide precipitation with clarification and filtration followed by ion exchange, a pond-based system would not be considered in BATEA selection and the system currently utilized would likely be considered BATEA. This would have the greatest impact on BATEA selection at operations where the BATEA selected for the (sub)sector achieves lower removal efficiencies, or is a more basic system than what is currently employed at that operation.
    - Untreated effluent concentration and speciation can impact both the viability of best available technologies, and the costs for installation and operation. Operations whose untreated effluent contains higher concentrations of the parameters than the model effluent treatment system may have a larger number of BAT that could be considered augmentative (e.g., for diamond operations with ammonia concentrations higher than 3 mg/L, there is a wider suite of augmentative technology choices that may be suitable for ammonia control). Operations with higher concentrations of

parameters in untreated effluent could also potentially experience greater operating costs due to greater reagent and maintenance requirements.

- Treatment system flow rates can impact augmentative equipment and installation capital cost estimates; lower treatment volumes could, for some technologies, result in lower capital cost estimates for equipment and installation, while higher treatment volumes could result in higher capital cost estimates for equipment and installation. This could impact where BATEA selection is based largely on the magnitude of cost rather than a BATEA selection based on technical considerations.

10.1 Metals Sector: Base Metal

10.1.1 BATEA Selection Table

Table 10-1: Base Metal Subsector BATEA Selection Summary Table

Technology [proposed location in model]	Effluent Concentration[55]	Incremental Operating Cost ($/$m^3$)	Incremental Capital Cost ($/$m^3$/h)	Process Reliability, Robustness	Risks and Opportunities
Model Effluent Management and Treatment System (Figure 6-16) [n/a]	From Table 6-20: Al <0.79 mg/L As <0.01 mg/L Cu <0.06 mg/L Fe <1.05 mg/L Pb <0.015 mg/L Ni <0.36 mg/L Se <0.04 mg/L Zn <0.30 mg/L Ra-226 <0.11 Bq/L TSS <10 mg/L NH_3/NH_4^+ <4 mg-N/L	No incremental increase CAD$150,000 to 2,600,000/year (CAD$0.02 to 0.34/$m^3$ treated)	No incremental increase CAD$2,600,000 to 22,000,000 (CAD$1,300 to 11,000/$m^3$/h)	With sufficient footprint, capacity and diligent operator attention, pond-based systems can achieve consistent effluent quality; however, this system is very sensitive to fluctuations in flow rate, solids loading, and ambient conditions, and demands significant labour attention for reliable operation.	Susceptible to upsets that can re-suspend precipitates and cause downstream compliance issues. Residual total ammonia concentrations may interfere with hydroxide precipitation reactions.
Sulfide Precipitation [downstream of lime addition pond/TSF and settling pond(s) and upstream of polishing pond(s)]	From Table 8-5: As <0.01 mg/L Cu <0.03 mg/L Fe^{2+} <0.30 mg/L Pb <0.015 mg/L (no change) Ni <0.05 mg/L Se <0.04 mg/L (no change) Zn <0.02 mg/L	CAD$3,700,000 to 8,200,000/year (CAD$0.48 to CAD$1.08/m^3) depending on reagent dosage No operating cost discounts have been applied for value recovery through residuals re-processing.	CAD$11,000,000 (CAD$5,500/m^3/h)	Equalization of flow and contaminant loadings is required. Sulfide reagent dosage can be modulated to accommodate changes in effluent quality. However, technology is not capable of achieving consistent effluent concentration at hydraulic loadings and solids loadings/generation outside of equipment design window.	Equalization of flow and contaminant loadings is assumed to occur at the upstream lime addition pond/TSF and settling pond(s). It is assumed that the incremental generation of sulfide sludge can be accommodated by the existing TSF and retained under reducing conditions. Technique can improve metals removal efficiencies even with high complexing/chelating agent concentrations. However, the operating cost is high due to the high cost of proprietary reagents.

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[55] "(no change)" indicates that the concentration of the parameter has not changed from that achieved by the model effluent management and treatment system.

Technology [proposed location in model]	Effluent Concentration[55]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Sulfide Precipitation with Proprietary Polymeric Organosulfide Chemicals [downstream of lime addition pond/TSF and upstream of settling pond(s)]	From Table 8-6: As <0.01 mg/L (no change) Cu <0.03 mg/L Fe^{2+} <0.30 mg/L Pb <0.015 mg/L (no change) Ni <0.05 mg/L Se <0.04 mg/L (no change) Zn <0.02 mg/L	CAD$2,500,000/year (CAD$0.33/m^3) There is a potential for reduction of operating costs due to reductions in flocculant consumption, as the proprietary reagents are polymeric in nature and may offset flocculant demand. However, no discounts have been applied to this operating cost.	CAD$1,100,000 (CAD$550/m^3/h) There is a potential to reduce capital costs by using alternative technologies to agitated reactor tanks for mixing proprietary reagent with effluent. However, this has not been demonstrated.	Equalization of flow and contaminant loadings is required. Proprietary reagent dosage can be modulated to accommodate changes in effluent quality. However, technology is not capable of achieving consistent effluent concentration at hydraulic loadings and solids loadings/generation outside of design window. Pond-based solid/liquid separation is susceptible to upsets that can re-suspend precipitates and cause downstream compliance issues.	Equalization of flow and contaminant loadings is assumed to occur at the upstream lime addition pond/TSF. It is assumed that the incremental generation of sulfide sludge can be accommodated by the existing settling pond(s) and retained under reducing conditions. Can improve metals removal efficiencies even with high complexing/chelating agent concentrations with low capital cost investment. High operating cost due to high cost consumables. The chemicals may be acutely lethal to rainbow trout and *Daphnia magna* at certain residual chemical concentrations in effluent. Bench and/or pilot scale testing is advised to verify that treated effluent complies with toxicity requirements. Treated effluent should be discharged rather than recirculated. Due to the relatively recent adoption of these reagents and the proprietary nature of their formulations, little is known about the long term stability of residuals and the potential for acid generation and metals remobilization. If residuals are not kept stable, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.
Solid/Liquid Separation – Clarification [upstream of lime addition pond(s)/TSF]	From Section 8.2.7.2: TSS <10 mg/L (no change)	CAD$760,000/year (CAD$0.10/m^3) There is a potential for reduction of operating costs due to reductions in flocculant consumption, as the controlled solid/liquid separation process may offset flocculant demand. However, no discounts have been applied to this operating cost.	CAD$16,200,000 (CAD$8,100/m^3/h) Includes capital costs to upgrade existing lime addition system to agitated reactor tank.	Robust and reliable process that is well established in the mining industry. Significant variations in flow rate and TSS loading could impact operation and the quality of the effluent; equalization of flow and contaminant loadings is required.	Upstream equalization of flow and contaminant loadings is assumed. Smaller footprint and higher degree of control compared to pond-based solid/liquid separation. Complements other removal technologies, (e.g., can be applied downstream of hydroxide and sulfide precipitation to remove metal precipitates).

Technology [proposed location in model]	Effluent Concentration[55]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Enhanced Coagulation and Setting [upstream of lime addition pond(s)/TSF]	From Table 8-17: TSS <10 mg/L (no change)	ACTIFLO®: CAD$760,000/year (CAD$0.10/m^3) There is a potential for reduction of operating costs due to reductions in reagent consumption, due to the higher reagent efficiency associated with the upgraded lime addition system and due to the enhanced coagulation provided by ballast or sludge recycle. However, no discounts have been applied to the operating cost presented here.	ACTIFLO®: CAD$9,800,000 (CAD$4,900/m^3/h) Includes capital costs to upgrade existing lime addition system to include agitated reactor tank.	Enhanced coagulation and settling is a proprietary technique that is claimed by vendors to be robust and a process that can reliably achieve low TSS concentrations, when operating within the design window for hydraulic loadings and solids loadings/generation.	Upstream equalization of flow and contaminant loadings is assumed. Smaller footprint compared to pond-based solid/liquid separation or clarification. Complements other removal technologies, (e.g., can be applied downstream of hydroxide and sulfide precipitation to remove metal precipitates). Less established technique for the Canadian mining industry than other solid/liquid separation technologies.
Solid/Liquid Separation – Filtration [downstream of polishing pond(s)]	From Section 8.2.7.4: TSS <5 mg/L	CAD$380,000/year (CAD$0.05/m^3)	CAD$10,300,000 (CAD$5,150/m^3/h)	Robust and reliable process that is well established in the mining industry. Significant variations in flow rate and TSS loading could impact operation and the quality of the effluent; equalization of flow and contaminant loadings is required.	Equalization of flow and contaminant loadings is assumed to occur at the upstream lime addition pond/TSF, settling pond(s), and polishing pond(s). It is assumed that the incremental generation of solids in backwash can be accommodated by the existing TSF. Complements other removal technologies, (e.g., can be applied downstream of hydroxide and sulfide precipitation to remove metal precipitates and can provide filtration prior to polishing steps such as ion exchange or RO/NF). Not necessarily required to meet (current) discharge TSS limits; however can contribute to the removal of other contaminants that present as suspended solids (e.g., metals).
Air Stripping [n/a]	From Section 8.2.10: NH_3/NH_4^+ <4 mg-N/L (no change)	Technology not economically feasible at untreated effluent ammonia below 10 mg-N/L.			

Technology [proposed location in model]	Effluent Concentration[55]	Incremental Operating Cost (\$/m^3)	Incremental Capital Cost (\$/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Selective Ion Exchange – Metals Polishing [downstream of polishing pond(s)]	From Table 8-23: Al <0.05 mg/L As <0.01 mg/L (no change) Cu <0.03 mg/L Fe <0.2 mg/L Pb <0.02 mg/L (no change) Ni <0.01 mg/L Se <0.01 mg/L Zn <0.02 mg/L	CAD\$5,000,000/year (CAD\$0.65/m^3) Includes operating costs for media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment could add additional operating cost. Depending on approach, regenerant management could add significant additional operating cost.	CAD\$39,600,000 (CAD\$19,800/m^3/h) Includes capital costs for media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment could add additional capital cost. Depending on approach, regenerant management could add significant additional capital cost.	Equalization of flow and contaminant loadings required to achieve consistent effluent quality. Increased loading requires more frequent regeneration and increases residual production.	Equalization of flow and contaminant loadings is assumed to occur at the upstream lime addition pond/TSF, settling pond(s), and polishing pond(s). At minimum, pre-filtration is required. However, depending on effluent chemistry, additional pre-treatment may be required. Regenerant management must be carefully considered based on site-specific factors and could add significant operating and capital costs. Can be employed for pre-concentration of effluent streams to reduce the total volume reporting to bulk removal technologies (e.g., hydroxide or sulphide precipitation).
Selective Ion Exchange - Zeolite [n/a]	From Table 8-24: NH$_3$/NH$_4^+$ <4 mg-N/L (no change)	Technology not technically feasible at untreated effluent ammonia below 9 mg-N/L.			
Adsorption – Zero Valent Iron [downstream of polishing pond(s)]	From Table 8-25: Se <0.010 mg/L	CAD\$17,7800,000/year to CAD\$24,300,000/year (CAD\$2.32/m^3 to CAD\$3.18/m^3)	CAD\$63,900,000 to CAD\$150,000,000 (CAD\$32,000/m^3/h to CAD\$75,000/m^3/h) There is a potential to reduce capital costs by using ZVI technology upstream of the lime addition pond, thereby eliminating the need for ZVI equipment associated with downstream iron precipitation and solid/liquid separation. However, this would require confirmation of upstream equalization capacity and effluent concentrations of oxyanions which compete with selenium for removal in the ZVI process.	Equalization of flow and contaminant loadings is required. Reagent dosages can be modulated to accommodate changes in effluent quality. However, technology is not capable of achieving consistent effluent concentration at hydraulic loadings and contaminant loadings outside of equipment design window.	Equalization of flow and contaminant loadings is assumed to occur at the upstream lime addition pond/TSF and settling pond(s). Large quantities of hydroxide sludge are produced with this technology. It is assumed that the sludge can be accommodated by the existing TSF and retained under reducing conditions. Most full-scale installations of this technology treat flow rates two orders of magnitude lower than the base metal subsector design flow rate. The applicability of this technology may be limited, accordingly. Few full-scale installations have been in operation for long enough to determine long term feasibility. The speciation of total selenium for the base metal subsector is unknown, and therefore, cost impacts of speciation cannot be determined.

Technology [proposed location in model]	Effluent Concentration[55]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
					Due to the relatively recent adoption of this technology, little is known about the long term stability of residuals and the potential for selenium remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.
Active Aerobic Biological Oxidation	From Table 8-26: NH_3/NH_4^+ <2 mg-N/L	Technology not economically feasible to reduce total ammonia from 4 mg-N/L.			
Active Anoxic/Anaerobic Biological Reduction [downstream of polishing pond(s)]	FBR from Table 8-27: Se ~ 0.005-0.020 mg/L ABMet® from Table 8-29: Se <0.005 mg/L	FBR: CAD$12,100,000/year CAD$1.59/m^3 treated ABMet®: CAD$9,700,000/year CAD$1.28/m^3 treated Operating cost for an FBR system could be as low as CAD$6,500,000/year to CAD$8,800,000/year if Envirogen cost estimates are used. However, as the base metal subsector model effluent treatment process is fairly rudimentary, the addition of an FBR system would require substantial wrap around and independent sludge handling, thickening, and disposal systems. Therefore, the operating cost may be closer to the higher end of the range presented.	FBR: CAD$128,600,000 (CAD$64,300/m^3/h) ABMet®: CAD$171,000,000 (CAD$85,500/m^3/h) Total installed capital cost for an FBR system could be as low as CAD$33,700,000 to CAD$54,800,000 if Envirogen cost estimates are used. Total installed capital costs for ABMet® system could be as low as CAD$43,400,000 to CAD$64,400,000 if GE estimates are used. However, as the base metal subsector model effluent treatment process is fairly rudimentary, the addition of an FBR or ABMet® system would require substantial wrap around and independent sludge handling, thickening, and disposal systems. Therefore, the total installed cost may be closer to the higher end of the range presented.	Equalization of flow and contaminant loadings is required as systems cannot accommodate loadings of selenium and other oxyanions (nitrate) outside of design window, as well as hydraulic loadings outside of design window.	Equalization of flow and contaminant loadings is assumed to occur at the upstream lime addition pond/TSF and settling pond(s). High feed nitrate concentration increases operating and capital costs and residuals production. Residual biomass typically requires thickening and dewatering prior to disposal. It is assumed that residuals can be accommodated at the existing TSF and retained under reducing conditions. Few full-scale FBR installations have been in operation for long enough to determine long term feasibility. The speciation of total selenium for the base metal subsector is unknown, and therefore, cost impacts of speciation cannot be determined. Due to the relatively recent adoption of this technology, little is known about the long term stability of residual biomass and the potential for selenium remobilization under various disposal conditions. If residuals are not stable, significant costs associated with biomass stabilization technology or re-treatment of residual leachate could be incurred.
Reverse Osmosis	Calculated from removal efficiencies in Table 8-31	CAD$7,000,000/year (CAD$0.88/m^3)	CAD$103,000,000 (CAD$51,500/m^3/h)	Low concentrations can be reliably achieved by this technology due to the removal mechanism via	Equalization of flow and contaminant loadings is assumed to occur at the upstream lime addition

Technology [proposed location in model]	Effluent Concentration[55]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
[downstream of polishing pond(s)]	and values in Table 6-20: Al <0.016 mg/L NH_3/NH_4^+ <0.60 mg-N/L As <0.003 mg/L Cu <0.003 mg/L Ni <0.02 mg/L Se <0.002 mg/L Fe <0.05 mg/L Pb <0.0024 mg/L Zn <0.02 mg/L	Operating cost is highly dependent on site-specific energy costs. Includes operating costs for media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional operating cost. Depending on approach, concentrate management could add significant additional operating cost.	Includes capital costs for media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional capital cost. Depending on approach, concentrate management could add significant additional capital cost.	size/charge exclusion. Increased contaminant loading would increase feed pump pressure required to maintain flux as well as increase the proportion of concentrate generated (i.e., reduce recovery).	pond/TSF and settling pond(s). At minimum, pre-filtration is required. However, depending on effluent chemistry, additional pre-treatment may be required. Concentrate management must be carefully considered based on site-specific factor. If concentrate is returned to water management features on site (e.g., TSF), there is a risk of solutes (e.g., Cl^-, Na^+) cycling up in site water. Concentrate management may require advanced technology (e.g., evaporator/crystallizer) which would add significant capital and operating costs. For example, assuming 70% recovery in the RO, an evaporator/crystallizer system for concentrate management would be associated with an incremental capital cost of CAD$191,400,000 and an incremental operating cost of CAD$11,400,000/year. RO permeate is typically lower pH than feed pH and is low in alkalinity. pH adjustment and re-mineralization may be required prior to discharge to meet pH and acute toxicity requirements. Can be used as polishing step for metals and ammonia (as NH_4^+) removal following bulk removal steps. Can be employed for pre-concentration of effluent streams to reduce the total volume reporting to bulk removal technologies (e.g., hydroxide or sulfide precipitation).

Technology [proposed location in model]	Effluent Concentration[55]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Nanofiltration [downstream of polishing pond(s)]	Calculated from removal efficiencies in Table 8-33 and values in Table 6-20: Al <0.04 mg/L As <0.003 mg/L Cu <0.006 mg/L Fe <0.05 mg/L Pb <0.003 mg/L Ni <0.02 mg/L Se <0.004 mg/L Zn <0.02 mg/L	CAD$5,400,000/year (CAD$0.71/m^3) Operating cost is highly dependent on site-specific energy costs. Includes operating costs for media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional operating cost. Depending on approach, concentrate management could add significant additional operating cost.	CAD$103,000,000 (CAD$51,500/m^3/h) Includes capital costs for media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional capital cost. Depending on approach, concentrate management could add significant additional capital cost.	Little performance information is available concerning NF in full scale operation for the treatment of mining effluent; however, it is expected that NF would be similar to RO in performance, and that due to the mechanism of removal (size/charge exclusion), low concentrations could be reliably achieved. Increased contaminant loading would increase feed pump pressure required to maintain flux as well as increase the proportion of concentrate generated (i.e., reduce recovery).	Equalization of flow and contaminant loadings is assumed to occur at the upstream lime addition pond/TSF and settling pond(s). At minimum, pre-filtration is required. However, depending on effluent chemistry, additional pre-treatment may be required. Concentrate management must be carefully considered based on site-specific factor. If concentrate is returned to water management features on site (e.g., TSF), there is a risk of certain solutes cycling up in site water. Concentrate management may require advanced technology (e.g., evaporator/crystallizer) which would add significant capital and operating costs. For example, assuming 70% recovery in the NF, an evaporator/crystallizer system for concentrate management would be associated with an incremental capital cost of CAD$191,400,000 and an incremental operating cost of CAD$11,400,000/year. NF permeate may be low in alkalinity. Re-mineralization may be required prior to discharge to meet acute toxicity requirements. Can be used as polishing step for metals removal following bulk removal steps. Can be employed for pre-concentration of effluent streams to reduce the total volume reporting to bulk removal technologies (e.g., hydroxide or sulfide precipitation).

10.1.2 *Discussion of BATEA Selection*

For the base metal subsector, Table 10-2 summarizes the technologies that have been selected as BATEA. A discussion of BATEA selection for each targeted parameter (e.g., ammonia, selenium, total suspended solids) or group of targeted parameters (e.g., metals), is provided in the following sections.

1

Table 10-2: Selected BATEA Technologies for the Base Metal Subsector

Targeted Parameters	Selected BATEA	BATEA Technology
Bulk Metals Removal	• Model flow sheet for bulk metals removal (including aluminum, arsenic, copper, iron, lead, nickel, and zinc).	Pond-Based Hydroxide Precipitation • Precipitation of dissolved metals as metal hydroxides and metal complexes, achieved by lime and coagulant addition to a pond-based system.
Metals Polishing	• Sulfide precipitation with proprietary polymeric organosulfide chemicals for dissolved metals polishing (including copper, iron, nickel, and zinc).	Sulfide Precipitation Using Proprietary Organosulfide Polymers • Precipitation of dissolved metals as metal sulfides, achieved by the addition of proprietary polymeric organosulfide reagents to a pond-based system.
Total Suspended Solids Removal	• Model flow sheet for solids (TSS) removal.	Pond-Based Settling • Suspended solids sedimentation, achieved by allowing sufficient residence time for gravity to settle solids, promoted by the use of coagulant and flocculant, within a pond system.
Ammonia Removal	• Model flow sheet for total ammonia removal.	Natural Degradation of Ammonia and Explosives Best Management Plan • An explosives best management plan is followed to minimize the release of ammonia into site water. • Natural degradation of ammonia occurring by volatilization of un-ionized ammonia gas (NH_3) and biological oxidation, achieved by allowing ample residence time in pond systems, especially during periods where ambient climate conditions promote these processes. These processes are influenced by pH, temperature, and dissolved oxygen concentration.
Selenium Removal	• Model flow sheet for selenium removal.	Synergistic Coagulation/Co-precipitation • Though the model flow sheet is not designed to specifically target selenium, the addition of

Targeted Parameters	Selected BATEA	BATEA Technology
		coagulant within a pond system for bulk metals removal could promote co-precipitation of selenium and achieve minor levels of removal via this mechanism.

10.1.2.1 BATEA for Dissolved Metals Polishing

In contrast to the other dissolved metal polishing technologies considered in Table 10-1 (chemical sulfide precipitation, selective ion exchange, reverse osmosis, and nanofiltration), sulfide precipitation with proprietary polymeric organosulfide chemicals was found to offer the following benefits:

- Similar (order of magnitude) reduction in most of the metals of concern.
- Significantly lower capital cost.
- Lower operating cost.
- The potential benefit of lowering base case operating costs by offsetting flocculant demand.
- No generation of spent regenerant (ion exchange) or concentrate (reverse osmosis, nanofiltration) stream. Other technologies evaluated produce these residual streams, which require specific management, therefore increasing the overall capital and operating cost of these options.
- As base metal subsector effluent typically has very low concentrations of copper, nickel, and zinc after bulk metals removal in the model flow sheet, there is no opportunity to use sulfide precipitation to produce recoverable/saleable metal products which could offset the higher capital and operating costs associated with the technology.
- Consideration was given to employing reverse osmosis or nanofiltration to pre-concentrate the effluent (thus increasing the metals concentration) prior to metals removal through chemical sulfide or proprietary polymeric organosulfide chemical precipitation. However, the capital and operating cost associated with using reverse osmosis or nanofiltration for pre-concentration are not offset by the capital cost savings for either sulfide precipitation technology. Moreover, the operating costs for either sulfide precipitation technology are only marginally reduced through pre-concentration, as the major operating cost for both technologies is reagent consumption which is proportional to metal loading. Pre-concentration does not change metal loading.

The addition of this BATEA to the model flow sheet is estimated to require a capital cost investment of roughly CAD$550/m^3/h and would result in an operating cost increase of roughly CAD$0.33/m^3. When compared to the model flow sheet capital and operating costs, this represents an upgrade capital cost investment of roughly 5 to 42% of the model flow sheet capital cost and an operating cost increase of almost 100% up to 1,640%. This represents a minor to moderate capital cost investment but a major operating cost expenditure for the model operation. The capital cost for this BATEA is within the reported range of previous capital investments for upgrades and retrofits to existing base metal effluent management and treatment systems (less than CAD$5,000,000). It is of interest to note that two Canadian base metal operations have already undertaken upgrades to include this technique within their effluent management and treatment systems; however, both of these operations have equipment-based effluent treatment systems rather than pond-based systems.

These costs assume that equalization and bulk solids and metals removal would be provided by the upstream lime addition pond(s)/tailings storage facility and that incremental sludge generation could be accommodated within the settling pond(s) in the model flow sheet. Sulfide sludge produced with proprietary polymeric organosulfide chemicals will settle but can be difficult to thicken and dewater due to the polymeric nature of the reagents. This is especially important to note for this application, as pond-based solid/liquid separation in the existing settling pond(s) is assumed. Pond-based solid/liquid separation reliability is affected by variations in effluent flow rate, solids loading, and temperature, as well as heavy rainfall events, high winds and wave action, and inversions that can re-suspend precipitates, potentially causing downstream non-compliance. Pond-based solid/liquid separation systems also require regular maintenance (e.g., dredging) to maintain settling capacity and prevent carryover, which can cause downstream non-compliance.

The operating cost is directly influenced by the metals removal efficiency required to meet a specified discharge limit. Lower limits increase reagent consumption and operating cost. Soluble oils and high concentrations of non-metallic suspended solids may interfere with sulfide precipitation via adsorption.

Testwork is recommended to confirm proprietary reagent demand, efficacy, and precipitate settleability. Also, as the chemicals may be acutely lethal to rainbow trout and *Daphnia magna* at certain residual chemical concentrations in effluent, testing is advised to verify that treated effluent complies with toxicity requirements. It is also advised that treated effluent be discharged rather than recirculated for any purpose such that cycling up of residual chemical concentration is limited.

Due to the relatively recent adoption of these reagents and the proprietary nature of their formulations, little is known about the long term stability of residuals and the potential for acid generation and metals remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.

Hatch cautions that this technique should only be considered BATEA for operations that are capable of and dedicated to careful control of operating regimes to prevent effluent toxicity as well as careful control of residuals storage conditions to prevent long term instability and the potential generation of acid through sulfide oxidation and metals remobilization. 1

10.1.2.2 BATEA for Selenium Removal 1

The base metal subsector model was selected as BATEA for selenium removal, as augmentative selenium removal technologies (ZVI, FBR, ABMet®, reverse osmosis and nanofiltration) are considered to be uneconomic and technically limited for application to the model. Since ZVI technology can achieve <0.010 mg/L Se, FBR technology can achieve approximately 0.005 to 0.020 mg/L Se, ABMet® technology can achieve <0.005 mg/L, and membrane separation technologies (reverse osmosis and nanofiltration) can achieve <0.004 mg/L, it is possible that only marginal removal could be achieved from the untreated effluent concentration of 0.04 mg/L total selenium for the base metal subsector, especially since the speciation of total selenium is not known.

Should further removal of selenium beyond that achievable by the model be required (i.e., Se < 0.04 mg/L), active anoxic/anaerobic biological reduction (e.g., FBR or ABMet®) is the least cost prohibitive of the technologies capable of achieving low selenium concentrations. In contrast to zero valent iron adsorption and membrane separation (considering capital and operating costs of brine management through the use of evaporative technologies), active anoxic/anaerobic biological reduction (e.g., FBR or ABMet®) was found to offer the following benefits:

- Greater or equivalent selenium removal and lower or equivalent achievable selenium concentration.
- Lower capital cost.
- Lower operating cost.
- Lower mass/volume of residuals generated requiring less handling and disposal costs.

Consideration was given to employing reverse osmosis to pre-concentrate the effluent (thus increasing the selenium concentration) prior to zero valent iron adsorption or active anoxic/anaerobic biological reduction. However, the capital and operating costs associated with using reverse osmosis for pre-concentration are not offset by the capital cost savings for zero valent iron technology. Moreover, the operating cost savings for zero valent iron technology are only marginally reduced through pre-concentration, as the major operating cost is zero valent iron reagent consumption which is proportional to selenium loading. Additionally, the capital and operating costs for active anoxic/anaerobic biological reduction are dependent on both selenium loading than on hydraulic capacity. As pre-concentrating changes hydraulic capacity, but does not change selenium loading, there is likely to be little economic advantage to pre-concentrating using reverse osmosis. One coal operation contested this assertion during the review period for the Draft MEND BATEA Study Report, stating that it is contrary to their findings from technology assessments. However, follow-up to seek clarification on this comment was unsuccessful.

As an example, the addition of FBR BAT to the model flow sheet is estimated to require a capital cost investment of roughly CAD$64,300/m^3/h and would result in an operating cost increase of roughly CAD$1.59/m^3.[56] When compared to the model flow sheet capital and operating costs, this represents an upgrade capital cost investment of roughly 584 to 5,000% of the model flow sheet capital cost and an operating cost increase of roughly 500 to 8,000%. This represents a prohibitive investment for the model operation. The capital cost for this BAT greatly exceeds the reported range of previous capital investments for upgrades and retrofits to base metal effluent management and treatment systems (less than CAD$5,000,000). These two last statements stand true even when lower end cost estimates based on cost estimates provided by Envirogen are considered.

Moreover, due to the relatively recent adoption of this technology, little is known about the long term stability of residual biomass and the potential for selenium remobilization under various disposal conditions. If residuals are not stable, significant costs associated with biomass stabilization technology or re-treatment of residual leachate could be incurred.

10.1.2.3 *BATEA for Total Ammonia Removal*

The BATEA selected for total ammonia removal is the base case model flow sheet which is assumed to incorporate explosives best management practices and passive natural degradation. Since the majority of base metal operations do not use cyanide or ammonia in ore processing, the origin of ammonia in base metal effluent is explosives used in mining operations. Well established and executed explosives best management plans can minimize the amount of ammonia that reports to effluent. Moreover, conditions that are conducive to natural degradation of ammonia in pond(s) could be promoted to achieve further ammonia removal within the subsector model effluent management and treatment system (e.g., elevating pH, aerating, maximizing surface area to depth ratio). Therefore, explosives best management plans and natural degradation of ammonia was selected as BATEA for ammonia removal. This is consistent with the findings of a previous BAT study (10).

The concentration of total ammonia achieved by the model effluent treatment system in the base metal subsector is 4 mg-N/L. At such a low feed concentration, air stripping would not be technically feasible and active aerobic biological oxidation would not be very effective in lowering the total ammonia concentration much below the untreated effluent concentration and would therefore not be economically feasible. Zeolite ion exchange for total ammonia removal is not technically feasible since the total ammonia concentration in the feed is lower than the achievable total ammonia concentration from a zeolite ion exchange system.

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[56] High end cost estimates based on CH2MHill cost estimates are utilized here since the rudimentary base metal subsector model would require substantial wrap around and independent sludge handling, thickening, and disposal systems.

Consideration was given to employing reverse osmosis or zeolite ion exchange to pre-concentrate the effluent (thus increasing the total ammonia concentration) prior to air stripping or aerobic biological oxidation. However, active aerobic biological oxidation is more dependent on ammonia loading than on hydraulic capacity and air stripping is dependent on both ammonia loading and hydraulic capacity. As pre-concentrating does not change ammonia loading, there is little economic advantage to pre-concentrating using reverse osmosis. Moreover, a recent Finnish study demonstrated that nitrification is less efficient for pre-concentrated mine effluent, due to combined inhibition by metals and possibly salts (69).

10.1.2.4 BATEA for Bulk Metals Removal

The BATEA selected for bulk removal of metals is the base case model flow sheet, which employs hydroxide precipitation through lime addition and pond-based solid/liquid separation. Although equipment-based hydroxide precipitation and solid/liquid separation are more efficient in terms of reagent demand and solids production and more reliable in terms of treated effluent quality (and would be the recommended technology for greenfield implementation), it is not economical to retrofit the base case model flow sheet.

10.1.2.5 BATEA for Solids Removal

Canadian base metal operations as a total cohort achieve TSS concentrations of less than 5 mg/L on average and 95% of all concentrations from model effluent treatment systems are less than 12 mg/L. This is consistent with expectations that well designed and operated pond-based solid/liquid separation systems should achieve TSS concentrations less than 15 mg/L.

The addition of clarification, enhanced coagulation and settling, and/or filtration solid/liquid separation technologies would not achieve significant improvements in TSS removal over the existing well designed and operated pond-based solid/liquid separation systems (at most 60% improvement). As such, there is no justification for the additional capital and operating costs for the implementation of equipment-based solid/liquid separation technologies.

However, for greenfield applications, solid/liquid separation by clarification or enhanced coagulation and settling would be recommended as BATEA as opposed to pond-based solid/liquid separation for the following reasons:

- Equipment-based solid/liquid separation is more easily monitored and controlled than pond-based solid/liquid separation in terms of flow rate, reagent dosing and other process conditions.
- Equipment-based systems are not as susceptible to upsets due to climatic conditions such as heavy rainfall events, high winds and wave action, and pond turnovers due to temperature inversions that can re-suspend precipitates and cause downstream compliance issues.
- Reducing pond footprints can reduce the net precipitation inputs into water balances, thereby reducing the volumes of water/effluent potentially requiring management and treatment and reducing operating and capital costs.

- Equipment-based solids removal technologies have improved sludge management and handling capabilities over pond systems. Dredging of ponds is often not done frequently enough to prevent solids carryover and downstream non-compliance due to the logistical challenges or significant costs. Equipment-based solids removal technologies are more efficient at collecting and removing sludge from the system at regular intervals.

- Equipment-based solid/liquid separation should be integrated with reactor-based metals precipitation, coagulation, and flocculation technology. This will improve reagent/reaction efficiency, reducing reagent costs and minimizing sludge production. These systems can also be configured with underflow recycle to further improve reagent/reaction efficiency, if applicable.

- Equipment-based solid/liquid separation should be integrated with upstream/downstream pond systems for equalization and passive natural degradation of ammonia.

10.2 Metals Sector: Precious Metal

10.2.1 BATEA Selection Table

Table 10-3: Precious Metal Subsector BATEA Selection Summary Table

Technique [proposed location in model]	Effluent Concentration[57]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Model Effluent Management and Treatment System (Figure 6-31) [n/a]	From Table 6-40: Al <0.05 mg/L As <0.3 mg/L Cu <0.11mg/L CN <0.1 mg/L Fe <1.2 mg/L Pb <0.006 mg/L Ni <0.1 mg/L Se <0.05 mg/L Zn <0.03 mg/L TSS <12 mg/L NH_3/NH_4^+ <12 mg-N/L	No incremental increase CAD$530,000 to 5,000,000/year (CAD$0.34 to 3.18/m^3 treated)	No incremental increase CAD$3,700,000 to 60,000,000 (CAD$6,000 to 100,000/m^3/h)	With diligent operator attention, the system can achieve consistent effluent quality. Equalization provided by the TSF should minimize the fluctuations in flow rate, solids and contaminant concentrations. As no ammonia removal is incorporated, seasonal fluctuations may occur due to residual cyanide degradation in the TSF.	Residual cyanide and total ammonia concentrations may interfere with hydroxide precipitation reactions.
Sulfide Precipitation [downstream of overflow tank and upstream of monitoring/polishing pond(s)]	From Table 8-5: As <0.05 mg/L Cu <0.03 mg/L Fe^{2+} <0.30 mg/L <Pb <0.006 mg/L (no change) Ni <0.05 mg/L Se <0.05 mg/L (no change) Zn <0.02 mg/L	CAD$1,500,000 /year to CAD$2,500,000/year (CAD$0.97/m^3 to CAD$1.57/m^3) depending on reagent dosage No operating cost discounts have been applied for value recovery through residuals re-processing.	CAD$4,600,000 (CAD$7,670/m^3/h)	Equalization of flow and contaminant loadings is required. Sulfide reagent dosage can be modulated to accommodate changes in effluent quality. However, the technology is not capable of achieving consistent effluent concentration at hydraulic loadings and solids loadings/generation outside of equipment design window.	Equalization of flow and contaminant loadings is assumed to occur at the upstream TSF and upstream processes. It is assumed that the incremental generation of sulfide sludge can be accommodated by the existing TSF and retained under reducing conditions. Technique can improve metals removal efficiencies even with high complexing/chelating agent concentrations. However, the operating cost is high due to the high cost of proprietary reagents.

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[57] "(no change)" indicates that the concentration of the parameter has not changed from that achieved by the model effluent management and treatment system.

Technique [proposed location in model]	Effluent Concentration[57]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Sulfide Precipitation with Proprietary Polymeric Organosulfide Chemicals [within hydroxide precipitation stage]	From Table 8-6: As <0.05 mg/L Cu <0.03 mg/L Fe^{2+} <0.30 mg/L Pb <0.006 mg/L (no change) Ni <0.05 mg/L Se <0.05 mg/L (no change) Zn <0.02 mg/L	CAD$310,000/year (CAD$0.20/m^3) There is a potential for reduction of operating costs due to reductions in flocculant consumption, as the proprietary reagents are polymeric in nature and may offset flocculant demand. However, no discounts have been applied to this operating cost.	CAD$29,000 (CAD$50/m^3/h)	Equalization of flow and contaminant loadings is required. Proprietary reagent dosage can be modulated to accommodate changes in effluent quality. However, technology is not capable of achieving consistent effluent concentration at hydraulic loadings and solids loadings/generation outside of design window. Pond-based solid/liquid separation is susceptible to upsets that can re-suspend precipitates and cause downstream compliance issues.	Equalization of flow and contaminant loadings is assumed to occur at the upstream TSF and upstream processes. It is assumed that the incremental generation of sulfide sludge can be accommodated by the existing clarifier, underflow equipment, and TSF and retained under reducing conditions. It is assumed that the sulfide reagent would not compete with hydroxide for metals since it is dosed in-line to the clarifier and lime is dosed upstream in the reactor tank(s). Such a treatment system is considered suitable for lower strength effluents (total metals concentration <100 mg/L). However, testwork would be required to verify this assertion. Can improve metals removal efficiencies even with high complexing/chelating agent concentrations with low capital cost investment. High operating cost due to high cost consumables. The chemicals may be acutely lethal to rainbow trout and *Daphnia magna* at certain residual chemical concentrations in effluent. Bench and/or pilot scale testing is advised to verify that treated effluent complies with toxicity requirements. Treated effluent should be discharged rather than recirculated. Due to the relatively recent adoption of these reagents and the proprietary nature of their formulations, little is known about the long term stability of residuals and the potential for acid generation and metals remobilization. If residuals are not kept stable, significant costs associated with residuals stabilization technology or re-treatment of residual leachate

Technique [proposed location in model]	Effluent Concentration[57]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
					could be incurred.
Solid/Liquid Separation – Filtration [downstream of clarifier overflow tank]	From Section 8.2.7.2: TSS <5 mg/L	CAD$78,400/year (CAD$0.05/m^3)	CAD$2,600,000 (CAD$4,330/m^3/h)	Robust and reliable process that is well established in the mining industry. Significant variations in flow rate and TSS loading could impact operation and the quality of the effluent; equalization of flow and contaminant loadings is required.	Equalization of flow and contaminant loadings is assumed to occur at the upstream TSF and upstream processes. It is assumed that the incremental generation of solids in backwash can be accommodated by the existing TSF. Complements other removal technologies, (e.g., can be applied downstream of hydroxide and sulfide precipitation to remove metal precipitates and can provide filtration prior to polishing steps such as ion exchange or RO/NF). Not necessarily required to meet (current) discharge TSS limits; however can contribute to the removal of other contaminants that present as suspended solids (e.g., metals).
Air Stripping [downstream of clarifier overflow tank]	From Section 8.2.10: NH_3/NH_4^+ > 3 mg-N/L (lower achievable limit, but effluent concentration is a key design parameter)	CAD$840,000/year (CAD$0.53/m^3)	CAD$25,800,000 (CAD$43,000/m^3/h)	Technique performance is very sensitive to ambient temperatures and a heat exchange system is required to maintain ammonia removal efficiency year round. Towers are susceptible to scaling and plugging depending on effluent quality. Scaling and plugging impact performance and at minimum, pre-filtration is required for reliable operation. Moreover, technology is not capable of achieving consistent effluent concentration at hydraulic loadings and solids loadings outside of design window.	Equalization of flow and contaminant loadings is required and assumed to occur at the upstream TSF and upstream processes. It is assumed that ammonia discharge to the local airshed is acceptable. It is assumed that space is available to accommodate large footprint of equipment. Capital cost estimates assume that the existing lime make-up, storage, and distribution system can be utilized for pH adjustment. High operating cost due to power consumption. Pre-heating of air and/or effluent would likely be required for a good portion of the year for those operations with year-round treatment

Technique [proposed location in model]	Effluent Concentration[57]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
					and discharge, leading to high energy costs (e.g., could almost double operating costs).
Selective Ion Exchange – Metals Polishing [downstream of clarifier overflow tank]	From Table 8-23: Al <0.05 mg/L (no change) As <0.01 mg/L Cu <0.03 mg/L Fe <0.2 mg/L Pb <0.006 mg/L (no change) Ni <0.01 mg/L Se <0.01 mg/L Zn <0.02 mg/L	CAD$1,000,000/year (CAD$0.65/m^3) Includes operating costs for media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment could add additional operating cost. Depending on approach, regenerant management could add significant additional operating cost.	CAD$7,800,000 (CAD$13,000/m^3/h) Includes capital costs for media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment could add additional capital cost. Depending on approach, regenerant management could add significant additional capital cost.	Equalization of flow and contaminant loadings required to achieve consistent effluent quality. Increased loading requires more frequent regeneration and increases residual production.	Equalization of flow and contaminant loadings is required and assumed to occur at the upstream TSF and upstream processes. At minimum, pre-filtration is required. However, depending on effluent chemistry, additional pre-treatment may be required. Regenerant management must be carefully considered based on site-specific factors and could add significant operating and capital costs. Can be employed for pre-concentration of effluent streams to reduce the total volume reporting to bulk removal technologies (e.g., hydroxide or sulfide precipitation).

Technique [proposed location in model]	Effluent Concentration[57]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Selective Ion Exchange – Zeolite [downstream of clarifier overflow tank]	From Table 8-24: NH_3/NH_4^+ <9 mg-N/L	CAD$940,000/year (CAD$0.60/m^3) Includes operating costs for media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment could add additional operating cost. Depending on approach, regenerant management could add significant additional operating cost.	CAD$16,300,000 (CAD$27,170/m^3/h) Includes capital costs for media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment could add additional capital cost. Depending on approach, regenerant management could add significant additional capital cost.	Little information on process robustness is available for full scale treatment of mining effluent. Reportedly does not tolerate variations in feed temperature, volume and composition well. Equalization of flow and contaminant loadings required to achieve consistent effluent quality.	Equalization of flow and contaminant loadings is required and assumed to occur at the upstream TSF and upstream processes. At minimum, pre-filtration is required. However, depending on effluent chemistry, additional pre-treatment may be required. Regenerant management must be carefully considered based on site-specific factors and could add significant operating and capital costs. Can be employed for pre-concentration of effluent streams to reduce the total volume reporting to bulk removal technologies (e.g., air stripping or active aerobic biological oxidation).
Adsorption – Zero Valent Iron [downstream of clarifier overflow tank]	From Table 8-25: Se <0.010 mg/L	CAD$3,700,000/year to CAD$5,000,000/year (CAD$2.32/m^3 to CAD$3.18/m^3)	CAD$31,000,000 to CAD$72,800,000 (CAD$51,700/m^3/h to CAD$121,300/m^3/h) There is a potential to reduce capital costs by using ZVI technology upstream of the lime addition pond, thereby eliminating the need for ZVI equipment associated with downstream iron precipitation and solid/liquid separation. However, this would require confirmation of upstream equalization capacity and effluent concentrations of oxyanions which compete with selenium for removal in the ZVI process.	Equalization of flow and contaminant loadings is required. Reagent dosages can be modulated to accommodate changes in effluent quality. However, technology is not capable of achieving consistent effluent concentration at hydraulic loadings and contaminant loadings outside of equipment design window.	Equalization of flow and contaminant loadings is required and assumed to occur at the upstream TSF and upstream processes. Large quantities of hydroxide sludge are produced with this technology. It is assumed that the sludge can be accommodated by the existing TSF and retained under reducing conditions. Most full-scale installations of this technology treat flow rates one order of magnitude lower than the precious metal subsector design flow rate. The applicability of this technology may be limited, accordingly. Few full-scale installations have been in operation for long enough to determine long term feasibility. The speciation of total selenium for the precious metal subsector is unknown, and therefore, cost impacts of speciation cannot be determined.

Technique [proposed location in model]	Effluent Concentration[57]	Incremental Operating Cost ($/$m^3$)	Incremental Capital Cost ($/$m^3$/h)	Process Reliability, Robustness	Risks and Opportunities
					Due to the relatively recent adoption of this technology, little is known about the long term stability of residuals and the potential for selenium remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.
Active Aerobic Biological Oxidation [downstream of clarifier overflow tank]	From Table 8-26: NH_3/NH_4^+ <2 mg-N/L CN <0.1 mg/L (no change)	CAD$950,000 (CAD$0.60/m^3)	CAD$19,600,000 (CAD$32,670/m^3/h)	Equalization of flow and contaminant loadings is required as systems cannot accommodate loadings of ammonia and other biodegradable matter outside of design window, as well as hydraulic loadings outside of design window. The MBBR system is robust to variations in effluent flow, quality and temperature, provided that they are within the design window. However, there is normally a lag after an effluent quality step change as biological populations re-adjust.	Equalization of flow and contaminant loadings is required and assumed to occur at the upstream TSF and upstream processes. Residual biomass typically requires thickening and dewatering prior to disposal. It is assumed that residuals can be accommodated at the existing TSF. Capital cost estimates assume that the existing lime make-up, storage, and distribution system can be utilized for pH adjustment/alkalinity control.
Active Anoxic/Anaerobic Biological Reduction [downstream of clarifier overflow tank]	FBR from Table 8-27: Se ~ 0.005-0.020 mg/L ABMet® from Table 8-29: Se <0.005 mg/L	FBR: CAD$2,500,000/year (CAD$1.59/m^3) ABMet®: CAD$2,000,000/year (CAD$1.28/m^3) Operating cost for an FBR system could be as low as CAD$1,300,000/year to CAD$1,800,000/year if Envirogen cost estimates are used. Since the precious metal subsector model effluent treatment process is moderately advanced, the addition of an FBR system would not necessarily need substantial wrap around and independent sludge handling, thickening, and disposal equipment, and the total installed costs may be in the lower range of costs.	FBR: CAD$62,400,000 (CAD$104,000/m^3/h) ABMet®: CAD$83,300,000 (CAD$138,830/m^3/h) Total installed capital cost for an FBR system could be as low as CAD$16,400,000 to CAD$26,600,000 if Envirogen cost estimates are used. Total installed capital costs for ABMet® system could be as low as CAD$21,100,000 to CAD$31,300,000 if GE estimates are used. Since the	Equalization of flow and contaminant loadings is required as systems cannot accommodate loadings of selenium and other oxyanions (nitrate) outside of design window, as well as hydraulic loadings outside of design window.	Equalization of flow and contaminant loadings is required and assumed to occur at the upstream TSF and upstream processes. High feed nitrate concentration increases operating and capital costs and residuals production. Residual biomass typically requires thickening and dewatering prior to disposal. It is assumed that residuals can be accommodated at the existing TSF and retained under reducing conditions. Few full-scale FBR installations have been in operation for long enough to determine long term feasibility.

Technique [proposed location in model]	Effluent Concentration[57]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
			precious metal subsector model effluent treatment process is moderately advanced, the addition of an FBR system would not necessarily need substantial wrap around and independent sludge handling, thickening, and disposal equipment, and the total installed costs may be in the lower range of costs.		The speciation of total selenium for the precious metal subsector is unknown, and therefore, cost impacts of speciation cannot be determined. Due to the relatively recent adoption of this technology, little is known about the long term stability of residual biomass and the potential for selenium remobilization under various disposal conditions. If residuals are not stable, significant costs associated with biomass stabilization technology or re-treatment of residual leachate could be incurred.
Reverse Osmosis [downstream of clarifier overflow tank]	Calculated from removal efficiencies in Table 8-31 and values in Table 6-40: Al <0.001 mg/L NH_3/NH_4^+ <2 mg-N/L As <0.01 mg/L Cu <0.001 mg/L Fe <0.06 mg/L Pb <0.001 mg/L Ni <0.005 mg/L Se <0.003 mg/L Zn <0.002 mg/L	CAD$1,500,000 (CAD$0.95/m^3) Operating cost is highly dependent on site-specific energy costs. Includes operating costs for media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional operating cost. Depending on approach, concentrate management could add significant additional operating cost.	CAD$30,300,000 (CAD$50,500/m^3/h) Includes capital costs for media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional capital cost. Depending on approach, concentrate management could add significant additional capital cost.	Low concentrations can be reliably achieved by this technology due to the removal mechanism via size/charge exclusion. Increased contaminant loading would increase feed pump pressure required to maintain flux as well as increase the proportion of concentrate generated (i.e., reduce recovery).	Equalization of flow and contaminant loadings is required and assumed to occur at the upstream TSF and upstream processes. At minimum, pre-filtration is required. However, depending on effluent chemistry, additional pre-treatment may be required. Concentrate management must be carefully considered based on site-specific factor. If concentrate is returned to water management features on site (e.g., TSF), there is a risk of solutes (e.g., Cl^-, Na^+) cycling up in site water. Concentrate management may require advanced technology (e.g., evaporator/crystallizer) which would add significant capital and operating costs. For example, assuming 70% recovery in the RO, an evaporator/crystallizer system for concentrate management would be associated with an incremental capital cost of CAD$60,000,000 and an incremental operating cost of CAD$2,500,000/year. RO permeate is typically lower pH than feed pH and is low in alkalinity. pH adjustment and re-mineralization may be required prior to

Technique [proposed location in model]	Effluent Concentration[57]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
					discharge to meet pH and acute toxicity requirements. Can be used as polishing step for metals and ammonia (as NH_4^+) removal following bulk removal steps. Can be employed for pre-concentration of effluent streams to reduce the total volume reporting to bulk removal technologies (e.g., air stripping or active aerobic biological oxidation and hydroxide or sulfide precipitation).
Nanofiltration [downstream of clarifier overflow tank]	Calculated from removal efficiencies in Table 8-33 and values in Table 6-40: Al <0.003 mg/L As <0.08 mg/L Cu <0.01 mg/L Fe <0.06 mg/L Pb <0.001 mg/L Ni <0.005 mg/L Zn <0.002 mg/L Se <0.005 mg/L	CAD$1,200,000 (CAD$0.79/m^3) Operating cost is highly dependent on site-specific energy costs. Includes operating costs for media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional operating cost. Depending on approach, concentrate management could add significant additional operating cost.	CAD$30,300,000 (CAD$50,500/m^3/h) Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional capital cost. Depending on approach, concentrate management could add significant additional capital cost.	Little performance information is available concerning NF in full scale operation for the treatment of mining effluent; however, it is expected that NF would be similar to RO in performance, and that due to the mechanism of removal (size/charge exclusion), low concentrations could be reliably achieved. Increased contaminant loading would increase feed pump pressure required to maintain flux as well as increase the proportion of concentrate generated (i.e., reduce recovery).	Equalization of flow and contaminant loadings is required and assumed to occur at the upstream TSF and upstream processes. At minimum, pre-filtration is required. However, depending on effluent chemistry, additional pre-treatment may be required. Concentrate management must be carefully considered based on site-specific factor. If concentrate is returned to water management features on site (e.g., TSF), there is a risk of certain solutes cycling up in site water. Concentrate management may require advanced technology (e.g., evaporator/crystallizer) which would add significant capital and operating costs. For example, assuming 70% recovery in the NF, an evaporator/crystallizer system for concentrate management would be associated with an incremental capital cost of CAD$60,000,000 and an incremental operating cost of CAD$2,500,000/year. NF permeate may be low in alkalinity. Re-mineralization may be required prior to discharge to meet acute toxicity requirements. Can be used as polishing step for metals

Technique [proposed location in model]	Effluent Concentration[57]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
					removal following bulk removal steps. Can be employed for pre-concentration of effluent streams to reduce the total volume reporting to bulk removal technologies (e.g., hydroxide or sulfide precipitation).

10.2.2 *Discussion of BATEA Selection*

For the precious metal subsector, Table 10-4 summarizes the technologies that have been selected as BATEA. A discussion of BATEA selection for each targeted parameter (e.g., ammonia, selenium, total suspended solids) or group of targeted parameters (e.g., metals), is provided in the following sections.

Table 10-4: Selected BATEA Technologies for the Precious Metal Subsector

	Selected BATEA	BATEA Technology
Bulk Metals Removal	• Model flow sheet for bulk metals removal (including aluminum, arsenic, copper, iron, lead, nickel, zinc).	Reactor-Based Hydroxide Precipitation • Precipitation of dissolved metals as metal hydroxides and metal complexes, achieved by lime and coagulant (e.g., ferric sulfate) addition within a reactor-based treatment process.
Metals Polishing	• Sulfide precipitation with proprietary polymeric organosulfide chemicals for dissolved metals polishing (including copper, iron, nickel, and zinc).	Sulfide Precipitation Using Proprietary Organosulfide Polymers • Precipitation of dissolved metals as metal sulfides, achieved by the addition of proprietary polymeric organosulfide reagents to a pond-based system.
Cyanide Removal	• Model flow sheet for cyanide removal.	INCO SO_2/Air Process • Oxidation of free and weak acid dissociable (WAD) cyanide to cyanate and precipitation of strong acid dissociable (SAD) cyanide as base metal-iron-cyanide complexes, achieved through the addition of sulfur dioxide (SO_2), oxygen (from air), and lime and ferric sulfate if necessary, in the presence of copper catalyst at elevated pH to oxidize cyanide to cyanate, and promote metal-iron-cyanide complex formation. • Cyanate generated then hydrolyzes to ammonia. Some dissolved metals may also precipitation as metal hydroxides in this process as it occurs at elevated pH.

	Selected BATEA	BATEA Technology
Total Suspended Solids Removal	• Model flow sheet for solids (TSS) removal.	Conventional Clarification • Suspended solids settling, achieved by allowing sufficient residence time for gravity to settle solids, promoted by the use of coagulant and flocculant, within a conventional clarifier (additional features within clarifier may be present to promote settling).
Ammonia Removal	• Active aerobic biological oxidation for total ammonia removal.	Active Aerobic Biological Oxidation • Ammonia is oxidized to nitrate, by autotrophic bacteria that are cultivated by a suspended growth process in a moving bed biofilm reactor.
Selenium Removal	• Model flow sheet for selenium removal.	Synergistic Coagulation/Co-precipitation • Though the model flow sheet is not designed to specifically target selenium, the addition of coagulant within a pond system for bulk metals removal could promote co-precipitation of selenium and achieve minor levels of removal via this mechanism.

10.2.2.1 BATEA for Dissolved Metals Polishing

In contrast to the other dissolved metal polishing technologies considered in Table 10-3 (chemical sulfide precipitation, selective ion exchange, reverse osmosis, and nanofiltration), sulfide precipitation with proprietary polymeric organosulfide chemicals was found to offer the following benefits:

- Similar (order of magnitude) reduction in most of the metals of concern.
- Significantly lower capital cost.
- Lower operating cost.
- The potential benefit of lowering base case operating costs by offsetting flocculant demand.
- No generation of spent regenerant (ion exchange) or concentrate (reverse osmosis, nanofiltration) stream. Other technologies evaluated produce these residual streams, which require specific management, therefore increasing the overall capital and operating cost of these options.

- As precious metal subsector effluent typically has very low concentrations of copper, nickel, and zinc after bulk metals removal in the model flow sheet, there is no opportunity to use sulfide precipitation to produce recoverable/saleable metal products which could offset the higher capital and operating costs associated with the technology.
- Consideration was given to employing reverse osmosis or nanofiltration to pre-concentrate the effluent (thus increasing the metals concentration) prior to metals removal through chemical sulfide or proprietary polymeric organosulfide chemical precipitation. However, the capital and operating cost associated with using reverse osmosis or nanofiltration for pre-concentration are not offset by the capital cost savings for either sulfide precipitation technology. Moreover, the operating costs for either sulfide precipitation technology are only marginally reduced through pre-concentration, as the major operating cost for both technologies is reagent consumption which is proportional to metal loading. Pre-concentration does not change metal loading.

The addition of this BATEA to the model flow sheet is estimated to require a capital cost investment of roughly CAD\$50/m^3/h and would result in an operating cost increase of roughly CAD\$0.20/m^3. When compared to the model flow sheet capital and operating costs, this represents an upgrade capital cost investment of less than 1% of the model flow sheet capital cost and an operating cost increase of roughly 6 to 58%. This represents a minor capital cost investment and a moderate to major operating cost expenditure for the model operation. The capital cost for this BATEA is within the reported range of previous capital investments for upgrades and retrofits to precious metal effluent management and treatment systems (less than CAD\$5,000,000).

These costs assume that equalization and bulk solids and metals removal would be provided by the upstream tailings storage facility and reactor tank(s), and that incremental sludge generation could be accommodated within the clarifier, underflow equipment, underflow piping, and tailings storage facility in the model flow sheet. Sulfide sludge produced with proprietary polymeric organosulfide chemicals will settle but can be difficult to thicken and dewater due to the polymeric nature of the reagents. This is especially important to note for this application, as the use of an existing clarifier and underflow system is proposed for solid/liquid separation and residuals management. The capability of the existing clarifier and underflow system to handle the sulfide sludge must be confirmed.

No dedicated agitated reactor tank is proposed for mixing effluent with the proprietary polymeric organosulfide chemical. It is assumed that the chemical can be mixed with effluent in the existing reactor tank(s) or in-line into the feed to the existing clarifier. Such a configuration has been demonstrated in the treatment of Canadian mining effluent. The operating costs and capital cost investment to implement this BATEA would be increased if a dedicated agitated reactor tank was required to achieve desired dissolved metals polishing performance.

The operating cost is directly influenced by the metals removal efficiency required to meet a specified discharge limit. Lower limits increase reagent consumption and operating cost. Soluble oils and high concentrations of non-metallic suspended solids may interfere with sulfide precipitation via adsorption. Testwork is recommended to confirm proprietary reagent demand, efficacy, and precipitate settleability and rheology. Also, as the chemicals may be acutely lethal to rainbow trout and *Daphnia magna* at certain residual chemical concentrations in effluent, testing is advised to verify that treated effluent complies with toxicity requirements. It is also advised that treated effluent be discharged rather than recirculated for any purpose such that cycling up of residual chemical concentration is limited.

Due to the relatively recent adoption of these reagents and the proprietary nature of their formulations, little is known about the long term stability of residuals and the potential for acid generation and metals remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.

Hatch cautions that this technique should only be considered BATEA for operations that are capable of and dedicated to careful control of operating regimes to prevent effluent toxicity as well as careful control of residuals storage conditions to prevent long term instability and the potential generation of acid through sulfide oxidation and metals remobilization.

10.2.2.2 BATEA for Total Ammonia Removal

Many precious metal operations use cyanide in ore processing. Cyanide which reports to tailings is oxidized to cyanate via cyanide destruction processes or passive natural degradation, and cyanate hydrolyzes to ammonia. Thus, the origins of ammonia in precious metal effluent are both explosives used in mining operations and cyanide used in ore processing. Well established and executed explosives best management plans can minimize some of the amount of ammonia that reports to effluent. Moreover, conditions that are conducive to natural degradation of ammonia in pond(s) could be promoted to achieve further ammonia removal within the subsector model effluent management and treatment system (e.g., elevating pH, aerating, maximizing surface area to depth ratio). Active aerobic biological oxidation (via MBBR) was selected as BATEA to achieve additional removal of total ammonia from the model flow sheet.

Active aerobic biological oxidation (via MBBR) has been shown to reduce total ammonia concentrations to <2 mg-N/L. Given that the concentration of total ammonia achieved by the model effluent treatment system in the precious metal subsector is 12 mg-N/L (Table 6-40), this represents an 83% reduction in total ammonia concentrations. For operations that are achieving effluent concentrations closer to the average total ammonia concentration of the sector, the addition of this BATEA technology would not be warranted.

In contrast to the other ammonia removal technologies considered in Table 10-3 (air stripping, zeolite ion exchange, and reverse osmosis), active aerobic biological oxidation was found to offer the following benefits:

- Similar reduction in ammonia.
- Lower capital cost.

- Lower operating cost.
- More robust to variation in ammonia loading and effluent temperature and lower operating costs associated with heat exchange systems than air stripping, as the system can adjust to changes in ammonia loading and effluent temperature once biological populations are established.
- Lower demand for pre-treatment and post-treatment pH adjustment reagents than air stripping.
- No generation of spent regenerant (ion exchange) or concentrate (reverse osmosis) stream. Other technologies evaluated produce these residual streams, which require specific management, therefore increasing the overall capital and operating cost of these options. However, unlike air stripping which generates no residuals, active aerobic biological oxidation generates residual biomass.

Consideration was given to employing reverse osmosis or zeolite ion exchange to pre-concentrate the effluent (thus increasing the total ammonia concentration) prior to air stripping or aerobic biological oxidation. However, active aerobic biological oxidation is more dependent on ammonia loading than on hydraulic capacity and air stripping is dependent on both ammonia loading and hydraulic capacity. As pre-concentrating does not change ammonia loading, there is little economic advantage to pre-concentrating using reverse osmosis. Moreover, a recent Finnish study demonstrated that nitrification is less efficient for pre-concentrated mine effluent, due to combined inhibition by metals and possibly salts (69).

The addition of this BATEA to the model flow sheet is estimated to require a capital cost investment of roughly CAD$32,670/m^3/h and would result in an operating cost increase of roughly CAD$0.60/m^3. When compared to the model flow sheet capital and operating costs, this represents an upgrade capital cost investment of 33 to 530% of the model flow sheet capital cost and an operating cost increase of roughly 19 to 178%. This represents a major capital cost investment and a moderate to major operating cost expenditure for the model operation. The capital cost for this BATEA exceeds the reported range of previous capital investments for upgrades and retrofits to precious metal effluent management and treatment systems (<CAD$5,000,000). However, the precious metal subsector seems to be developing more interest in the technology, with one operation in Quebec converting its RBC active aerobic biological oxidation process to MBBR, one operation in Saskatchewan implementing MBBR by the end of 2013, and one operation in Ontario piloting MBBR during winter 2013/2014. 1

These costs assume that equalization, bulk metals removal, and retention time for the degradation of cyanide to cyanate to ammonia would be provided by the upstream tailings storage facility and that residual biomass could be accommodated by the tailings storage facility in the model flow sheet. These costs also assume that the existing lime reagent systems could be utilized for pH adjustment/alkalinity control in the MBBR system.

The capital and operating costs are directly influenced by the total ammonia removal efficiency required to meet a specified discharge limit. Lower limits increase capital and operating costs.

Metals and other toxic chemicals in precious metal effluent can inhibit nitrification at relatively low concentrations and it is assumed that sufficient metals removal occurs in the existing hydroxide precipitation process. Cyanide itself is toxic to nitrifying bacteria at high concentrations; however, the concentration cyanide achieved by the model effluent treatment system in the precious metal subsector is very low (0.1 mg/L per Table 6-40).

Testwork is recommended to confirm effluent treatability and establish MBBR design parameters.

10.2.2.3 BATEA for Selenium Removal

The precious metal subsector model was selected as BATEA for selenium removal, as augmentative selenium removal technologies (ZVI, FBR, ABMet®, reverse osmosis and nanofiltration) are considered to be uneconomic and technically limited for application to the model. Since ZVI technology can achieve <0.010 mg/L Se, FBR technology can achieve approximately 0.005 to 0.020 mg/L Se, ABMet® technology can achieve <0.005 mg/L, and membrane separation technologies (reverse osmosis and nanofiltration) can achieve <0.005 mg/L, it is possible that only marginal removal could be achieved from the untreated effluent concentration of 0.04 mg/L total selenium for the precious metal subsector, especially since the speciation of total selenium is not known. Should further removal of selenium beyond that achievable by the model be required (i.e., Se <0.05 mg/L), active anoxic/anaerobic biological reduction (e.g., FBR or ABMet®) is the least cost prohibitive of the technologies capable of achieving low selenium concentrations. In contrast to zero valent iron adsorption and membrane separation (considering capital and operating costs of brine management through the use of evaporative technologies), active anoxic/anaerobic biological reduction (e.g., FBR or ABMet®) was found to offer the following benefits:

- Greater or equivalent selenium removal and lower or equivalent achievable selenium concentration.
- Lower capital cost.
- Lower operating cost.
- Lower mass/volume of residuals generated requiring less handling and disposal costs.

Consideration was given to employing reverse osmosis to pre-concentrate the effluent (thus increasing the selenium concentration) prior to zero valent iron adsorption or active anoxic/anaerobic biological reduction. However, the capital and operating cost associated with using reverse osmosis for pre-concentration are not offset by the capital cost savings for zero valent iron technology. Moreover, the operating cost savings for zero valent iron technology are only marginally reduced through pre-concentration, as the major operating cost is zero valent iron reagent consumption which is proportional to selenium loading. Additionally, the capital and operating costs for active anoxic/anaerobic biological reduction are dependent on both selenium loading than on hydraulic capacity. As pre-concentrating changes hydraulic capacity, but does not change selenium loading, there is likely to be little economic advantage to pre-concentrating using reverse osmosis. One operation contested this assertion during the review period for the Draft MEND BATEA Study Report, stating that it is contrary to their findings from technology assessments. However, follow-up to seek clarification on this comment was unsuccessful.

As an example, the addition of FBR BAT to the model flow sheet is estimated to require a capital cost investment of less than CAD$104,000/m^3/h [58] and would result in an operating cost increase of less CAD$1.59/m^3 [59]. When compared to the model flow sheet capital and operating costs, this represents an upgrade capital cost investment of roughly 100 to 1,700 % of the model flow sheet capital cost and an operating cost increase of roughly 50 to 470%. This represents a major investment for the model operation. The capital cost for this BAT greatly exceeds the reported range of previous capital investments for upgrades and retrofits to precious metal effluent management and treatment systems (less than CAD$5,000,000). These two last statements stand true even when lower end cost estimates based on cost estimates provided by Envirogen are considered.

Morever, due to the relatively recent adoption of this technology, little is known about the long term stability of residual biomass and the potential for selenium remobilization under various disposal conditions. If residuals are not stable, significant costs associated with biomass stabilization technology or re-treatment of residual leachate could be incurred.

10.2.2.4 BATEA for Cyanide Removal

The BATEA selected for cyanide removal is the base case model flow sheet, which employs active cyanide destruction (e.g., INCO SO_2/Air process) on tailings and passive natural degradation of cyanide in the tailings storage facility. Conditions that are conducive to natural degradation of cyanide in pond(s) could be promoted to achieve further cyanide removal within the subsector model effluent management and treatment system (e.g., aerating, maximizing surface area to depth ratio). Canadian precious metal operations achieve cyanide concentrations 0.03 mg/L on average and 95% of all reported concentrations are less than 0.09 mg/L.

10.2.2.5 BATEA for Bulk Metals Removal

The BATEA selected for bulk removal of metals is the base case model flow sheet, which employs both pond-based settling at the TSF and equipment-based hydroxide precipitation and solid/liquid separation.

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[58] CAD$104,000/m^3/h represents total installed costs estimated by CH2MHill. In contrast, augmentative total installed costs for an FBR system integrated into existing systems, as estimated by Envirogen, could be as low as CAD$27,300/m^3/h to $44,300/m^3/h.

[59] CAD$1.59/m^3 treated represents operating costs estimated by CH2MHill. In constrast, augmentative operating costs for an FBR system integrated into existings systems, as estimated by Envirogen, could be as low as CAD$0.85/m^3 treated to CAD$1.16/m^3 treated.

10.2.2.6 BATEA for Solids Removal

Canadian precious metal operations as a total cohort achieve TSS concentrations of less than 5 mg/L on average and 95% of all concentrations from model effluent treatment systems are less than 12 mg/L. This is consistent with expectations that well designed and operated pond-based and equipment-based solid/liquid separation systems should achieve TSS concentrations of less than 15 mg/L.

The addition of filtration solid/liquid separation technology would not achieve significant improvements in TSS removal over the model (at most 60% improvement). As such, there is no justification for the additional capital costs and operating costs for the implementation of this technology.

10.3 Metals Sector: Iron Ore

10.3.1 BATEA Selection Table

Table 10-5: Iron Ore Subsector BATEA Selection Table

Technique [proposed location in model]	Effluent Concentration[60]	Incremental Operating Cost (\$/m^3)	Incremental Capital Cost (\$/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Model Effluent Management and Treatment System (Figure 6-34) [n/a]	From Table 6-57: Al <0.8 mg/L As <0.001 mg/L Cu <0.005 mg/L Fe <5.5 mg/L Pb <0.003 mg/L Ni <0.003 mg/L Se <0.005 mg/L Zn <0.04 mg/L TSS <62 mg/L NH_3/NH_4^+ <7.76 mg-N/L	No incremental increase CAD\$340,000 to CAD\$1,000,000/year (CAD\$0.01 to CAD\$0.03/m^3)	No incremental increase CAD\$2,600,000 to CAD\$5,800,000 (CAD\$370 to CAD\$830/m^3/h)	With sufficient footprint, capacity and diligent operator attention, pond-based systems can achieve consistent effluent quality; however, this system is very sensitive to fluctuations in flow rate, solids loading, and ambient conditions, and demands significant labour attention for reliable operation.	Susceptible to upsets that can re-suspend precipitates and cause downstream compliance issues.
Hydroxide Precipitation [upstream of settling pond(s) if upstream equalization is available; upstream of polishing pond(s) if no upstream equalization is available]	From Table 8-2, no change from base case, except for: Al <0.50 mg/L Fe <0.10 mg/L	CAD\$1,700,000/year (CAD\$0.05/m^3)	CAD\$3,900,000 (CAD\$560/m^3/h)	Equalization of flow and contaminant loadings is required. Reliable and robust provided that ponds are adequately designed. However, increases in untreated effluent metals concentrations, TSS, and hydraulic loading may cause variations in effluent quality.	Equalization of flow and contaminant loadings is assumed to occur upstream. It is assumed that the incremental generation of hydroxide sludge can be accommodated by the existing settling pond(s) / polishing pond(s).
Sulfide Precipitation [n/a]	From Table 8-5, no change from base case, except for: Fe^{2+} <0.30 mg/L Zn <0.02 mg/L	Technology not economically feasible for removal of iron and marginal removal of zinc.			
Sulfide Precipitation with Proprietary Polymeric Organosulfide Chemicals [downstream of settling pond(s)]	From Table 8-6, no change from base case, except for: Fe^{2+} <0.30 mg/L Zn <0.02 mg/L	> CAD\$16,400,000/year (> CAD\$0.48/m^3)	Technology not economically feasible for removal of iron and marginal removal of zinc.		

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[60] "(no change)" indicates that the concentration of the parameter has not changed from that achieved by the model effluent management and treatment system.

Technique [proposed location in model]	Effluent Concentration[60]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Solid/Liquid Separation – Clarification [upstream of settling pond(s)]	From Section 8.2.7.2: TSS <15 mg/L	CAD$3,400,000/year (CAD$0.10/m^3) There is a potential for reduction of operating costs due to reductions in flocculant consumption, as the controlled solid/liquid separation process may offset flocculant demand. However, no discounts have been applied to this operating cost.	CAD$50,600,000 (CAD$7,230/m^3/h)	Robust and reliable process that is well established in the mining industry. Significant variations in flow rate and TSS loading could impact operation and the quality of the effluent; equalization of flow and contaminant loadings is required.	Upstream equalization of flow and contaminant loadings is assumed. Smaller footprint and higher degree of control compared to pond-based solid/liquid separation. Complements other removal technologies, (e.g., can be applied downstream of hydroxide and sulfide precipitation to remove metal precipitates).
Enhanced Coagulation and Settling [upstream of settling pond(s)]	From Table 8-17: TSS <10 mg/L	ACTIFLO®: CAD$3,400,000/year (CAD$0.10/m^3) There is a potential for reduction of operating costs due to reductions in reagent consumption, due to the enhanced coagulation provided by ballast or sludge recycle. However, no discounts have been applied to the operating cost presented here.	ACTIFLO®: CAD$22,100,000 (CAD$3,160/m^3/h)	Enhanced coagulation and settling is a proprietary technique that is claimed by vendors to be a robust and process that can reliably achieve low TSS concentrations, when operating within the design window for hydraulic loadings and solids loadings/generation.	Upstream equalization of flow and contaminant loadings is assumed. Smaller footprint compared to pond-based solid/liquid separation or clarification. Complements other removal technologies, (e.g., can be applied downstream of hydroxide and sulfide precipitation to remove metal precipitates). Less established technique for the Canadian mining industry than other solid/liquid separation technologies.
Solid/Liquid Separation – Filtration [upstream of settling pond(s)]	From Section 8.2.7.4: TSS <5 mg/L	CAD$5,100,000/year (CAD$0.15/m^3) Includes operating costs for clarification.	CAD$84,500,000 (CAD$12,070/m^3/h) Includes capital costs for clarification.	Robust and reliable process that is well established in the mining industry. Significant variations in flow rate and TSS loading could impact operation and the quality of the effluent; equalization of flow and contaminant loadings is required.	Upstream equalization of flow and contaminant loadings is assumed. The TSS concentration achieved by the model effluent treatment system in the iron ore subsector is 62 mg/L even after pond-based solid/liquid separation, therefore bulk removal of TSS would be required prior to media filtration. A clarifier system would thus be installed in addition to the media filtration system for bulk TSS removal. It is assumed that the incremental generation of solids in backwash can be accommodated by the settling pond(s).

Technique **[proposed location in model]**	**Effluent Concentration**[60]	**Incremental Operating Cost $(\$/m^3)$**	**Incremental Capital Cost $(\$/m^3/h)$**	**Process Reliability, Robustness**	**Risks and Opportunities**
Air Stripping [n/a]	From Section 8.2.10: NH_3/NH_4^+ <7.76 mg-N/L (no change)	Technology not economically feasible at untreated effluent ammonia below 10 mg-N/L.			
Selective Ion Exchange – Metals Polishing [n/a]	From Table 8-23: Al <0.05 mg/L As <0.0001 mg/L (no change) Cu <0.004 mg/L (no change) Fe <0.2 mg/L Ni <0.003 (no change) mg/L Pb <0.003 mg/L (no change) Zn <0.02 mg/L	Not calculated	>> CAD$84,500,000 This was deemed to be uneconomic for the marginal improvement in performance achieved.		
Selective Ion Exchange – Zeolite [n/a]	From Table 8-24: NH_3/NH_4^+ <9 mg-N/L	Not calculated	>> CAD$84,500,000 This was deemed to be uneconomic for the marginal improvement in performance achieved.		
Active Aerobic Biological Oxidation [n/a]	From Table 8-26: NH_3/NH_4^+ <7.76 mg-N/L (no change)	Technology not economically feasible to reduce total ammonia from 7.76 mg-N/L.			
Reverse Osmosis [n/a]	Calculated from removal efficiencies in Table 8-31 and values in Table 6-57: Al <0.02 mg/L NH_3/NH_4^+ <1.2 mg/L As <0.001 mg/L Cu <0.001 mg/L Fe <0.3 mg/L Pb <0.001 mg/L Ni <0.001 mg/L Zn <0.001 mg/L Se <0.001 mg/L	Not calculated	>> CAD$84,500,000 This was deemed to be uneconomic for the marginal improvement in performance achieved.		

Technique [proposed location in model]	Effluent Concentration[60]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Nanofiltration [n/a]	Calculated from removal efficiencies in Table 8-33 and values in Table 6-57: Al <0.04 mg/L As <0.001 mg/L Cu <0.001 mg/L Fe <0.3 mg/L Pb <0.001 mg/L Ni <0.001 mg/L Zn <0.001 mg/L Se <0.002 mg/L	Not calculated	>> CAD$84,500,000 This was deemed to be uneconomic for the marginal improvement in performance achieved.		

10.3.2 *Discussion of BATEA Selection*

For the iron ore subsector, Table 10-6 summarizes the technologies that have been selected as BATEA. A discussion of BATEA selection for each targeted parameter (e.g., ammonia, selenium, total suspended solids) or group of targeted parameters (e.g., metals), is provided in the following sections.

Table 10-6: Selected BATEA Technologies for the Iron Ore Subsector

Targeted Parameters	Selected BATEA	BATEA Technology
Bulk Metals Removal	• Model flow sheet for bulk metals removal (including aluminum, arsenic, copper, iron, lead, nickel, zinc).	Pond-Based Settling • Removal of metals present as suspended solids by sedimentation, achieved by allowing sufficient residence time for gravity to settle solids, promoted by the use of flocculant, within a pond system.
Total Suspended Solids Removal	• Model flow sheet for solids (TSS) removal.	Pond-Based Settling • Suspended solids sedimentation, achieved by allowing sufficient residence time for gravity to settle solids, promoted by the use of flocculant, within a pond system.
Ammonia Removal	• Model flow sheet for total ammonia removal.	Natural Degradation of Ammonia and Explosives Best Management Plan • An explosives best management plan is followed to minimize the release of ammonia into site water. • Natural degradation of ammonia occurring by volatilization of un-ionized ammonia gas (NH_3) and biological oxidation, achieved by allowing ample residence time in pond systems, especially during periods where ambient climate conditions promote these processes. These processes are influenced by pH, temperature, and dissolved oxygen concentration.
Selenium Removal	• No selenium removal technologies were evaluated for the iron ore subsector, due to the low total selenium 95th percentile (<0.005 mg/L) for the entire subsector.	

10.3.2.1 BATEA for Solids Removal

Canadian iron ore operations as a total cohort achieve TSS concentrations of less than 14 mg/L on average and 95% of all reported concentrations from model and model equivalent effluent treatment systems are less than 62 mg/L. This is somewhat consistent with expectations that well designed and operated pond-based solid/liquid separation systems should achieve TSS concentrations less than 15 mg/L.

The addition of clarification, enhanced coagulation and settling, and/or filtration solid/liquid separation technologies could achieve more reliable TSS removal than demonstrated by the subsector. However, improvements in existing pond infrastructure and operation could also improve TSS removal. For example, sediment/silt curtains and dykes to prevent short circuiting could be used to improve existing infrastructure. Better control of flocculant dosing regimes, addition of coagulant dosing regimes, and regular dredging of pond(s) are just a few operational practices to could improve TSS removal. As such, there is no justification for the additional capital costs and operating costs for the implementation of these equipment-based solid/liquid separation technologies.

However, for greenfield applications, solid/liquid separation by clarification or enhanced coagulation and settling would be recommended as BATEA as opposed to pond-based solid/liquid separation for the following reasons:

- Equipment-based solid/liquid separation is more easily monitored and controlled than pond-based solid/liquid separation in terms of flow rate, reagent dosing and other process conditions. Equipment-based systems are not as susceptible to upsets due to climatic conditions such as heavy rainfall events, high winds and wave action, and pond turnovers due to temperature inversions that can re-suspend precipitates and cause downstream compliance issues.
- Reducing pond footprints can reduce the net precipitation inputs into water balances, thereby reducing the volumes of water/effluent potentially requiring management and treatment and reducing operating and capital costs.
- Equipment-based solids removal technologies have improved sludge management and handling capabilities over pond systems. Dredging of ponds is often not done frequently enough to prevent solids carryover and downstream non-compliance due to the logistical challenges or significant costs. Equipment-based solids removal technologies are more efficient at collecting and removing sludge from the system at regular intervals.
- Equipment-based solid/liquid separation should be integrated with reactor-based metals precipitation, coagulation, and flocculation technology. This will improve reagent/reaction efficiency, reducing reagent costs and minimizing sludge production. These systems can also be configured with underflow recycle to further improve reagent/reaction efficiency, if applicable.
- Equipment-based solid/liquid separation should be integrated with upstream/downstream pond systems for equalization and passive natural degradation of ammonia.

10.3.2.2 BATEA for Metals

Hydroxide precipitation, sulfide precipitation, sulfide precipitation with proprietary polymeric organosulfide chemicals, selective ion exchange, reverse osmosis, and nanofiltration were all found to be uneconomic, as they have extremely high capital and/or operating costs at the high design and nominal treatment flow rates experienced by the iron ore subsector and they do not achieve significant reduction in most of the metals of concern. The incremental costs for these technologies could not be justified by improvements in treated effluent quality. Moreover, it is expected that a substantial portion of aluminum and iron in effluent may be present as particulate metal. Thus, improvements in aluminum and iron (as well as other metals) removal efficiency could be achieved through improvements in solid/liquid separation (TSS removal).

10.3.2.3 BATEA for Selenium Removal

No selenium removal technologies were evaluated for the iron ore subsector, due to the low total selenium 95th percentile (<0.005 mg/L) for the entire subsector.

10.3.2.4 BATEA for Total Ammonia Removal

The BATEA selected for total ammonia removal is the base case model flow sheet which is assumed to incorporate explosives best management practices and passive natural degradation of ammonia. Since the majority of iron ore operations do not use cyanide or ammonia in ore processing, the origin of ammonia in iron ore effluent is explosives used in mining operations. The iron ore operations that participated in this study employ bulk ANFO and only one reported operating under an explosives best management plan. Of all types of explosives, bulk ANFO is the least water resistant. Moreover, drill hole overfilling and spillage are more common with bulk ANFO than with packaged explosives. Well established and executed explosives best management plans can minimize the amount of ammonia that reports to effluent. Moreover, conditions that are conducive to natural degradation of ammonia in pond(s) could be promoted to achieve further ammonia removal within the subsector model effluent management and treatment system (e.g., elevating pH, aerating, maximizing surface area to depth ratio).

The concentration of total ammonia achieved by the model effluent treatment system in the iron ore metal subsector is 7.76 mg-N/L. At such a low feed concentration, air stripping would not be technically feasible and active aerobic biological oxidation would not be very effective in lowering the total ammonia concentration much below the untreated effluent concentration and would therefore not be economically feasible. Zeolite ion exchange for total ammonia removal is not technically feasible since the total ammonia concentration in the feed is lower than the achievable total ammonia concentration from a zeolite ion exchange system.

Consideration was given to employing reverse osmosis or zeolite ion exchange to pre-concentrate the effluent (thus increasing the total ammonia concentration) prior to air stripping or aerobic biological oxidation. However, active aerobic biological oxidation is more dependent on ammonia loading than on hydraulic capacity and air stripping is dependent on both ammonia loading and hydraulic capacity. Moreover, reverse osmosis and zeolite ion exchange would have extremely high capital and/or operating costs at the high design and nominal treatment flow rates for the iron ore subsector. Additionally, a recent Finnish study demonstrated that nitrification is less efficient for pre-concentrated mine effluent, due to combined inhibition by metals and possibly salts (69).

10.4 Metals Sector: Uranium

10.4.1 BATEA Selection Table

Table 10-7: Uranium Subsector BATEA Selection Summary Table

Technique [proposed location in model]	Effluent Concentration[61]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Model Effluent Management and Treatment System (Figure 6-48) [n/a]	From Table 6-77: Al <0.7 mg/L As <0.06 mg/L Cu <0.04 mg/L Fe <0.5 mg/L Pb <0.002 mg/L Ni <0.2 mg/L Se <0.02 mg/L Zn <0.04 mg/L Ra-226 <0.11 Bq/L TSS <2.0 mg/L NH_3 <23 mg-N/L	No incremental increase CAD$10,000,000 to 18,000,000/year (CAD$3.30 to 5.90/m^3)	No incremental increase CAD$65,000,000 to 200,000,000 (CAD$130,000 to 400,000/m^3/h)	With diligent operator attention, the system can achieve consistent effluent quality. Equalization provided by the surge/equalization pond should minimize the fluctuations in flow rate, solids and contaminant concentrations.	Equalization of flow and contaminant loadings is assumed to occur at the upstream surge/equalization pond. Residual total ammonia concentrations may interfere with hydroxide precipitation reactions.
Sulfide Precipitation [downstream of low pH media filter(s)]	From Table 8-5: As <0.05 mg/L Cu <0.03 mg/L Fe^{2+} <0.30 mg/L Ni <0.05 mg/L Pb <0.002 mg/L (no change) Se <0.02 mg/L (no change) Zn <0.02 mg/L	CAD$2,000,000/year to CAD$3,800,000/year (CAD$0.64/m^3 to CAD$1.24/m^3) depending on reagent dosage No operating cost discounts have been applied for value recovery through residuals re-processing.	CAD$4,100,000 (CAD$8,200/m^3/h)	Equalization of flow and contaminant loadings is required. Sulfide reagent dosage can be modulated to accommodate changes in effluent quality. However, technology is not capable of achieving consistent effluent concentration at hydraulic loadings and solids loadings/generation outside of equipment design window.	Equalization of flow and contaminant loadings is assumed to occur at the upstream surge/equalization pond and upstream processes. It is assumed that the incremental generation of sulfide sludge can be accommodated by the existing TSF and retained under reducing conditions. Technique can improve metals removal efficiencies even with high complexing/chelating agent concentrations. However, the operating cost is high due to the high cost of proprietary reagents.

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[61] "(no change)" indicates that the concentration of the parameter has not changed from that achieved by the model effluent management and treatment system.

Technique [proposed location in model]	Effluent Concentration[61]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Sulfide Precipitation with Proprietary Polymeric Organosulfide Chemicals [within low pH precipitation/co-precipitation stage]	From Table 8-6: As <0.05 mg/L Cu <0.03 mg/L Fe^{2+} <0.30 mg/L Ni <0.05 mg/L Pb <0.002 mg/L (no change) Se <0.02 mg/L (no change) Zn <0.02 mg/L	CAD$470,000/year (CAD$0.15/m^3) There is a potential for reduction of operating costs due to reductions in flocculant consumption, as the proprietary reagents are polymeric in nature and may offset flocculant demand. However, no discounts have been applied to this operating cost.	CAD$29,000 (CAD$60/m^3/h)	Equalization of flow and contaminant loadings is required. Proprietary reagent dosage can be modulated to accommodate changes in effluent quality. However, technology is not capable of achieving consistent effluent concentration at hydraulic loadings and solids loadings/generation outside of design window. Pond-based solid/liquid separation is susceptible to upsets that can re-suspend precipitates and cause downstream compliance issues.	Equalization of flow and contaminant loadings is assumed to occur at the upstream surge/equalization pond and upstream processes. It is assumed that the incremental generation of sulfide sludge can be accommodated by the existing clarifier, underflow equipment, and TSF and retained under reducing conditions. It is assumed that the sulfide reagent would not compete with ferric iron for metals since it is dosed in-line to the clarifier and ferric sulfate is dosed upstream in the reactor tank(s). Such a treatment system is considered suitable for lower strength effluents (total metals concentration <100 mg/L). However, testwork would be required to verify this assertion. Can improve metals removal efficiencies even with high complexing/chelating agent concentrations with low capital cost investment. High operating cost due to high cost consumables. The chemicals may be acutely lethal to rainbow trout and *Daphnia magna* at certain residual chemical concentrations in effluent. Bench and/or pilot scale testing is advised to verify that treated effluent complies with toxicity requirements. Treated effluent should be discharged rather than recirculated. Due to the relatively recent adoption of these reagents and the proprietary nature of their formulations, little is known about the long term stability of residuals and the potential for acid generation and metals remobilization. If residuals are not kept stable, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.

Technique [proposed location in model]	Effluent Concentration[61]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Air Stripping [downstream of high pH media filter(s)]	From Section 8.2.10: NH_3/NH_4^+ > 3 mg-N/L (lower achievable limit, but effluent concentration is a key design parameter)	CAD$1,380,000/year (CAD$0.45/m^3)	CAD$23,100,000 (CAD$46,200/m^3/h)	Technique performance is very sensitive to ambient temperatures and a heat exchange system is required to maintain ammonia removal efficiency year round. Towers are susceptible to scaling and plugging depending on effluent quality. Scaling and plugging impact performance and at minimum, pre-filtration is required for reliable operation. Moreover, technology is not capable of achieving consistent effluent concentration at hydraulic loadings and solids loadings outside of design window.	Equalization of flow and contaminant loadings is assumed to occur at the upstream surge/equalization pond and upstream processes. It is assumed that ammonia discharge to the local airshed is acceptable. It is assumed that space is available to accommodate large footprint of equipment. Capital cost estimates assume that the existing lime make-up, storage, and distribution system can be utilized for pH adjustment. High operating cost due to power consumption. Pre-heating of air and/or effluent would likely be required for a good portion of the year for those operations with year-round treatment and discharge, leading to high energy costs (e.g., could almost double operating costs).
Selective Ion Exchange – Metals Polishing [downstream of low pH media filter(s)]	From Table 8-23: Al <0.05 mg/L As <0.01 mg/L Cu <0.008 mg/L Fe <0.2 mg/L Ni <0.01 mg/L Pb <0.001 mg/L Se <0.01 mg/L Zn <0.02 mg/L	CAD$1,800,000/year (CAD$0.60/m^3) Depending on effluent chemistry, additional pre-treatment could add additional operating cost. Depending on approach, regenerant management could add significant additional operating cost.	CAD$7,800,000 (CAD$15,600/m^3/h) Depending on effluent chemistry, additional pre-treatment could add additional capital cost. Depending on approach, regenerant management could add significant additional capital cost.	Equalization of flow and contaminant loadings required to achieve consistent effluent quality. Increased loading requires more frequent regeneration and increases residual production.	Equalization of flow and contaminant loadings is assumed to occur at the upstream surge/equalization pond and upstream processes. Pre-filtration is included in the model flow sheet. However, depending on effluent chemistry, additional pre-treatment may be required. Regenerant management must be carefully considered based on site-specific factors and could add significant operating and capital costs. Can be employed for pre-concentration of effluent streams to reduce the total volume reporting to bulk removal technologies (e.g., existing hydroxide precipitation/co-precipitation processes or new sulfide precipitation process).

Technique [proposed location in model]	Effluent Concentration[61]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Selective Ion Exchange – Zeolite [downstream of low pH media filter(s)]	From Table 8-24: NH_3/NH_4^+ <9 mg-N/L	CAD$1,800,000/year (CAD$0.60/m^3) Depending on effluent chemistry, additional pre-treatment could add additional operating cost. Depending on approach, regenerant management could add significant additional operating cost.	CAD$12,700,000 (CAD$25,400/m^3/h) Depending on effluent chemistry, additional pre-treatment could add additional capital cost. Depending on approach, regenerant management could add significant additional capital cost.	Little information on process robustness is available for full scale treatment of mining effluent. Reportedly does not tolerate variations in feed temperature, volume and composition well. Equalization of flow and contaminant loadings required to achieve consistent effluent quality.	Equalization of flow and contaminant loadings is assumed to occur at the upstream surge/equalization pond and upstream processes. Pre-filtration is included in the model flow sheet. However, depending on effluent chemistry, additional pre-treatment may be required. Regenerant management must be carefully considered based on site-specific factors and could add significant operating and capital costs. Can be employed for pre-concentration of effluent streams to reduce the total volume reporting to bulk removal technologies (e.g., air stripping or active aerobic biological oxidation).
Adsoprtion – Zero Valent Iron [downstream of low pH media filter(s)]	From Table 8-25: Se <0.010 mg/L	CAD$7,100,000/year to CAD$9,800,000/year (CAD$2.32/m^3 to CAD$3.18/m^3)	CAD$27,800,000 to CAD$65,300,000 (CAD$55,600/m^3/h to CAD$131,000/m^3/h) There is a potential to reduce capital costs by using ZVI technology upstream of the model, thereby eliminating the need for ZVI equipment associated with downstream iron precipitation and solid/liquid separation. However, this would require confirmation of upstream equalization capacity and effluent concentrations of oxyanions which compete with selenium for removal in the ZVI process.	Equalization of flow and contaminant loadings is required. Reagent dosages can be modulated to accommodate changes in effluent quality. However, technology is not capable of achieving consistent effluent concentration at hydraulic loadings and contaminant loadings outside of equipment design window.	Equalization of flow and contaminant loadings is assumed to occur at the upstream surge/equalization pond and upstream processes. Large quantities of hydroxide sludge are produced with this technology. It is assumed that the sludge can be accommodated by the existing TSF and retained under reducing conditions. Most full-scale installations of this technology treat flow rates one order of magnitude lower than the uranium subsector design flow rate. The applicability of this technology may be limited, accordingly. Few full-scale installations have been in operation for long enough to determine long term feasibility. The speciation of total selenium for the uranium subsector is unknown, and therefore, cost impacts of speciation cannot be determined. Due to the relatively recent adoption of this technology, little is known about the long term stability of residuals and the potential for selenium remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.

Technique [proposed location in model]	Effluent Concentration[61]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Active Aerobic Biological Oxidation [downstream of low pH media filter(s)]	From Table 8-26: NH_3/NH_4^+ <2 mg-N/L	CAD$1,400,000 (CAD$0.45/m^3)	CAD$15,900,00 (CAD$31,800/m^3/h)	Equalization of flow and contaminant loadings is required as systems cannot accommodate loadings of ammonia and other biodegradable matter outside of design window, as well as hydraulic loadings outside of design window. The MBBR system is robust to variations in effluent flow, quality and temperature, provided that they are within the design window. However, there is normally a lag after an effluent quality step change as biological populations re-adjust.	Equalization of flow and contaminant loadings is assumed to occur at the upstream surge/equalization pond and upstream processes. MBBR systems are difficult to start-up/restart systems at low effluent temperatures (<10 °C) and require heat exchange systems. Residual biomass typically requires thickening and dewatering prior to disposal. It is assumed that residuals can be accommodated at the existing TSF. Capital cost estimates assume that the existing lime make-up, storage, and distribution system can be utilized for pH adjustment/alkalinity control.
Active Anoxic/Anaerobic Biological Reduction [downstream of low pH media filter(s)]	FBR from Table 8-27: Se ~ 0.005-0.020 mg/L ABMet® from Table 8-29: Se <0.005 mg/L	FBR: CAD$6,900,000/year (CAD$1.59/m^3) ABMet®: CAD$3,900,000/year (CAD$1.28/m^3) Operating cost for an FBR system could be as low as CAD$1,300,000/year to CAD$1,800,000/year if Envirogen cost estimates are used. Since the precious metal subsector model effluent treatment process is well advanced, the addition of an FBR system would not necessarily need substantial wrap around and independent sludge handling, thickening, and disposal equipment, and the total installed costs may be in the lower range of costs.	FBR: CAD$56,000,000 (CAD$112,000/m^3/h) ABMet®: CAD$74,600,000 (CAD$149,200/m^3/h) Total installed capital cost for an FBR system could be as low as CAD$16,400,000 to CAD$26,600,000 if Envirogen cost estimates are used. Total installed capital costs for ABMet® system could be as low as CAD$19,000,000 to CAD$28,000,000 if GE estimates are used. Since the uranium subsector model effluent treatment process is well advanced, the addition of an FBR system would not necessarily need substantial wrap around and independent sludge handling, thickening, and disposal equipment, and the total installed costs may be in the lower range of costs.	Equalization of flow and contaminant loadings is required as systems cannot accommodate loadings of selenium and other oxyanions (nitrate) outside of design window, as well as hydraulic loadings outside of design window.	Equalization of flow and contaminant loadings is assumed to occur at the upstream surge/equalization pond and upstream processes. High feed nitrate concentration increases operating and capital costs and residuals production. Residual biomass typically requires thickening and dewatering prior to disposal. It is assumed that residuals can be accommodated at the existing TSF and retained under reducing conditions. Few full-scale FBR installations have been in operation for long enough to determine long term feasibility. The speciation of total selenium for the precious metal subsector is unknown, and therefore, cost impacts of speciation cannot be determined. Due to the relatively recent adoption of this technology, little is known about the long term stability of residual biomass and the potential for selenium remobilization under various disposal conditions. If residuals are not stable, significant costs associated with biomass stabilization technology or re-treatment of residual leachate could be incurred.
Reverse Osmosis [downstream of low pH	Calculated from removal efficiencies in Table 8-31 and values in Table 6-77:	CAD$2,700,000/year	CAD$22,800,000 (CAD$45,600/m^3/h)	Low concentrations can be reliably achieved by this technology due to the removal mechanism via size/charge exclusion.	Equalization of flow and contaminant loadings is assumed to occur at the upstream surge/equalization pond and upstream processes.

Technique [proposed location in model]	Effluent Concentration[61]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
media filter(s)]	Al <0.015 mg/L NH_3/NH_4^+ <4 mg/L As <0.02 mg/L Cu <0.002 mg/L Fe <0.03 mg/L Pb <0.001 mg/L Ni <0.01 mg/L Se <0.001 mg/L Zn <0.002 mg/L	Operating cost is highly dependent on site-specific energy costs. Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional operating cost. Depending on approach, concentrate management could add significant additional operating cost.	Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional capital cost. Depending on approach, concentrate management could add significant additional capital cost.	Increased contaminant loading would increase feed pump pressure required to maintain flux as well as increase the proportion of concentrate generated (i.e., reduce recovery).	Pre-filtration is included in the model flow sheet. However, depending on effluent chemistry, additional pre-treatment may be required. Concentrate management must be carefully considered based on site-specific factor. If concentrate is returned to water management features on site (e.g., TSF), there is a risk of solutes (e.g., Cl^-, Na^+) cycling up in site water. Concentrate management may require advanced technology (e.g., evaporator/crystallizer) which would add significant capital and operating costs. For example, assuming 70% recovery in the RO, an evaporator/crystallizer system for concentrate management would be associated with an incremental capital cost of CAD$50,000,000 and an incremental operating cost of CAD$4,600,000/year. RO permeate is typically lower pH than feed pH and is low in alkalinity. pH adjustment and re-mineralization may be required prior to discharge to meet pH and acute toxicity requirements. Can be used as polishing step for metals and ammonia (as NH_4^+) removal following bulk removal steps. Can be employed for pre-concentration of effluent streams to reduce the total volume reporting to bulk removal technologies (e.g., air stripping or active aerobic biological oxidation and hydroxide or sulfide precipitation).

Technique [proposed location in model]	Effluent Concentration[61]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Nanofiltration [downstream of low pH media filter(s)]	Calculated from removal efficiencies in Table 8-33 and values in Table 6-77: Al <0.04 mg/L As <0.02 mg/L Cu <0.004 mg/L Fe <0.03 mg/L Pb <0.001 mg/L Ni <0.01 mg/L Zn <0.002 mg/L Se <0.002 mg/L	CAD$2,100,000/year (CAD$0.70/m^3) Operating cost is highly dependent on site-specific energy costs. Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional operating cost. Depending on approach, concentrate management could add significant additional operating cost.	CAD$22,800,000 (CAD$45,600/m^3/h) Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional capital cost. Depending on approach, concentrate management could add significant additional capital cost.	Little performance information is available concerning NF in full scale operation for the treatment of mining effluent; however, it is expected that NF would be similar to RO in performance, and that due to the mechanism of removal (size/charge exclusion), low concentrations could be reliably achieved. Increased contaminant loading would increase feed pump pressure required to maintain flux as well as increase the proportion of concentrate generated (i.e., reduce recovery).	Equalization of flow and contaminant loadings is assumed to occur at the upstream surge/equalization pond and upstream processes. Pre-filtration is included in the model flow sheet. However, depending on effluent chemistry, additional pre-treatment may be required. Concentrate management must be carefully considered based on site-specific factor. If concentrate is returned to water management features on site (e.g., TSF), there is a risk of certain solutes cycling up in site water. Concentrate management may require advanced technology (e.g., evaporator/crystallizer) which would add significant capital and operating costs. For example, assuming 70% recovery in the NF, an evaporator/crystallizer system for concentrate management would be associated with an incremental capital cost of CAD$50,000,000 and an incremental operating cost of CAD$4,600,000/year. NF permeate may be low in alkalinity. Re-mineralization may be required prior to discharge to meet acute toxicity requirements. Can be used as polishing step for metals removal following bulk removal steps. Can be employed for pre-concentration of effluent streams to reduce the total volume reporting to bulk removal technologies (e.g., hydroxide or sulfide precipitation).

10.4.2 Discussion of BATEA Selection

For the uranium subsector, Table 10-8 summarizes the technologies that have been selected as BATEA. A discussion of BATEA selection for each targeted parameter (e.g., ammonia, selenium, total suspended solids) or group of targeted parameters (e.g., metals), is provided in the following sections.

Table 10-8: Selected BATEA Technologies for the Uranium Subsector

Targeted Parameters	Selected BATEA	BATEA Technology
Bulk Metals Removal and Metals Polishing	• Model flow sheet for bulk metals removal (including aluminum, arsenic, copper, iron, lead, nickel, zinc).	Multi-Stage Reactor-Based Hydroxide Precipitation • Precipitation of dissolved metals as metal hydroxides and metal complexes, achieved by lime, coagulant (e.g., ferric sulfate) and acid addition within a reactor-based treatment process. Multiple stages with specific pH setpoints are utilized in the treatment process to target multiple parameters that each are optimally removed at specific and differing pH values.
Radium-226 Removal	• Model flow sheet for radium-226 removal.	Co-Precipitation • Co-precipitation of dissolved radium-226 with barium sulfate achieved by addition of lime, ferric sulfate and barium chloride at depressed pH within a reactor-based treatment process.
Total Suspended Solids Removal	• Model flow sheet for solids (TSS) removal.	Conventional Clarification and Media Filtration • Suspended solids settling achieved by allowing sufficient residence time for gravity to settle solids, promoted by the use of coagulant and flocculant, within a conventional clarifier (additional features within clarifier may be present to promote settling), followed by media filtration.
Ammonia Removal	• Active aerobic biological oxidation for total ammonia removal.	Active Aerobic Biological Oxidation • Ammonia is oxidized to nitrite, then to nitrate, by autotrophic bacteria that are cultivated by a suspended growth process in a moving bed biofilm reactor.

Targeted Parameters	Selected BATEA	BATEA Technology
Selenium Removal	• Model flow sheet for selenium removal.	Coagulation/Co-precipitation • Co-precipitation of selenium, achieved by the addition of coagulant at depressed pH within a reactor-based system.

10.4.2.1 *BATEA for Total Ammonia Removal*

Some uranium operations use ammonia during ore processing. Thus, the origins of ammonia in uranium effluent are both explosives used in mining operations and ammonia used in ore processing. Well established and executed explosives best management plans can reduce the amount of ammonia that reports to effluent as a result of explosives use. Moreover, conditions that are conducive to natural degradation of ammonia in pond(s) could be promoted to achieve further ammonia removal within the subsector model effluent management and treatment system (e.g., elevating pH, aerating, maximizing surface area to depth ratio). Active aerobic biological oxidation (via MBBR) was selected as BATEA to achieve additional removal of total ammonia from the model flow sheet.

Active aerobic biological oxidation (via MBBR) has been shown to reduce total ammonia concentrations to <2 mg-N/L. Given that the concentration of total ammonia achieved by the model effluent treatment system in the uranium subsector is 23 mg-N/L, this represents a 91% reduction in total ammonia concentrations. For operations that are achieving effluent concentrations closer to the average total ammonia concentration of the sector, the addition of this BATEA technology would not be warranted.

In contrast to the other ammonia removal technologies considered in Table 10-7 (air stripping, zeolite ion exchange, and reverse osmosis), active aerobic biological oxidation was found to offer the following benefits:

- Similar reduction in ammonia.
- Lower capital cost.
- Lower operating cost.
- More robust to variation in ammonia loading and effluent temperature and lower operating costs associated with heat exchange systems than air stripping, as the system can adjust to changes in ammonia loading and effluent temperature once biological populations are established.
- Lower demand for pre-treatment and post-treatment pH adjustment reagents than air stripping.

- No generation of spent regenerant (ion exchange) or concentrate (reverse osmosis) stream. Other technologies evaluated produce these residual streams, which require specific management, therefore increasing the overall capital and operating cost of these options. However, unlike air stripping which generates no residuals, active aerobic biological oxidation generates residual biomass.

Though active aerobic biological oxidation was selected as BATEA for the uranium subsector, it is noted that zeolite ion exchange may have potential as a viable ammonia removal technology in some applications. Zeolite compounds that have been thermally treated are reported to better reject competing ions (e.g., Ca^{2+}) in effluent. This type of zeolite is being tested for ammonia treatment at one uranium operation. At this operation, the zeolite is regenerated with sodium sulfate and the spent regenerant, ammonium sulfate, may be used as a milling/processing reagent. In this situation, the use of zeolite for ammonia removal offers synergies with other site processes that minimize the need for regenerant disposal and the associated costs. Should pilot testing indicate that the utilization of the thermally treated zeolite minimizes or eliminates the previously reported difficulties with zeolite (e.g., reduced capacity following subsequent loading and regeneration cycles, temperature sensitivity, sensitivity to TSS, etc., as described in Section 8.2.11.2), this technology may be well-suited in some site-specific contexts (e.g., where the regenerant management is simplified by spent regenerant re-use, etc.). However, at this time, the bulk of the operational evidence concerning zeolite ion exchange for ammonia removal does not support the selection of zeolite as BATEA.

Consideration was given to employing reverse osmosis or zeolite ion exchange to pre-concentrate the effluent (thus increasing the total ammonia concentration) prior to air stripping or aerobic biological oxidation. However, active aerobic biological oxidation is more dependent on ammonia loading than on hydraulic capacity and air stripping is dependent on both ammonia loading and hydraulic capacity. As pre-concentrating does not change ammonia loading, there is little economic advantage to pre-concentrating using reverse osmosis. Moreover, a recent Finnish study demonstrated that nitrification is less efficient for pre-concentrated mine effluent, due to combined inhibition by metals and possibly salts (69).

The addition of this BATEA to the model flow sheet is estimated to require a capital cost investment of roughly CAD\$31,800/m^3/h and would result in an operating cost increase of roughly CAD\$0.45/m^3. When compared to the model flow sheet capital and operating costs, this represents an upgrade capital cost investment of 8 to 24% of the model flow sheet capital cost and an operating cost increase of roughly 8 to 14%. This represents a moderate capital cost investment and a minor to moderate operating cost expenditure for the model operation. The capital cost for this BATEA exceeds the reported range of previous capital investments for upgrades and retrofits to uranium effluent management and treatment systems (CAD\$1,000,000 to CAD\$2,000,000).

These costs assume that equalization would be provided by the upstream surge/equalization pond and upstream processes, and that residual biomass could be accommodated by the tailings storage facility in the model flow sheet. These costs also assume that the existing lime reagent systems could be utilized for pH adjustment/alkalinity control in the MBBR system.

The capital and operating costs are directly influenced by the total ammonia removal efficiency required to meet a specified discharge limit. Lower limits increase capital and operating costs.

Metals and other toxic chemicals in uranium effluent can inhibit nitrification at relatively low concentrations and it is assumed that sufficient metals removal occurs in the existing hydroxide precipitation and co-precipitation processes.

Testwork is recommended to confirm effluent treatability and establish MBBR design parameters.

10.4.2.2 BATEA for Selenium Removal

The uranium subsector model was selected as BATEA for selenium removal, as augmentative selenium removal technologies (ZVI, FBR, ABMet®, reverse osmosis and nanofiltration) are considered to be technically limited uneconomic for application to the model. Since ZVI technology can achieve <0.010 mg/L Se, FBR technology can achieve approximately 0.005 to 0.020 mg/L Se, ABMet® technology can achieve <0.005 mg/L, and membrane separation technologies (reverse osmosis and nanofiltration) can achieve <0.002 mg/L, it is possible that only marginal removal could be achieved from the untreated effluent concentration of 0.02 mg/L total selenium for the uranium subsector, especially since the speciation of total selenium is not known. Should further removal of selenium beyond that achievable by the model be required (i.e., Se <0.020 mg/L), active anoxic/anaerobic biological reduction (e.g., FBR or ABMet®) is the least cost prohibitive of the technologies capable of achieving low selenium concentrations. In contrast to zero valent iron adsorption and membrane separation (considering capital and operating costs of brine management through the use of evaporative technologies), active anoxic/anaerobic biological reduction (e.g., FBR or ABMet®) was found to offer the following benefits:

- Greater or similar selenium removal and lower or similar achievable selenium concentration.
- Lower capital cost.
- Lower operating cost.
- Lower mass/volume of residuals generated requiring less handling and disposal costs.

Consideration was given to employing reverse osmosis to pre-concentrate the effluent (thus increasing the selenium concentration) prior to zero valent iron adsorption or active anoxic/anaerobic biological reduction. However, the capital and operating cost associated with using reverse osmosis for pre-concentration are not offset by the capital cost savings for zero valent iron technology. Moreover, the operating cost savings for zero valent iron technology are only marginally reduced through pre-concentration, as the major operating cost is zero valent iron reagent consumption which is proportional to selenium loading. Additionally, the capital and operating costs for active anoxic/anaerobic biological reduction are dependent on both selenium loading than on hydraulic capacity. As pre-concentrating changes hydraulic capacity, but does not change selenium loading, there is likely to be little economic advantage to pre-concentrating using reverse osmosis. One operation contested this assertion during the review period for the Draft MEND BATEA Study Report, stating that it is contrary to their findings from technology assessments. However, follow-up to seek clarification on this comment was unsuccessful.

The addition of this BAT to the model flow sheet is estimated to require a capital cost investment of roughly CAD$112,000/m^3/h[62] and would result in an operating cost increase of roughly CAD$1.59/m^3 [63]. When compared to the model flow sheet capital and operating costs, this represents an upgrade capital cost investment of roughly 28 to 86% of the model flow sheet capital cost and an operating cost increase of roughly 27 to 48%. This represents a moderate investment for the model operation. The capital cost for this BAT greatly exceeds the reported range of previous capital investments for upgrades and retrofits to uranium effluent management and treatment systems (CAD$1,000,000 to CAD$2,000,000). These two last statements stand true even when lower end cost estimates based on cost estimates provided by Envirogen are considered.

Moreover, due to the relatively recent adoption of this technology, little is known about the long term stability of residual biomass and the potential for selenium remobilization under various disposal conditions. If residuals are not stable, significant costs associated with biomass stabilization technology or re-treatment of residual leachate could be incurred.
BATEA for Metals Removal

The BATEA selected for removal of metals is the base case model flow sheet, which employs both pond-based settling at the surge/equalization pond and equipment-based hydroxide precipitation, co-precipitation and solid/liquid separation. Sulfide precipitation would achieve only marginal improvements in treated effluent quality for iron and nickel, and near negligible improvements for arsenic and zinc.

In Revision 0 of this report, sulfide precipitation with proprietary polymeric organosulfide polymers was recommended as BATEA for dissolved metals polishing. However, based on the Revision 1 analysis of concentrations achieved by the model effluent treatment system for the uranium subsector, augmentation of the model effluent treatment system with sulfide precipitation with proprietary polymeric organosulfide polymers would only permit an order of magnitude reduction in treated effluent concentration for nickel (0.20 mg/L to 0.05 mg/L) and marginal reductions in treated effluent concentrations for arsenic (0.06 mg/L to 0.05 mg/L), copper (0.04 mg/L to 0.03 mg/L), iron (0.5 mg/L to 0.3 mg/L), and zinc (0.04 mg/L to 0.02 mg/L). Treated effluent concentrations for lead and selenium would not be reduced by this technology. Moreoever, since the nickel concentration achieved by the model effluent treatment system for the uranium subsector (0.2 mg/L) is lower than the lowest proposed *MMER* nickel limit for the metal mining sector (0.250 mg/L), this technology would not be required for compliance with proposed *MMER* limits.

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[62] CAD$112,000/m^3/h represents total installed costs estimated by CH2MHill. In contrast, augmentative total installed costs for an FBR system integrated into existing systems, as estimated by Envirogen, could be as low as CAD$29,300/m^3/h to $47,700/m^3/h.

[63] CAD$1.59/m^3 treated represents operating costs estimated by CH2MHill. In constrast, augmentative operating costs for an FBR system integrated into existings systems, as estimated by Envirogen, could be as low as CAD$0.85/m^3 treated to CAD$1.16/m^3 treated.

10.4.2.3 BATEA for Solids Removal

Canadian uranium operations as a total cohort achieve TSS concentrations of less than 5 mg/L on average and 95% of all concentrations from model and model equivalent effluent treatment systems are less than 5 mg/L as well. This is consistent with expectations that well designed and operated pond-based and equipment-based solid/liquid separation systems should achieve TSS concentrations less than 15 mg/L and that filtration can achieve TSS concentrations less than 5 mg/L. The addition of clarification, enhanced coagulation and settling, or filtration solid/liquid separation technology would be redundant.

10.5 Diamond Sector

10.5.1 BATEA Selection Table

Table 10-9: Diamond Sector BATEA Selection Table

Technique [proposed location in model]	Effluent Concentration[64]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Model Effluent Management and Treatment System (Figure 6-59) [n/a]	From Table 6-90: Cl^- <1,240 mg/L P <0.1 mg/L TSS <7 mg/L NH_3/NH_4^+ <2.35 mg-N/L	No incremental increase CAD$352,000 to 3,500,000/year (CAD$0.02 to CAD$0.20/m^3)	No incremental increase CAD$55,700,000 to CAD$146,500,000 (CAD$18,600 to CAD$48,800/m^3/h)	With diligent operator attention, the system can achieve consistent effluent quality. Equalization provided by the surge/equalization pond should minimize the fluctuations in flow rate, solids and contaminant concentrations.	Equalization of flow and contaminant loadings is assumed to occur at the upstream equalization/settling pond(s). Residual total ammonia concentrations may interfere with metals precipitation reactions.
Air Stripping [after media filter(s)]	From Section 8.2.10: NH_3/NH_4^+ <2.35 mg-N/L (no change)	Technology not economically feasible at untreated effluent ammonia below 10 mg-N/L.			
Selective Ion Exchange – Zeolite [after media filter(s)]	From Table 8-24: NH_3/NH_4^+ <2.35 mg-N/L (no change)	Technology not technically feasible at untreated effluent ammonia below 9 mg-N/L.			
Active Aerobic Biological Oxidation [after media filter(s)]	From Table 8-26: NH_3/NH_4^+ <2 mg-N/L	Technology not economically feasible to reduce total ammonia from 2.8 mg-N/L.			

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[64] "(no change)" indicates that the concentration of the parameter has not changed from that achieved by the model effluent management and treatment system.

Technique [proposed location in model]	Effluent Concentration[64]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Reverse Osmosis [after media filter(s)]	Calculated from removal efficiencies in Table 8-31 and values in Table 6-90: Cl^- <25 mg/L P <0.02 mg/L NH_3/NH_4^+ <0.4 mg/L	CAD$13,900,000/year (CAD$0.80/m^3) Operating cost is highly dependent on site-specific energy costs. Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional operating cost. Depending on approach, concentrate management could add significant additional operating cost.	CAD$136,400,000 (CAD$45,470/m^3/h) Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional capital cost. Depending on approach, concentrate management could add significant additional capital cost.	Low concentrations can be reliably achieved by this technology due to the removal mechanism via size/charge exclusion. Increased contaminant loading would increase feed pump pressure required to maintain flux as well as increase the proportion of concentrate generated (i.e., reduce recovery).	Equalization of flow and contaminant loadings is assumed to occur at the upstream equalization/settling pond(s) and upstream processes. Pre-filtration is included in the model flow sheet. However, depending on effluent chemistry, additional pre-treatment may be required. Concentrate management must be carefully considered based on site-specific factor. If concentrate is returned to water management features on site (e.g., TSF), there is a risk of solutes (e.g., Cl^-, Na^+) cycling up in site water. Concentrate management may require advanced technology (e.g., evaporator/crystallizer) which would add significant capital and operating costs. For example, assuming 70% recovery in the RO, an evaporator/crystallizer system for concentrate management would be associated with an incremental capital cost of CAD$290,000,000 and an incremental operating cost of CAD$26,000,000/year. RO permeate is typically lower pH than feed pH and is low in alkalinity. pH adjustment and re-mineralization may be required prior to discharge to meet pH and acute toxicity requirements. Can be used as polishing step for metals and ammonia (as NH_4^+) removal following bulk removal steps. Can be employed for pre-concentration of effluent streams to reduce the total volume reporting to bulk removal technologies (e.g., air stripping or active aerobic biological oxidation and hydroxide or sulfide precipitation).

Technique [proposed location in model]	Effluent Concentration[64]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Nanofiltration [after media filter(s)]	No removal of chlorides or total ammonia is achieved via nanofiltration.	CAD$11,000,000/year (CAD$0.63/m^3) Operating cost is highly dependent on site-specific energy costs. Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional operating cost. Depending on approach, concentrate management could add significant additional operating cost.	CAD$136,400,000 (CAD$45,470/m^3/h) Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional capital cost. Depending on approach, concentrate management could add significant additional capital cost.	Little performance information is available concerning NF in full scale operation for the treatment of mining effluent; however, it is expected that NF would be similar to RO in performance, and that due to the mechanism of removal (size/charge exclusion), low concentrations could be reliably achieved. Increased contaminant loading would increase feed pump pressure required to maintain flux as well as increase the proportion of concentrate generated (i.e., reduce recovery).	Equalization of flow and contaminant loadings is assumed to occur at the upstream equalization/settling pond(s) and upstream processes. Pre-filtration is included in the model flow sheet. However, depending on effluent chemistry, additional pre-treatment may be required. Concentrate management must be carefully considered based on site-specific factor. If concentrate is returned to water management features on site (e.g., TSF), there is a risk of certain solutes cycling up in site water. Concentrate management may require advanced technology (e.g., evaporator/crystallizer) which would add significant capital and operating costs. For example, assuming 70% recovery in the NF, an evaporator/crystallizer system for concentrate management would be associated with an incremental capital cost of CAD$290,000,000 and an incremental operating cost of CAD$26,000,000/year. NF permeate may be low in alkalinity. Re-mineralization may be required prior to discharge to meet acute toxicity requirements. Can be used as polishing step for metals removal following bulk removal steps. Can be employed for pre-concentration of effluent streams to reduce the total volume reporting to bulk removal technologies (e.g., hydroxide or sulfide precipitation).

10.5.2 Discussion of BATEA Selection

For the diamond sector, Table 10-10 summarizes the technologies that have been selected as BATEA. A discussion of BATEA selection for each targeted parameter (e.g., ammonia, selenium, total suspended solids) or group of targeted parameters (e.g., metals), is provided in the following sections. The model flow sheet is consistent with the BAT and BACT findings of previous studies (10) (6).

Table 10-10: Selected BATEA Technologies for the Diamond Sector

Targeted Parameters	Selected BATEA	BATEA Technology
Bulk Metals Removal and Metals Polishing	• Model flow sheet for bulk metals removal (including aluminum, arsenic, copper, iron, lead, nickel, zinc, phosphorus).	Reactor-Based Settling with Provisional Hydroxide Reagent Addition • Removal of metals present as suspended solids by sedimentation, achieved by allowing sufficient residence time for gravity to settle solids, promoted by the use of flocculant and coagulant, within a pond system followed by a reactor-based system. • Precipitation of dissolved metals as metal hydroxides and metal complexes, achieved by addition of coagulant (e.g., ferric sulfate), with provisional hydroxide reagent dosing if necessary, within a reactor-based treatment process.
Chloride Removal	• Model flow sheet for chloride removal.	• The model flow sheet is not designed to specifically target chloride for removal, and no BATEA was selected for removal of chloride, as all applicable technologies (i.e., reverse osmosis, ion exchange) are considered to be uneconomic for application to the diamond sector model. Chloride is believed to be a site-specific issue.

Targeted Parameters	Selected BATEA	BATEA Technology
Total Suspended Solids Removal	• Model flow sheet for solids (TSS) removal.	Conventional Clarification and Media Filtration • Suspended solids settling achieved by allowing sufficient residence time for gravity to settle solids, promoted by the use of coagulant and flocculant, within a conventional clarifier (additional features within clarifier may be present to promote settling), followed by media filtration.
Ammonia Removal	• Model flow sheet for total ammonia removal.	Natural Degradation of Ammonia and Explosives Best Management Plan • An explosives best management plan is followed to minimize the release of ammonia into site water. • Natural degradation of ammonia occurring by volatilization of un-ionized ammonia gas (NH_3) and biological oxidation, achieved by allowing ample residence time in pond systems, especially during periods where ambient climate conditions promote these processes. These processes are influenced by pH, temperature, and dissolved oxygen concentration.

10.5.2.1 BATEA for Total Ammonia Removal

The BATEA selected for total ammonia removal is the base case model flow sheet which is assumed to incorporate explosives best management practices and passive natural degradation. Diamond operations do not utilize ammonia for ore processing. Thus, the origin of ammonia in diamond effluent is explosives. Well established and executed explosives best management plans can minimize the amount of ammonia that reports to effluent. Moreover, conditions that are conducive to natural degradation of ammonia in pond(s) could be promoted to achieve further ammonia removal within the sector model effluent management and treatment system (e.g., elevating pH, aerating, maximizing surface area to depth ratio). Therefore, explosives best management plans and natural degradation of ammonia was selected as BATEA for ammonia removal. This is consistent with the findings of a previous BAT study (10). Moreover, one operation has investigated a wide range of technologies for the removal of ammonia from mine effluent and combined effluent and found that even the most feasible treatment approach to be environmentally and financially prohibitive.

The concentration of total ammonia achieved by the model effluent treatment system in the diamond sector is 2.35 mg-N/L (see Table 6-90). At such a low feed concentration, air stripping and zeolite ion exchange for ammonia removal would not be technically feasible, and active aerobic biological oxidation would not be very effective in lowering the total ammonia concentration much below the untreated effluent concentration.

Consideration was given to employing reverse osmosis or zeolite ion exchange to pre-concentrate the effluent (thus increasing the total ammonia concentration) prior to air stripping or aerobic biological oxidation. However, active aerobic biological oxidation is more dependent on ammonia loading than on hydraulic capacity and air stripping is dependent on both ammonia loading and hydraulic capacity. As pre-concentrating does not change ammonia loading, there is little economic advantage to pre-concentrating using reverse osmosis. Moreover, a recent Finnish study demonstrated that nitrification is less efficient for pre-concentrated mine effluent, due to combined inhibition by metals and possibly salts (69).

No technology-based BATEA was selected for additional ammonia removal as all technologies are considered to be technically infeasible or uneconomic for application to the diamond sector model. This finding is supported by a detailed investigation of ammonia removal technologies by one diamond operation (see Section 6.5.2.2).

10.5.2.2 BATEA for Chloride Removal

No BATEA was selected for removal of chloride, as all applicable technologies (i.e., reverse osmosis, ion exchange) are considered to be uneconomic for application to the diamond sector model. In any case, chloride is believed to be a site-specific issue due to interception of a saline groundwater feature(s) (refer to Section 6.5.1). This finding is supported by an investigation of chloride removal technologies by one diamond operation (see Section 6.5.3).

10.5.2.3 BATEA for Phosphorus Removal

The BATEA selected for phosphorus removal is the base case model flow sheet, as the concentration achieved by the model effluent treatment system in the diamond sector is very low (<0.1 mg/L, Table 6-90) and technologies that could increase phosphorus removal efficiency (e.g., reverse osmosis, nanofiltration) are considered to be uneconomic for application to the diamond sector model.

10.5.2.4 BATEA for Bulk Metals Removal

The BATEA selected for bulk removal of metals is the base case model flow sheet, which employs both pond-based settling at the equalization/settling pond(s) and equipment-based co-precipitation/coagulation and solid/liquid separation.

No other metals removal technologies (including selenium removal technologies) were evaluated as metals are not proposed *MMER* parameters for the diamond sector.

10.5.2.5 BATEA for Solids Removal

The TSS concentration achieved by the model effluent treatment system in the diamond sector is <5 mg/L. This is consistent with expectations that well designed and operated pond-based and equipment-based solid/liquid separation systems should achieve TSS concentrations less than 15 mg/L and that filtration can achieve TSS less than 5 mg/L. The addition of clarification, enhanced coagulation and settling, or filtration solid/liquid separation technology would be redundant.

10.6 Coal Sector

10.6.1 BATEA Selection Table

Table 10-11: Coal Sector BATEA Selection Table

Technique [proposed location in model]	Effluent Concentration[65]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
Model Effluent Management and Treatment System (Figure 6-71) [n/a]	From Table 6-98: Al <0.90 mg/L As <0.0013 mg/L Fe <0.82 mg/L Mn <0.13 mg/L Se <0.38 mg/L TSS <77 mg/L NH_3/NH_4^+ <0.37 mg-N/L	No incremental increase <CAD$100,000/year (unknown CAD$/m^3)	No incremental increase <CAD$5,000,000 (unknown CAD$/m^3/h)	With sufficient footprint, capacity and diligent operator attention, pond-based systems can achieve consistent effluent quality; however, this system is very sensitive to fluctuations in flow rate, solids loading, and ambient conditions, and demands significant labour attention for reliable operation.	Susceptible to upsets that can re-suspend precipitates and cause downstream compliance issues.
Hydroxide Precipitation [upstream of settling pond(s) if upstream equalization is available; upstream of polishing pond(s) if no upstream equalization is available]	From Table 8-2, no change from base case, except for: Al <0.50 mg/L Fe <0.10 mg/L	CAD$400,000/year (CAD$0.05/m^3)	CAD$2,600,000 (CAD$870/m^3/h)	Equalization of flow and contaminant loadings is required. Reliable and robust provided that ponds are adequately designed. However, increases in untreated effluent metals concentrations, TSS, and hydraulic loading may cause variations in effluent quality.	Equalization of flow and contaminant loadings is assumed to occur upstream. It is assumed that the incremental generation of hydroxide sludge can be accommodated by the existing settling pond(s) / polishing pond(s).
Sulfide Precipitation [n/a]	From Table 8-5, no change from base case, except for: Fe^{2+} <0.30 mg/L Mn^{2+} <0.05 mg/L Se <0.05 mg/L	Technology not economically feasible for the removal of iron, manganese, and/or selenium.			
Sulfide Precipitation with Proprietary Polymeric Organosulfide Chemicals [downstream of settling pond(s)]	From Table 8-6, no change from base case, except for: Fe^{2+} <0.30 mg/L Mn^{2+} <0.05 mg/L Se <0.05 mg/L	CAD$1,800,000/year (CAD$0.21/m^3) There is a potential for reduction of operating costs due to reductions in flocculant consumption, as the proprietary reagents are polymeric in nature and may offset flocculant demand. However, no discounts have been applied to this operating cost.	CAD$1,100,000 (CAD$370/m^3/h) There is a potential to reduce capital costs by using alternative technologies to agitated reactor tanks for mixing proprietary reagent with effluent. However, this has not been demonstrated.	Equalization of flow and contaminant loadings is required. Proprietary reagent dosage can be modulated to accommodate changes in effluent quality. However, technology is not capable of achieving consistent effluent concentration at hydraulic loadings and solids loadings/generation outside of design window. Pond-based solid/liquid separation is susceptible to upsets that can re-suspend precipitates and cause downstream compliance issues.	Equalization of flow and contaminant loadings is assumed to occur upstream. It is assumed that the incremental generation of sulfide sludge can be accommodated by the existing settling pond(s) and retained under reducing conditions. Can improve metals removal efficiencies even with high complexing/chelating agent concentrations with low capital cost investment.

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[65] "(no change)" indicates that the concentration of the parameter has not changed from that achieved by the model effluent management and treatment system.

Technique [proposed location in model]	Effluent Concentration[65]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
					High operating cost due to high cost consumables. The chemicals may be acutely lethal to rainbow trout and *Daphnia magna* at certain residual chemical concentrations in effluent. Bench and/or pilot scale testing is advised to verify that treated effluent complies with toxicity requirements. Treated effluent should be discharged rather than recirculated. Due to the relatively recent adoption of these reagents and the proprietary nature of their formulations, little is known about the long term stability of residuals and the potential for acid generation and metals remobilization. If residuals are not kept stable, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.
Ferric Iron Co-Precipitation [upstream of settling pond(s) if upstream equalization is available; upstream of polishing pond(s) if no upstream equalization is available]	From Table 8-10, no change from base case, except for: Se <0.090 mg/L	CAD$24,300,00/year to CAD$30,900,000/year (CAD$2.78/m^3 to CAD$3.53/m^3)	CAD$58,600,000 to CAD$72,700,000 (CAD$19,540/m^3/h to CAD$24,240/m^3/h)	Equalization of flow and contaminant loadings is required.	Equalization of flow and contaminant loadings is assumed to occur upstream. It is assumed that the incremental generation of sludge can be accommodated by the existing settling pond(s). The United States Environmental Protection Agency (USEPA) does not consider the technology to be economically feasible to use at a large scale. The speciation of total selenium for the coal sector is unknown, and therefore, cost impacts of speciation cannot be determined. Residuals may be hazardous waste. Little is known about the long term stability of residuals and the potential for selenium remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.
Solid/Liquid Separation – Clarification	From Section 8.2.7.2: TSS <15 mg/L	CAD$880,000/year (CAD$0.10/m^3)	CAD$21,500,000 (CAD$7,170/m^3/h)	Robust and reliable process that is well established in the mining industry. Significant variations in flow rate	Upstream equalization of flow and contaminant loadings is assumed.

Technique [proposed location in model]	Effluent Concentration[65]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
[upstream of settling pond(s)]		There is a potential for reduction of operating costs due to reductions in flocculant consumption, as the controlled solid/liquid separation process may offset flocculant demand. However, no discounts have been applied to this operating cost.		and TSS loading could impact operation and the quality of the effluent; equalization of flow and contaminant loadings is required.	It is assumed that the sludge can be accommodated by the existing settling pond(s). Smaller footprint and higher degree of control compared to pond-based solid/liquid separation. Complements other removal technologies, (e.g., can be applied downstream of hydroxide and sulfide precipitation to remove metal precipitates).
Enhanced Coagulation and Setting [upstream of settling pond(s)]	From Table 8-17: TSS <10 mg/L	ACTIFLO®: CAD$880,000/year (CAD$0.10/m^3) There is a potential for reduction of operating costs due to reductions in reagent consumption, due to the enhanced coagulation provided by ballast or sludge recycle. However, no discounts have been applied to the operating cost presented here.	ACTIFLO®: CAD$10,700,000 (CAD$3,570/m^3/h)	Enhanced coagulation and settling is a proprietary technique that is claimed by vendors to be a robust and process that can reliably achieve low TSS concentrations, when operating within the design window for hydraulic loadings and solids loadings/generation.	Upstream equalization of flow and contaminant loadings is assumed. It is assumed that the sludge can be accommodated by the existing settling pond(s). Smaller footprint compared to pond-based solid/liquid separation or clarification. Complements other removal technologies, (e.g., can be applied downstream of hydroxide and sulfide precipitation to remove metal precipitates). Less established technique for the Canadian mining industry than other solid/liquid separation technologies.
Solid/Liquid Separation – Filtration [upstream of settling pond(s)]	From Section 8.2.7.4: TSS <5 mg/L	CAD$1,300,000/year (CAD$0.15/m^3) Includes operating costs for clarification pre-treatment. There is a potential for reduction of operating costs due to reductions in flocculant consumption, as the controlled solid/liquid separation process may offset flocculant demand. However, no discounts have been applied to this operating cost.	CAD$35,600,000 (CAD$11,870/m^3/h) Includes capital costs for clarification pre-treatment.	Robust and reliable process that is well established in the mining industry. Significant variations in flow rate and TSS loading could impact operation and the quality of the effluent; equalization of flow and contaminant loadings is required.	Upstream equalization of flow and contaminant loadings is assumed. It is assumed that the incremental generation of solids in backwash can be accommodated by the existing settling pond(s). Complements other removal technologies, (e.g., can be applied downstream of hydroxide and sulfide precipitation to remove metal precipitates and can provide filtration prior to polishing steps such as ion exchange or RO/NF). Not necessarily required to meet (current) discharge TSS limits; however can contribute to the removal of other contaminants that present as suspended solids

Technique [proposed location in model]	Effluent Concentration[65]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
					(e.g., metals). The TSS value after pond-based solid/liquid separation is expected to be <77 mg/L, therefore bulk removal of TSS would be required prior to media filtration. A clarifier system would thus be installed in addition to the media filtration system for bulk TSS removal.
Selective Ion Exchange – Metals Polishing [upstream of settling pond(s)]	From Table 8-23: Al <0.05 mg/L As <0.0013 mg/L (no change) Fe <0.2 mg/L Mn <0.13 mg/L (no change) Se <0.01 mg/L	CAD$7,400,000/year (CAD$0.85/m^3) Includes operating costs for clarification and filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment could add additional operating cost. Depending on approach, regenerant management could add significant additional operating cost.	CAD$76,400,000 (CAD$25,470/m^3/h) Includes capital costs for clarification and filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment could add additional capital cost. Depending on approach, regenerant management could add significant additional capital cost.	Equalization of flow and contaminant loadings required to achieve consistent effluent quality. Increased loading requires more frequent regeneration and increases residual production.	Upstream equalization of flow and contaminant loadings is assumed. At minimum, pre-filtration (and thus pre-clarification) is required. However, depending on effluent chemistry, additional pre-treatment may be required. Regenerant management must be carefully considered based on site-specific factors and could add significant operating and capital costs. Can be employed for pre-concentration of effluent streams to reduce the total volume reporting to bulk removal technologies (e.g., hydroxide or sulfide precipitation).
Adsoprtion – Zero Valent Iron [downstream of polishing pond(s)]	From Table 8-25: Se <0.010 mg/L	CAD$20,300,000/year to CAD$27,900,000/year (CAD$2.32 to CAD$3.18/m^3)	CAD$81,400,000 to CAD$191,200,000 (CAD$27,100/m^3/h to CAD$63,730/m^3/h)	Equalization of flow and contaminant loadings is required. Reagent dosages can be modulated to accommodate changes in effluent quality. However, technology is not capable of achieving consistent effluent concentration at hydraulic loadings and contaminant loadings outside of equipment design window.	Equalization of flow and contaminant loadings is assumed to occur at the upstream settling and polishing pond(s). Large quantities of hydroxide sludge are produced with this technology. It is assumed that the sludge can be accommodated by the existing TSF and retained under reducing conditions. Most full-scale installations of this technology treat flow rates two orders of magnitude lower than the coal sector design flow rate. The applicability of this technology may be limited, accordingly. Few full-scale installations have been in operation for long enough to determine long term feasibility. The speciation of total selenium for the coal sector is unknown, and therefore, cost impacts of speciation

Technique [proposed location in model]	Effluent Concentration[65]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
					cannot be determined. Due to the relatively recent adoption of this technology, little is known about the long term stability of residuals and the potential for selenium remobilization. If residuals are not kept stable through prudent disposal techniques, significant costs associated with residuals stabilization technology or re-treatment of residual leachate could be incurred.
Active Anoxic/Anaerobic Biological Reduction [downstream of polishing pond(s)]	FBR from Table 8-27: Se ~ 0.005-0.020 mg/L ABMet® from Table 8-29: Se <0.005 mg/L	FBR: CAD$14,000,000/year CAD$1.59/m^3 treated ABMet®: CAD$11,200,000/year CAD$1.28/m^3 treated Operating cost for an FBR system could be as low as CAD$7,400,000/year to CAD$10,200,000/year if Envirogen cost estimates are used. However, as the coal sector model effluent treatment process is fairly rudimentary and since the 95th percentile selenium concentration for the coal sector model is 0.38 mg/L (<0.050 mg/L), the addition of an FBR system would require substantial wrap around, advanced downstream solid/liquid separation equipment, and independent sludge handling, thickening, and disposal systems. Therefore, the operating cost may be closer to the higher end of the range presented.	FBR: CAD$164,000,000 (CAD$54,670/m^3/h) ABMet®: CAD$218,700,000 (CAD$72,900/m^3/h) Total installed capital cost for an FBR system could be as low as CAD$43,000,000 to CAD$70,000,000 if Envirogen cost estimates are used. Total installed capital costs for ABMet® system could be as low as CAD$55,400,000 to CAD$82,100,000 if GE estimates are used. However, as the coal sector model effluent treatment process is fairly rudimentary and since the 95th percentile selenium concentration for the coal sector model is 0.38 mg/L (>0.050 mg/L), the addition of an FBR or ABMet® system would require substantial wrap around, advanced downstream solid/liquid separation equipment, and independent sludge handling, thickening, and disposal systems. Therefore, the costs may be closer to the higher end of the range presented.	Equalization of flow and contaminant loadings is required as systems cannot accommodate loadings of selenium and other oxyanions (nitrate) outside of design window, as well as hydraulic loadings outside of design window.	Equalization of flow and contaminant loadings is assumed to occur at the upstream settling and polishing pond(s). High feed nitrate concentration increases operating and capital costs and residuals production. Residual biomass typically requires thickening and dewatering prior to disposal. It is assumed that residuals can be accommodated at the existing TSF and retained under reducing conditions. Few full-scale FBR installations have been in operation for long enough to determine long term feasibility. Active anoxic/anaerobic biological reduction (FBR/ABMet®) applications with untreated effluent selenium concentrations exceeding 0.050 mg/L, such as for the coal sector model with a concentration achieved of 0.38 mg/L total selenium, may require more advanced solid/liquid separation technology such as filtration or membrane filtration (particularly microfiltration and ultrafiltration) to achieve treated effluent selenium concentrations below 0.010 mg/L (26), as colloidal forms and fine particles of reduced selenium that are not filterable to 0.1 to 0.4 µm are found in effluents with as little as 0.100 mg/L selenium (73). Such advanced downstream solid/liquid separation technology could add considerably to overall implementation costs. As such, the coal sector capital and operating costs for FBR and ABMet® are likely to be on the higher end of

Technique [proposed location in model]	Effluent Concentration[65]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
					the ranges presented above. The speciation of total selenium for the coal sector is unknown, and therefore, cost impacts of speciation cannot be determined. Due to the relatively recent adoption of this technology, little is known about the long term stability of residual biomass and the potential for selenium remobilization under various disposal conditions. If residuals are not stable, significant costs associated with biomass stabilization technology or re-treatment of residual leachate could be incurred.
Reverse Osmosis [downstream of polishing pond(s)]	Calculated from removal efficiencies in Table 8-31 and values in Table 6-98: Al <0.02 mg/L NH_3/NH_4^+ <0.05 mg/L As <0.001 mg/L Fe <0.04 mg/L Mn <0.007 mg/L Ni <0.001 mg/L Se <0.02 mg/L Zn <0.001 mg/L	CAD$8,400,000/year (CAD$0.96/m^3) Operating cost is highly dependent on site-specific energy costs. Includes operating costs for clarification and media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional operating cost. Depending on approach, concentrate management could add significant additional operating cost.	CAD$177,300,000 (CAD$59,100/m^3/h) Includes capital costs for clarification and media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional capital cost. Depending on approach, concentrate management could add significant additional capital cost.	Low concentrations can be reliably achieved by this technology due to the removal mechanism via size/charge exclusion. Increased contaminant loading would increase feed pump pressure required to maintain flux as well as increase the proportion of concentrate generated (i.e., reduce recovery).	Equalization of flow and contaminant loadings is assumed to occur at the upstream settling and polishing pond(s). At minimum, pre-filtration is required. The TSS value after pond-based solid/liquid separation is expected to be <77 mg/L, therefore bulk removal of TSS would be required prior to media filtration. A clarifier system would thus be installed in addition to the media filtration system for bulk TSS removal. Concentrate management must be carefully considered based on site-specific factor. If concentrate is returned to water management features on site (e.g., TSF), there is a risk of solutes (e.g., Cl^-, Na^+) cycling up in site water. Concentrate management may require advanced technology (e.g., evaporator/crystallizer) which would add significant capital and operating costs. For example, assuming 70% recovery in the RO, an evaporator/crystallizer system for concentrate management would be associated with an incremental capital cost of CAD$287,100,000 and an incremental operating cost of CAD$13,100,000/year. RO permeate is typically lower pH than feed pH and is low in alkalinity. pH adjustment and re-mineralization may be required prior to discharge to meet pH and

Technique [proposed location in model]	Effluent Concentration[65]	Incremental Operating Cost ($/m^3)	Incremental Capital Cost ($/m^3/h)	Process Reliability, Robustness	Risks and Opportunities
					acute toxicity requirements. Can be used as polishing step for metals removal following bulk removal steps. Can be employed for pre-concentration of effluent streams to reduce the total volume reporting to bulk removal technologies (e.g., hydroxide or sulfide precipitation).
Nanofiltration [downstream of polishing pond(s)]	Calculated from removal efficiencies in Table 8-33 and values in Table 6-98: Al <0.05 mg/L As <0.001 mg/L Fe <0.04 mg/L Mn <0.007 mg/L Se <0.04 mg/L Pb <0.002 mg/L Mn <0.05 mg/L Ni <0.008 mg/L Zn <0.005 mg/L	CAD$6,900,000/year (CAD$0.79/m^3) Operating cost is highly dependent on site-specific energy costs. Includes operating costs for clarification and media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional operating cost. Depending on approach, concentrate management could add significant additional operating cost.	CAD$177,300,000 (CAD$59,100/m^3/h) Includes capital costs for clarification and media filtration pre-treatment. Depending on effluent chemistry, additional pre-treatment, post-treatment, and membrane cleaning requirements could add additional capital cost. Depending on approach, concentrate management could add significant additional capital cost.	Little performance information is available concerning NF in full scale operation for the treatment of mining effluent; however, it is expected that NF would be similar to RO in performance, and that due to the mechanism of removal (size/charge exclusion), low concentrations could be reliably achieved. Increased contaminant loading would increase feed pump pressure required to maintain flux as well as increase the proportion of concentrate generated (i.e., reduce recovery).	Equalization of flow and contaminant loadings is assumed to occur at the upstream settling and polishing pond(s). At minimum, pre-filtration is required. The TSS value after pond-based solid/liquid separation is expected to be <77 mg/L, therefore bulk removal of TSS would be required prior to media filtration. A clarifier system would thus be installed in addition to the media filtration system for bulk TSS removal. Concentrate management must be carefully considered based on site-specific factor. If concentrate is returned to water management features on site (e.g., TSF), there is a risk of certain solutes cycling up in site water. Concentrate management may require advanced technology (e.g., evaporator/crystallizer) which would add significant capital and operating costs. For example, assuming 70% recovery in the RO, an evaporator/crystallizer system for concentrate management would be associated with an incremental capital cost of CAD$287,100,000 and an incremental operating cost of CAD$13,100,000/year. NF permeate may be low in alkalinity. Re-mineralization may be required prior to discharge to meet acute toxicity requirements. Can be used as polishing step for metals removal following bulk removal steps. Can be employed for pre-concentration of effluent streams to reduce the total volume reporting to bulk removal technologies (e.g., hydroxide or sulfide precipitation).

10.6.2 Discussion of BATEA Selection

For the coal sector, Table 10-12 summarizes the technologies that have been selected as BATEA. A discussion of BATEA selection for each targeted parameter (e.g., ammonia, selenium, total suspended solids) or group of targeted parameters (e.g., metals), is provided in the following sections.

Table 10-12: Selected BATEA Technologies for the Coal Subsector

Targeted Parameters	Selected BATEA	BATEA Technology
Bulk Metals Removal	• Model flow sheet for bulk metals removal (including aluminum, arsenic, copper, iron, lead, nickel, zinc).	Pond-Based Settling • Removal of metals present as suspended solids by sedimentation, achieved by allowing sufficient residence time for gravity to settle solids, promoted by the use of flocculant, within a pond system.
Total Suspended Solids Removal	• Model flow sheet for solids (TSS) removal.	Pond-Based Settling • Suspended solids sedimentation, achieved by allowing sufficient residence time for gravity to settle solids, promoted by the use of flocculant, within a pond system.
Ammonia Removal	• Model flow sheet for total ammonia removal.	Natural Degradation of Ammonia and Explosives Best Management Plan • An explosives best management plan is followed to minimize the release of ammonia into site water. • Natural degradation of ammonia occurring by volatilization of un-ionized ammonia gas (NH_3) and biological oxidation, achieved by allowing ample residence time in pond systems, especially during periods where ambient climate conditions promote these processes. These processes are influenced by pH, temperature, and dissolved oxygen concentration.
Selenium Removal	• Model flow sheet for selenium removal.	• The model flow sheet is not designed to specifically target selenium. Augmentative selenium removal technologies are considered to be uneconomic for application to the model.

10.6.2.1 *BATEA for Metals Removal*

Hydroxide precipitation, sulfide precipitation, sulfide precipitation with proprietary polymeric organosulfide chemicals, selective ion exchange, reverse osmosis, and nanofiltration were all found to be uneconomic for the coal sector, as they have high capital and/or operating costs and do not achieve significant reduction in most of the metals of concern. The incremental costs for these technologies could not be justified by improvements in treated effluent quality.

10.6.2.2 *BATEA for Selenium Removal*

The coal sector model was selected as BATEA for selenium removal, as augmentative selenium removal technologies (ZVI, FBR, ABMet®, reverse osmosis and nanofiltration) are considered to be uneconomic for application to the model. Should further removal of selenium beyond that achievable by the model be required (i.e., Se <0.38 mg/L), active anoxic/anaerobic biological reduction (e.g., FBR or ABMet®) is the least cost prohibitive of the technologies capable of achieving low selenium concentrations. In contrast to ferric iron co-precipitation, zero valent iron adsorption, and membrane separation (considering capital and operating costs of brine management through the use of evaporative technologies), active anoxic/anaerobic biological reduction (e.g., FBR or ABMet®) was found to offer the following benefits:

- Greater or equivalent selenium removal and lower or equivalent achievable selenium concentration.
- Lower capital cost (with the exception of ferric iron co-precipitation)[66].
- Lower operating cost.
- Lower mass/volume of residuals generated requiring less handling and disposal costs.

Consideration was given to employing reverse osmosis to pre-concentrate the effluent (thus increasing the selenium concentration) prior to zero valent iron adsorption or active anoxic/anaerobic biological reduction. However, the capital and operating cost associated with using reverse osmosis for pre-concentration are not offset by the capital cost savings for zero valent iron technology. Moreover, the operating cost savings for zero valent iron technology are only marginally reduced through pre-concentration, as the major operating cost is zero valent iron reagent consumption which is proportional to selenium loading. Additionally, the capital and operating costs for active anoxic/anaerobic biological reduction are dependent on both selenium loading than on hydraulic capacity. As pre-concentrating changes hydraulic capacity, but does not change selenium loading, there is likely to be little economic advantage to pre-concentrating using reverse osmosis. One operation contested this assertion during the review period for the Draft MEND BATEA Study Report, stating that it is contrary to their findings from technology assessments. However, follow-up to seek clarification on this comment was unsuccessful.

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[66] Although ferric iron co-precipitation has significantly lower capital cost estimatesthan active anaoxic/anaerobic biological reduction, it can only achieve total selenium <0.090 mg/L, whereas active anoxic/anaerobic biological reduction can achieve total selenium <0.005 mg/L.

As an example, the addition of FBR BAT to the model flow sheet is estimated to require a capital cost investment of roughly CAD$164,000,000 and would result in an operating cost increase of roughly CAD$14,000,000/year.[67] When compared to the model flow sheet capital and operating costs (although it is acknowledged that these costs are not supported by a wealth of data), this represents an upgrade capital cost investment of roughly 3,280% of the model flow sheet capital cost and an operating cost increase of roughly 14,000%. This represents a major investment for the model operation. The capital cost for this BAT greatly exceeds the reported previous capital investments for an upgrade/retrofit to one coal sector effluent management and treatment systems (less than CAD$1,000,000). These two last statements stand true even when lower end cost estimates based on cost estimates provided by Envirogen are considered. One operation reported the use of a passive bioreactor system to treat a seep for selenium; however, insufficient information was provided to draw any conclusions for this study.

Moreover, due to the relatively recent adoption of this technology, little is known about the long term stability of residual biomass and the potential for selenium remobilization under various disposal conditions. If residuals are not stable, significant costs associated with biomass stabilization technology or re-treatment of residual leachate could be incurred.

10.6.2.3 *BATEA for Total Ammonia Removal*

The BATEA selected for total ammonia removal is the base case model flow sheet which is assumed to incorporate explosives best management practices and passive natural degradation of ammonia. Since coal operations do not use cyanide or ammonia in coal processing, the origin of ammonia in coal effluent is explosives used in mining operations. Many operations do not use explosives as coal can be found in softer rock that may not require blasting for extraction. The concentration of total ammonia achieved by the model effluent treatment system in the coal sector is very low at <0.37 mg-N/L (Table 6-98).

10.6.2.4 *BATEA for Solids Removal*

According to the analysis of final discharge effluent quality at coal operations provided by the Coal Association of Canada, Canadian coal operations achieve TSS concentrations of less than 62 mg/L on average and 95% of all reported concentrations are less than 77 mg/L. This is inconsistent with the expectation that coal operations achieve compliance with existing permits, specifically, the typical permitted maximum mean concentration for all Canadian coal operations of 50 mg/L TSS and the typical permitted maximum daily limit of 350 mg/L TSS (with the exception of some coal mines in British Columbia and in Nova Scotia which have much lower maximum mean and maximum daily limits in existing permits) (13). As such, it is expected that, at minimum, Canadian coal operations achieve compliance with the maximum mean concentration limit of 50 mg/L.

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[67] High end cost estimates based on CH2MHill cost estimates are utilized here since the rudimentary coal sector model with a relatively high 95th percentile selenium concentration would require substantial wrap around, advanced downstream solid/liquid separation equipment, and independent sludge handling, thickening, and disposal systems.

The addition of clarification, enhanced coagulation and settling, and/or filtration solid/liquid separation technologies could achieve lower TSS concentrations and more reliable TSS removal than demonstrated by the sector. However, improvements in existing pond infrastructure and operation could also improve TSS removal. For example, sediment/silt curtains and dykes to prevent short circuiting could be used to improve existing infrastructure. Better control of flocculant dosing regimes, addition of coagulant dosing regimes, and regular dredging of pond(s) are just a few operational practices to could improve TSS removal. As such, there is no justification for the additional capital costs and operating costs for the implementation of equipment-based solid/liquid separation technologies.

However, for greenfield applications, solid/liquid separation by clarification or enhanced coagulation and settling would be recommended as BATEA as opposed to pond-based solid/liquid separation for the following reasons:

- Equipment-based solid/liquid separation is more easily monitored and controlled than pond-based solid/liquid separation in terms of flow rate, reagent dosing and other process conditions. Equipment-based systems are not as susceptible to upsets due to climatic conditions such as heavy rainfall events, high winds and wave action, and pond turnovers due to temperature inversions that can re-suspend precipitates and cause downstream compliance issues.
- Reducing pond footprints can reduce the net precipitation inputs into water balances, thereby reducing the volumes of water/effluent potentially requiring management and treatment and reducing operating and capital costs.
- Equipment-based solids removal technologies have improved sludge management and handling capabilities over pond systems. Dredging of ponds is often not done frequently enough to prevent solids carryover and downstream non-compliance due to the logistical challenges or significant costs. Equipment-based solids removal technologies are more efficient at collecting and removing sludge from the system at regular intervals.
- Equipment-based solid/liquid separation should be integrated with reactor-based metals precipitation, coagulation, and flocculation technology. This will improve reagent/reaction efficiency, reducing reagent costs and minimizing sludge production. These systems can also be configured with underflow recycle to further improve reagent/reaction efficiency, if applicable.
- Equipment-based solid/liquid separation should be integrated with upstream/downstream pond systems for equalization and passive natural degradation of ammonia.

11. Conclusions and Recommendations

For each (sub)sector, utilizing best professional judgement to assess the summarized information, the best available technology/ies economically achievable (BATEA) for the removal of current and proposed *MMER* parameters has been selected in comparison to the model flow sheet ("base case").

It is important to note that BATEA selection is not universal for each (sub)sector due to site-specific considerations. The BATEA selection is bounded by strict criteria for BAT (e.g., technology/technique has been demonstrated at full scale on mining effluent and under representative climate conditions) and in the context of a model non-greenfield operation with an existing effluent management and treatment system for given nominal and design treatment capacities.

Selected BATEA would be upgrades or retrofits to existing equipment for which capital has already been expended and therefore, associated with sustaining costs rather than initial capital costs. This affects the consideration of what is economically achievable. BATEA selected for greenfield operations may be different than that selected for existing model operations. Selection of BATEA for greenfield operations was not the focus of this study; however, some suggestions for greenfield operations are made. Technologies screened out as BAT and not selected as BATEA in this report could, in fact, prove to be BATEA for some site-specific applications.

11.1 Metals Sector: Base Metal

The model effluent treatment system is illustrated in Figure 6-16. In this model, effluent is treated via hydroxide precipitation and bulk TSS removal via pond-based settling. The lime addition/holding/settling pond(s) also allows time for passive natural degradation of ammonia. The effluent is dosed with coagulant and flocculant before precipitates and TSS are then allowed to settle in the settling pond. Settling pond decant is pH adjusted with carbon dioxide to meet *MMER* pH limits and/or un-ionized ammonia/toxicity requirements prior to discharge to the environment.

For the base metal subsector, BATEA has been defined as:

- Sulfide precipitation with proprietary polymeric organosulfide chemicals for dissolved metals polishing (including copper, iron, nickel, and zinc).
- Model flow sheet for total ammonia, bulk metals (including aluminum, arsenic, copper, iron, lead, nickel, radium-226, selenium, zinc), and solids (TSS) removal.

11.2 Metals Sector: Precious Metal

The typical model effluent treatment system for precious metal operations carried forward in this study is INCO SO_2/air cyanide destruction applied to tailings prior to final deposition, followed by low density sludge lime hydroxide precipitation for treatment of tailings run-off, tailings supernatant and mine and waste rock untreated effluent prior to discharge. This treatment process is illustrated in Figure 6-31.

It is acknowledged that due to the high variability in treatment processes among operations, this process is not representative of the majority of the effluent treatment systems reviewed.

However, this process is expected to achieve an effluent quality similar to systems employing other cyanide destruction processes and so provides a system representative of the achievable effluent concentrations.

For the precious metal subsector, BATEA has been defined as:

- Sulfide precipitation with proprietary polymeric organosulfide chemicals for dissolved metals polishing (including arsenic, copper, iron, nickel, and zinc).
- Active aerobic biological oxidation for total ammonia removal.
- Model flow sheet for cyanide, bulk metals (including aluminum, arsenic, copper, iron, lead, nickel, radium-226, selenium, zinc), and solids (TSS) removal.

11.3 Metals Subsector: Iron Ore

The model treatment system is illustrated in Figure 6-34. In this model, effluent is treated for solids removal via pond-based settling. The use of flocculant to aid in the settling of solids is employed. This system closely resembles several effluent treatment systems, but is not identical to any one treatment system.

For the iron ore sector, BATEA has been defined as:

- Model flow sheet for solids (TSS), metals (aluminum, arsenic, copper, iron, lead, nickel, radium-226, selenium, and zinc) and total ammonia removal.

11.4 Metals Subsector: Uranium

The model system is illustrated in Figure 6-48. In this model, effluent is treated by 2 stages of treatment, to target parameters that are removed at significantly different pHs; one high pH stage for precipitation of metals which precipitate in basic conditions (i.e., nickel) and one low pH stage for metals and other parameters that precipitate or co-precipitate in acidic conditions (i.e., molybdenum, selenium, radium co-precipitation with barium sulfate). Between the chemical reaction stages, there is a clarification step to separate precipitates from the treated water followed by filtration for additional suspended solids removal. Ponds are employed for pre-treatment equalization and for post-treatment monitoring and/or settling.

For the uranium subsector, BATEA has been defined as:

- Active aerobic biological oxidation for total ammonia removal.
- Model flow sheet for metals (including aluminum, arsenic, copper, iron, lead, nickel, radium-226, selenium, zinc) and solids (TSS) removal.

In Revision 0 of this report, sulfide precipitation with proprietary polymeric organosulfide polymers was recommended as BATEA for dissolved metals polishing. However, this recommendation was eliminated based on the Revision 1 analysis of concentrations achieved by the model effluent treatment system for the uranium subsector which showed that augmentation of the model effluent treatment system with sulfide precipitation with proprietary polymeric organosulfide polymers would only permit an order of magnitude reduction in treated effluent concentration for nickel and marginal reductions in treated effluent concentrations for arsenic, copper, iron, and zinc.

11.5 Diamond Sector

The model system is illustrated in Figure 6-59. In this model, effluent is equalized prior to treatment and bulk TSS is removed via pond-based settling. The equalization/settling pond(s) also allow time for passive natural degradation of ammonia and phosphorus. The effluent is coagulated (e.g., with ferric sulfate or aluminum sulfate). If required, to adjust effluent pH, hydroxide reagent (e.g., lime, sodium hydroxide) may be added on a contingency basis. Coagulated TSS and precipitates are then allowed to settle, aided by flocculant, in a clarifier. Clarifier overflow is then polished by media filtration before being pH adjusted with sulfuric acid to meet un-ionized ammonia/toxicity limits prior to discharge to the environment. Clarifier underflow is co-disposed with tailings.This system closely resembles several existing effluent treatment systems, but is not identical to any one treatment system. This system is consistent with the BAT and BACT findings of previous studies(10) (6).

For the diamond sector, BATEA has been defined as:

- Model flow sheet for chloride, bulk metals (including aluminum, arsenic, copper, iron, lead, manganese, nickel, phosphorus, radium-226, selenium, zinc), ammonia, and bulk solids (TSS) removal.
- This BATEA selection is supported by multiple effluent treatment technology investigations by sector operations.

11.6 Coal Sector

The model treatment system is illustrated in Figure 6-71. In this model, bulk TSS is removed via pond-based settling and polishing which may be assisted by the addition of flocculant. The settling and polishing pond(s) also allow time for passive natural degradation of ammonia. This system closely resembles several existing effluent treatment systems, but is not identical to any one existing system.

For the coal sector, BATEA has been defined as:

- Model flow sheet for metals (including arsenic, aluminum, iron, and manganese), selenium, total ammonia, and solids (TSS) removal.

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12.2 Operations Questionnaire Reviewers

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12.3 Operations Questionnaire and Follow-Up Inquiry Respondents

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Appendix A
MMER Existing Authorized Concentration Limits for Existing Deleterious Substances

Deleterious Substance	**Metal Mining Sector Existing Limit[68]**		
Deleterious Substance/ Parameter	**Maximum Authorized Monthly Mean Concentration**	**Maximum Authorized Concentration in a Composite Sample**	**Maximum Authorized Concentration in a Grab sample**
pH	6.0 - 9.5 pH units		
Aluminum	-	-	-
Arsenic	0.50	0.75	1.00
Chloride	-	-	-
Copper	0.30	0.45	0.60
Cyanide	1.00	1.50	2.00
Iron	-	-	-
Lead	0.20	0.30	0.40
Manganese	-	-	-
Nickel	0.50	0.75	1.00
Phosphorus	-	-	-
Selenium	-	-	-
Zinc	0.50	0.75	1.00
Radium-226	0.37 Bq/L	0.74 Bq/L	1.11 Bq/L
Total Suspended Solids	15.00	22.50	30.00
Total Ammonia (as nitrogen)	-	-	-

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[68] Canada (2012). "*Metal Mining Effluent Regulations*". (SOR/2002-222).

Appendix B
Operations Questionnaire

Appendix C
Vendor Questionnaire

1

Appendix D
Comparison of Monthly Mean Data vs. Grab Data

This Appendix provides a comparison of the Schedule 4 monthly mean data for the period of 2008 – 2010 to grab concentration data reported to Environment Canada for the period of 2009 – 2011 to assess whether monthly mean data (used in Revision 0 of this study) adequately describes variation in concentrations of effluent produced by operations and what impact any differences between the data sets may have on the model effluent treatment systems achievable concentrations. Only Schedule 4 data has been compared as the Schedule 5 data provided by Environment Canada is grab and composite data reported by operations as opposed to monthly mean data.

In the model effluent treatment systems, the 95th percentiles of the Schedules 4 and 5 data have been used to establish the achievable concentrations for the model effluent treatment systems. Where the average and 95th percentile are largely the same between the monthly mean data and the grab data, it is assumed that the use of the monthly means adequately represent the effluent quality.

Base Metal

For the base metal subsector, the average and 95th percentile values of the monthly mean and grab values are very similar or identical for pH, arsenic, and lead. They align reasonably well for copper, nickel, zinc and radium-226. For cyanide and TSS, the monthly mean values are slightly higher than the grab values.

The maximum values are where the largest discrepancies are observed between the monthly mean and grab data. However, the differences are within an order of magnitude, with the exception of zinc, where the maximum of monthly mean data is significantly higher, and TSS, where the maximum of the grab data is significantly higher. Maximum values are not used as representative of the model effluent treatment system in any analysis and therefore these differences are not anticipated to impact any conclusions of the study.

The differences between the monthly mean and grab values for average and 95th percentiles for the base metal subsector are minimal. The monthly average values therefore adequately represent the effluent concentration data reported to Environment Canada and will continue to be used in Revision 1.

Parameters	Units	Effluent Concentration Basis	Minimum	Average	95th Percentile	Maximum
pH		Monthly Mean	3.7	7.8	9.0	12.3
		Grab	0.7	7.9	9.0	10
Arsenic	mg/L	Monthly Mean	0.00005	0.003	0.02	0.1
	mg/L	Grab	0.000025	0.004	0.02	0.38
Copper	mg/L	Monthly Mean	0.0008	0.02	0.06	4.2
	mg/L	Grab	0.00005	0.02	0.05	6.15
Cyanide	mg/L	Monthly Mean	0.0005	0.010	0.040	0.9
	mg/L	Grab	0.0001	0.0046	0.016	0.85
Lead	mg/L	Monthly Mean	0.00002	0.005	0.02	0.1
	mg/L	Grab	0.000005	0.005	0.02	0.3
Nickel	mg/L	Monthly Mean	0.0003	0.090	0.38	14.7
	mg/L	Grab	0.00007	0.11	0.41	19
Radium-226	Bq/L	Monthly Mean	0.005	0.030	0.11	0.8
	Bq/L	Grab	0.00025	0.030	0.11	1.4
Zinc	mg/L	Monthly Mean	0.0001	0.060	0.25	17.5
	mg/L	Grab	0.00005	0.050	0.20	1.92
TSS	mg/L	Monthly Mean	0.006	4.3	13	106
	mg/L	Grab	0.0002	3.9	11.2	1540

Notes:
Values reported as less than the method detection limit have been incorporated at 50% of the MDL value.
All metal concentrations are total metal concentrations, i.e., the sum of dissolved and suspended fractions.

Precious Metal

For the precious metal subsector, the average and 95th percentile values of the monthly mean and grab values are very similar or identical for pH, arsenic, copper, cyanide, lead, nickel, TSS and zinc. For radium-226, the grab values are lower than the monthly mean values and the difference is somewhat significant; however, radium-226 is not a significant parameter of concern for the precious metal subsector and so this difference will have little impact on the outcomes of the study.

The maximum values are where the largest discrepancies are observed between the monthly mean and grab data. However, the differences are within an order of magnitude, with the exception of TSS, where the maximum of the grab data is significantly higher. Maximum values are not used as representative of the model effluent treatment system in any analysis and therefore these differences are not anticipated to impact any conclusions of the study.

The differences between the monthly mean and grab values for average and 95th percentiles for the precious metal subsector are minimal. The monthly average values therefore adequately represent the effluent concentration data reported to Environment Canada and will continue to be used in Revision 1.

Parameters	Unit	Effluent Concentration Basis	Minimum	Average	95th Percentile	Maximum
pH		Monthly Mean	5.9	7.6	8.3	9.3
		Grab	5.6	7.6	8.4	9.7
Arsenic	mg/L	Monthly Mean	0.0005	0.030	0.17	0.55

Parameters	Unit	Effluent Concentration Basis	Minimum	Average	95th Percentile	Maximum
	mg/L	Grab	0.000001	0.031	0.18	1.15
Copper	mg/L	Monthly Mean	0.0003	0.01	0.04	0.96
	mg/L	Grab	0.00001	0.01	0.04	2.87
Cyanide	mg/L	Monthly Mean	0.0003	0.03	0.09	1.28
	mg/L	Grab	0.00025	0.04	0.1	9.6
Lead	mg/L	Monthly Mean	0.00002	0.002	0.005	0.079
	mg/L	Grab	0.000003	0.002	0.006	0.3
Nickel	mg/L	Monthly Mean	0.00005	0.02	0.07	0.30
	mg/L	Grab	0.00005	0.022	0.083	0.81
Radium-226	Bq/L	Monthly Mean	0.0005	0.010	0.05	0.43
	Bq/L	Grab	0.00025	0.00025	0.02	0.06
TSS	mg/L	Monthly Mean	0.3	4.7	13	58
	mg/L	Grab	0.0005	4.4	13	134
Zinc	mg/L	Monthly Mean	0.0002	0.02	0.07	0.56
	mg/L	Grab	0.0001	0.019	0.079	1.26

Notes:
Values reported as less than the method detection limit have been incorporated at 50% of the MDL value.
All metal concentrations are total metal concentrations, i.e., the sum of dissolved and suspended fractions.

Iron Ore

For the iron ore subsector, the average and 95th percentile values of the monthly mean and grab values align reasonably well for pH, arsenic, and nickel. Copper, lead, radium-226, zinc have different averages but very similar 95th percentile values. For TSS, the average value of the grab data is almost 200 times different but the 95th percentile is almost identical. This suggests that the grab data for TSS has a couple of very high values near the maximum which are likely skewing the average high. As the 95th percentile is similar, this difference is not anticipated to impact the study as the 95th percentile is the value carried forward to represent achievable concentration.

The maximum values are where the largest discrepancies are observed between the monthly mean and grab data. The maximum grab data values for arsenic, copper, lead, nickel, radium-226, zinc and TSS are all higher than the monthly mean data.

The differences between the monthly mean and grab values for average and 95th percentiles for the iron ore subsector are minimal, except for TSS. The discrepancies between the maximum values of the grab data and the maximum values of the monthly data indicate that the monthly values may be slightly reduced by averaging of the grab data. However, the maximum values are not utilized in any analysis of the data (e.g., for the model effluent treatment system) – and the 95th percentiles, which are used to represent the concentrations from the systems are almost identical for most parameters. The monthly average values therefore adequately represent the effluent concentration data reported to Environment Canada and will continue to be used in Revision 1.

Parameters	Unit	Effluent Concentration Basis	Minimum	Average	95th Percentile	Maximum
pH		Monthly Mean	3.8 (AD)	7.2 (AD)	8.2 (AD)	9.2 (AD)
		Grab	3.8	7.3	8.1	9.2
Arsenic	mg/L	Monthly Mean	0.0003	0.0006	0.001	0.014 (AD)

Parameters	Unit	Effluent Concentration Basis	Minimum	Average	95th Percentile	Maximum
						0.004 (EC)
	mg/L	Grab	0.0005	0.0053	0.001	4
Copper	mg/L	Monthly Mean	0.0005	0.0016 (AD) 0.0015 (EC)	0.003 (AD) 0.004 (EC)	0.058 (AD) 0.020 (EC)
	mg/L	Grab	0.0005	0.0107	0.005	11
Lead	mg/L	Monthly Mean	0.00009 (AD) 0.00010 (EC)	0.0008 (AD) 0.0010 (EC)	0.001 (AD) 0.002 (EC)	0.022
	mg/L	Grab	0.000025	0.0017	0.001	0.252
Nickel	mg/L	Monthly Mean	0.00039 (AD) 0.00050 (EC)	0.0024 (AD) 0.0031 (EC)	0.013 (AD) 0.020 (EC)	0.029
	mg/L	Grab	0.0005	0.0055	0.020	0.4
Radium-226	Bq/L	Monthly Mean	0.0005 (AD)	0.006 (AD)	0.016 (AD)	0.1 (AD)
	Bq/L	Grab	0.0005	0.0147	0.020	2
Zinc	mg/L	Monthly Mean	0.00075 (AD) 0.00100 (EC)	0.0078 (AD) 0.0100 (EC)	0.024 (AD) 0.028 (EC)	0.071
	mg/L	Grab	0.00025	0.0131	0.023	0.824
TSS[69]	mg/L	Monthly Mean	0.32 (AD)	13 (AD)	55 (AD)	315 (AD)
	mg/L	Grab	0.5	2,513	54.5	598,300

Notes:
Values reported as less than the method detection limit have been incorporated at 50% of the MDL value.
All metal concentrations are total metal concentrations, i.e., the sum of dissolved and suspended fractions.
AD: Aggregate data from *MMER* Schedule 4 reporting and Newfoundland & Labrador provincial reporting. These data are from monthly average values.
EC: Data from Appendix 2 Table 3.2 – 3 of Environment Canada's 10-Year Review of the Metal Mining Effluent Regulations Discussion Paper. These data are from monthly average values.
AD2: Aggregate data from *MMER* Schedule 5 reporting and Newfoundland & Labrador provincial reporting. These data are from grab samples.

Uranium
For the uranium subsector, the average and 95th percentile values of the monthly mean and grab values are very similar or identical for copper, lead, zinc . The average and 95th percentile values of the monthly mean and grab values align reasonably well for pH, arsenic, nickel and TSS. Radium-226 average values are similar while the 95th percentile is somewhat different (0.09 mg/L monthly average versus 0.03 mg/L grab). This different is not expected to significantly change any outcome of the study.

The maximum values are fairly close for most parameters with the exception of TSS, where the monthly mean value (9.1 mg/L) is smaller than the grab value (17.2 mg/L). However, the 95th percentile values for this parameter are nearly identical and as the maximum values are not used in analysis, this difference is not anticipated to impact the study conclusions.

The differences between the monthly mean and grab values for average and 95th percentiles for the uranium subsector are minimal. The monthly average values therefore adequately represent the effluent concentration data reported to Environment Canada and will continue to be used in Revision 1.

Parameters	Unit	Effluent Concentration Basis	Minimum	Average	95th Percentile	Maximum
pH		Monthly Mean	6.0	7.1	7.6	8.8

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[69] Average exceeds 95th percentile as a result of extremely high values in top 5% of the data set.

Parameters	Unit	Effluent Concentration Basis	Minimum	Average	95th Percentile	Maximum
		Grab	6.0	7.05	7.4	8.4
Arsenic	mg/L	Monthly Mean	0.00005	0.01	0.06	0.25
	mg/L	Grab	0.00005	0.001	0.04	0.5
Copper	mg/L	Monthly Mean	0.0001	0.003	0.008	0.045
	mg/L	Grab	0.0001	0.003	0.008	0.12
Lead	mg/L	Monthly Mean	0.00005	0.0003	0.001	0.005
	mg/L	Grab	0.000005	0.0003	0.001	0.01
Nickel	mg/L	Monthly Mean	0.0004	0.04	0.13	0.34
	mg/L	Grab	0.0002	0.03	0.10	0.34
Radium-226	Bq/L	Monthly Mean	0.0025	0.02	0.09	0.17
	Bq/L	Grab	0.00025	0.01	0.03	0.18
Zinc	mg/L	Monthly Mean	0.0004	0.009	0.03	0.13
	mg/L	Grab	0.00025	0.01	0.03	0.18
TSS	mg/L	Monthly Mean	0.1	1.6	4.1	9.1
	mg/L	Grab	0.1	1.45	4.00	17.2

Notes:
Values reported as less than the method detection limit have been incorporated at 50% of the MDL value.
All metal concentrations are total metal concentrations, i.e., the sum of dissolved and suspended fractions.
Values in this table are based on effluent quality data reported to Environment Canada as part of *MMER* Schedule 4 and Schedule 5 reporting.