Management of Acid Rock Drainage at Britannia Mine, BC
Part 1: Context and Technical Studies

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Abstract
The Britannia Mine, located 45 km north of Vancouver, British Columbia, Canada, commenced production of copper ore over 100 years ago. Some 37 years after the mine closed, it continues to generate an average of about 300 kg/day each of copper and zinc, as well as relatively minor amounts of other metals, dissolved in some 4 million cubic metres (m^3) of acid rock drainage (ARD) each year. Environmental remediation work by the Province of British Columbia commenced in 2001 with the objective of the mine meeting applicable environmental laws. Many technical studies aimed at collecting data to support a remedial concept for the mine were undertaken, several of which focussed on the feasibility of a water treatment plant (WTP) for the ARD and metal-contaminated groundwater. Design considerations leading to the construction of the WTP by a Design, Build, Finance, Operate (DBFO) form of contract in 2005 are discussed, together with a summary of remediation milestones at the mine. Part 2 of this paper looks at the WTP design, procurement, construction and operations.

Key Words: Britannia, Environmental, Mine, ARD, Water Treatment, HDS, Remediation

Britannia Mine History
The Britannia Mine is located at Britannia Beach on the east shore of Howe Sound, approximately 45 km north of Vancouver, BC, Canada (Figure 1). The main mining activity was some 5 to 7 km inland from Britannia Beach, with mineral processing activities taking place at Mount Sheer, around 5 km inland, and at the Britannia Beach town area on the coast, to the south of Britannia Creek. The mine site covers an extensive area, with mineral tenure associated with the mine extending over some 36.5 km^2 (approximately 9,000 acres). The mining took place underground and in open pits and glory holes (the 'Jane Basin' area) located on the top of Britannia Ridge, at an elevation of over 1,000 m above sea level (asl).

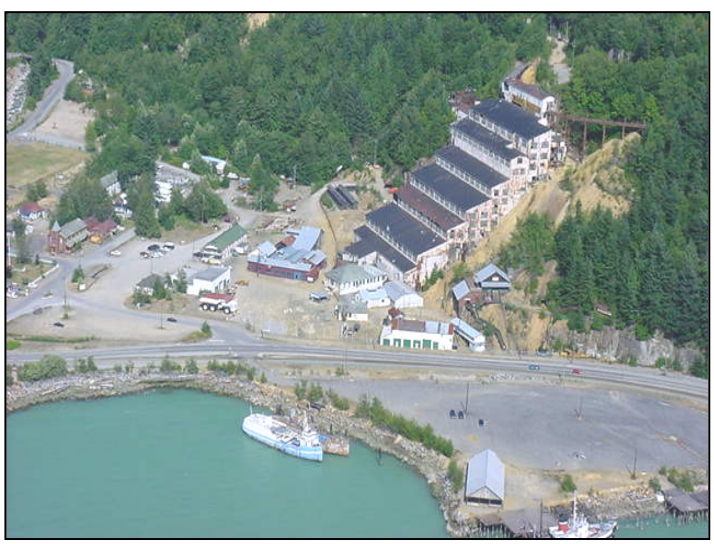

Figure 1. Britannia Beach: South 'Fan Area' and Mining Museum (c. 2004)

The mine was operated from 1904 to 1958 by the Britannia Mining and Smelting Company Ltd., from 1958 to 1963 by the Howe Sound Corporation, and from 1963 to 1974 by Anaconda Canada Ltd.

Seven ore bodies were mined through a combination of open pit, glory hole and underground developments. Many tens of kilometres of underground workings, numerous stopes and four open pits were developed to extract the ore. The open pits were glory-holed into the underground workings to facilitate removal of the ore using the extensive underground mine infrastructure. Since the mine ceased operations in 1974, surface water and groundwater continue to enter the mine workings. Drainage is routed through the underground workings, the majority eventually discharging via portals at the 2200 Level[1] and 4100 Level of the mine, the latter some 60 m above sea level. Prior to the start of the Britannia Mine Remediation Project (BMRP) in 2001, undertaken by the (now) BC Ministry of Forests, Lands and Natural Resource Operations (MFLNRO), the untreated acid rock drainage (ARD) from the mine workings discharged from the 2200 Level into local watercourses (Jane Creek and then to Britannia Creek), and from the 4100 Level to a discharge pipe into Howe Sound at a depth of approximately 26 m below sea level.

Summary of Environmental Issues

The mine water discharge typically has a pH of around 3.5 to 4.5, with elevated concentrations of dissolved metals, in particular copper, zinc, and cadmium. It is the adverse impact of these metals in the aquatic environment that is the primary environmental concern at the mine (Figure 2), with around 4 million m^3 of ARD draining through the mine annually. Prior to treating, an average of approximately 300 kg/day each of copper and zinc discharged to Howe Sound from the mine workings. The second environmental issue at the mine is the presence of large quantities of mineralized rock, waste rock, tailings, remnant concentrate and other process wastes found at various locations around the mine property. The largest accumulation of these materials (with the exception of outcrops of mineralized rock and mine waste in the Jane Basin open pit/glory-hole area) is in the southern portion of the alluvial fan of Britannia Creek, referred to as the ‘Fan Area’. Other areas of note in this regard are the 2200 Level, 2700 Level and Victoria Camp areas, the latter located in the Furry Creek watershed to the south of the main mine site.

Figure 2. ARD discharging from the 2200 Level Portal into Jane Creek in 2001 prior to remedial action.

[1] Elevations in the mine are referenced from a datum near the top of Britannia Ridge and measured down from this in feet. Thus sea level is 4300 feet using this nomenclature.

Offshore of the mine in the deeper waters of Howe Sound, some 40 million tonnes of mine process waste ('tailings') were deposited during the operational life of the mine. The offshore sediments do not form part the BMRP being undertaken by MFLNRO; however, Environment Canada has undertaken a program of investigation and evaluation of the nature and distribution of the nearshore sediments (Hagen et al., 2004) that indicated that the metal content of the tailings were not readily bioavailable as they were at depths of around 200 m, were being covered by (clean) sediments from the Squamish River, and would preferably not be disturbed by attempts at remediation.

The mine is required to comply with the Provincial Contaminated Sites Regulation (CSR) under the BC *Environmental Management Act*. The BC Ministry of Environment (BCMoE) has responsibility to make sure that the remediation activities bring the mine into compliance with the requirements of the CSR. Environment Canada and the Department of Fisheries and Oceans have responsibility to make sure that Federal requirements are met, including compliance with the provisions of the Fisheries Act. The remediation work at the mine is also subject to the BC Mines Act, administered by the BC Ministry of Energy and Mines, which regulates activities on mine sites, including mine reclamation efforts, particularly regarding health and safety aspects, and compliance with the provisions of the Health, Safety and Reclamation Code for Mines in British Columbia (Code).

Remediation Program

In the early 1990s, a Technical Advisory Committee (TAC) was formed by the Province to help coordinate Federal and Provincial efforts to remediate the mine, undertake/recommend technical studies, and develop a remedial concept for the mine. The Province also worked towards developing a full understanding of the mine ownership history and potential liabilities (Azevedo and O'Hara, 2007). Following new BC environmental legislation introduced in the mid-1990s (the then BC Waste Management Act and the Contaminated Sites Regulation, or 'CSR') and with full knowledge of historical ownership, the Province pursued the former owners for funds to remediate the mine. This culminated in 2001 with the Province receiving a $30M settlement from the former owners in exchange for indemnification against environmental issues relating to the mine.

Ownership of the mine property since closure was also identified as an issue that could influence the progress of remediation of the mine. By 2001, the (then) landowner had defaulted on a mortgage taken out on the property, had sold-off large tracts of uncontaminated land without assigning any of the proceeds to environmental remediation, had allowed the infrastructure of Britannia Beach to become dilapidated, and was effectively broke. In 2003, Macdonald Development Corporation (MDC) acquired and foreclosed on that mortgage. Subsequently, an agreement between the Province and MDC was implemented that included clear ownership of the mine lands by the Province, additional funding towards the environmental remediation work from development activities undertaken by MDC, and the removal of the residential properties from the mine lands (and from MEM jurisdiction). This enabled free access for remediation activities on the mine site, unfettered rejuvenation of the community, and promotion of its long-term sustainability (O'Hara et al., 2007).

Technical Studies

Figure 3 illustrates the remedial concept developed by the TAC during the late-1990s, essentially comprising the reduction of influent water, use of the mine as a storage reservoir to regulate seasonally-influenced mine discharge volumes, direction of the mine water to a single discharge point to facilitate feeding this to a water treatment plant, before discharging to a new deep-water outfall. Also in this concept, contaminated soil 'hot-spots' would be managed on-site, and contaminated groundwater and surface water would be intercepted and treated and/or discharged to the deep outfall in a controlled manner.

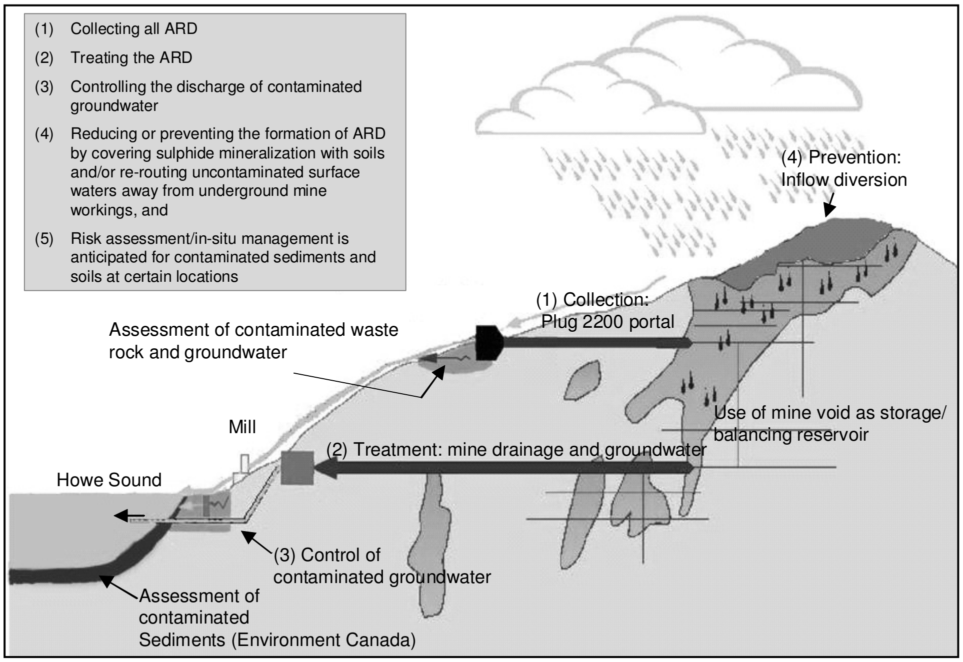

Figure 3. Province's Remedial Concept

Since mid-2001, the Province has progressively implemented this remedial concept with the following major annual milestones:

- 2001: 2200 Level Plug (installed by UBC-CERM3/CBEL), ensuring almost all ARD from the mine workings reported to the 4100 Level, and major technical study contracts awarded, including those for mine geology, hydrology/hydrogeology, contaminated sites issues, water treatment feasibility and flood risk assessments);
- 2002: Full-scale mine reservoir studies undertaken, proving the TAC's concept of using the mine as a storage reservoir;
- 2003: Completion of major technical studies and the submission of the Mine Reclamation and Closure Plan to the BCMoE, together with completing negotiations with the land developer (MDC) to secure long-term site access for the Province and additional remediation funding;
- 2004: Completion of preliminary surface water drainage works, long-term groundwater pumping tests and 'hot-spot' management, including permitting the Jane Basin open pit complex of the mine as a disposal site for contaminated soils and WTP waste products, together with procurement of the WTP design-build-finance-operate (DBFO) contractor, EPCOR Water Services Ltd (EPCOR), and the construction of the WTP access road through the Britannia Beach community. In addition, an environmental effects baseline study was undertaken at the mine;
- 2005: Construction of the Fan Area groundwater management system (GMS), the WTP (Figure 4), related infrastructure (including underground mine rehabilitation, deep-water outfall and micro-hydro power generation system) and three surface water diversions (SWDs) to reduce mine inflows of uncontaminated surface water. A long-term program of environmental effects monitoring (EEM) was implemented to assess the efficacy of the environmental improvements, this leading eventually to risk assessments;
- 2006: Improvements to the SWDs, supplementary technical studies aimed at improving surface water drainages, assessment of surface and storm water quality in and peripheral to the Fan Area, together with several safety improvements, including capping two shafts in the Furry Creek watershed, and ongoing EEM;

Figure 4. The Water Treatment Plant, Designed, Financed, Built and Operated by EPCOR

- 2007: Additional mine infrastructure safety improvements completed, upgrades to the GMS and SWDs, hot-spot removal of metal-contaminated soils from the 2200 Level waste dump, and ongoing EEM.
- 2008: Further safety improvements to mine infrastructure, design of improvements to surface water drainages in and peripheral to the Fan Area, GMS infrastructure upgrades undertaken to increase groundwater capture efficiency, a Fan Area surface water drainage engineering feasibility study, and ongoing EEM.
- 2009: Capture and diversion of flows from minor creeks peripheral to the Fan Area to reduce volume of contaminated storm water drainage from the mine, preliminary assessment of metals loadings, optimization of the GMS, and re-focus of EEM program to address risk assessment requirements.
- 2010: Development and implementation of an Overall Closure Plan for the mine, capture and diversion of metal-contaminated flows from adjacent Britannia Mine Museum property, commencement of hydrogeological/hydrological investigation at Jane Creek/2200 Level, commencement of risk assessment program for the Furry Creek watershed, and ongoing EEM.
- 2011: Further safety improvements to mine infrastructure, ongoing inspection and assessment of GMS infrastructure and performance, extensive sampling program to support risk assessment of Furry Creek watershed, re-assessment of Fan Area storm water quality and management options, and ongoing EEM.

Water Treatment Plant Design Considerations

Technology review

Treatment of ARD has been undertaken worldwide for decades, with the dominant technology being based on increasing the pH of the ARD such that the metals are precipitated from solution. The earliest implementations of this technique simply added a high-pH additive (e.g., lime slurry) to the ARD. However, this method is inefficient and the precipitated metals and waste products of the reaction (e.g., gypsum) are in a liquid slurry form that is bulky and difficult to handle, transport, and dispose of. Therefore, this technique, known as ‘Low-Density Sludge’ (LDS) is not in common use, especially for higher-throughput treatment plants.

In the 1970s, development of this process resulted in the 'High-Density Sludge' (HDS) technique (Figure 5), which has become the industry standard for treatment of ARD. In this technique, some of the precipitated waste product is used to 'seed' the precipitation process, resulting in larger particulates forming in a more efficient manner. This, coupled with the use of polymer flocculants and hydraulic pressing techniques, can result in a 'filter cake' that is approximately 50% water content and which can be handled much more easily and has a much lower volume required for disposal.

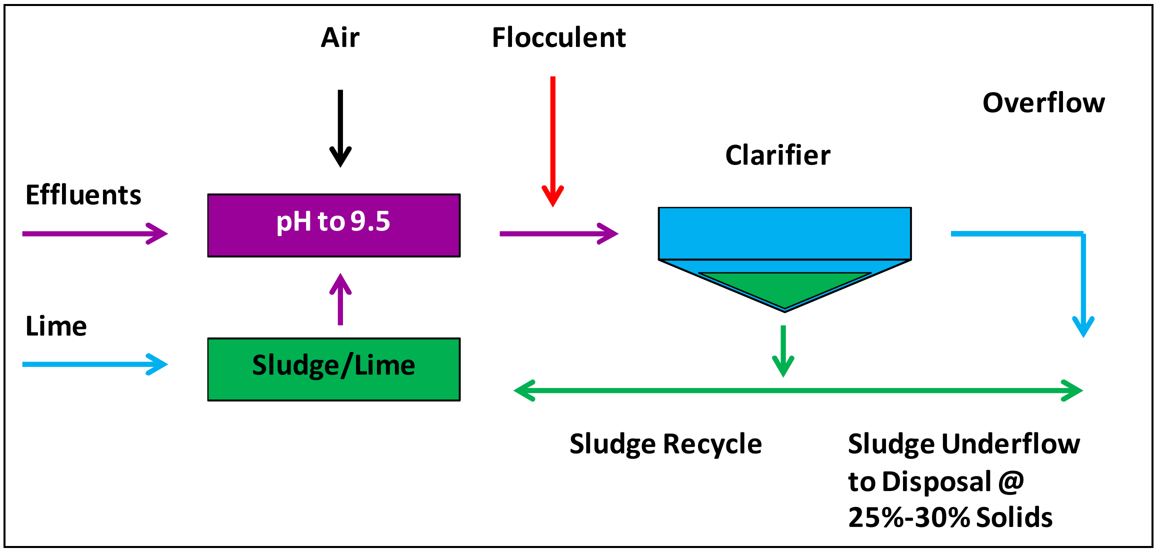

Figure 5. Simplified block diagram of an HDS treatment plant

By the 1990s and 2000s, various metal extraction technologies (e.g., sulphide chemistry) were introduced onto the market, in ever-increasing size of treatment plants. The BMRP undertook a scoping exercise on potentially-applicable technologies in 2003 and concluded that none of the metal extraction technologies that were available at that time when assessed against the (then) copper prices were economic or well-enough proven at the scale that would be required at Britannia. A pilot HDS plant was established on-site to assess the efficacy of this treatment method and provide an indication of performance. However, it was decided that in the procurement process the actual technology should be proposed by the various proponents and would be evaluated against the performance specifications developed during the conceptual design stage, along with economic considerations.

Water treatment plant sizing

The size (capacity) of the WTP was a significant issue during the early stages of the BMRP and took considerable effort by the project team. As noted above, the conceptual remedial design for the mine included the following:

- inflow diversions;
- containment and diversion of mine waters to one primary discharge location;
- use of the mine workings as a storage reservoir (to be used for flow balancing);
- treatment of mine effluent via the Water Treatment Plant; and
- discharge of treated water to the new deep-water outfall.

The inflow diversions, if implemented, would reduce the inflow to the mine, however, the efficiency of such diversions was difficult to predict with any accuracy. It was therefore decided to ignore the possible (beneficial) effects of implementing any such diversions in consideration of the WTP capacity, thus introducing a level of conservatism into the design.

The potential use of the mine workings as a storage reservoir necessitated considerable evaluation of the mine workings, the plug located in the 4100 Level tunnel and the potential effect of flooding sections of the mine on the discharge water chemistry. To this end, a significant portion of the technical study scope focussed on this issue. Associated investigations included:

- mine inflow modelling;
- detailed assessment of the configuration of the mine workings from historical mine records;
- geological structure of the mine host rock;
- non-destructive testing of the concrete plug (installed some 400 metres into the 4100 Level in 1978 and incorporating three pipes fitted with manually-operated valves to allow the mine to drain);
- assessment of the mine discharge water quality from historical records and geochemical forward-modelling of the mine water quality (prediction) during operation of the mine as a storage reservoir;
- mine filling tests if the above indicated that the concept was feasible, to confirm water quality predictions, mine overflow point and dynamic capacity of the usable mine workings; and,
- rehabilitation requirements for the 4100 Level tunnel and/or plug facility.

SRK undertook the majority of the above, using historical mine records, NRCAN (Geological Survey of Canada) data, Environment Canada records, meteorological data, *in-situ* testing and a modified UBC watershed hydrological model to predict mine inflows and behaviour of the reservoir. It was ascertained that the dynamic capacity of the mine workings up to the first 'pierce point' (the 3250 Level) was approximately 430,000 m^3. Predictions of outflow and chemistry were complicated by the (then) recent installation of a plug in the 2200 Level. This plug diverts mine water (ARD) that used to discharge at this elevation back into the mine, totalling around one third of the total mine discharge volume, which had significantly different chemistry.

Golder adapted the watershed model of the mine developed by SRK to assess how the reservoir could be managed to optimize the capacity of the WTP. SRK's assessment was that in the absence of any surface water diversions (worst case) a plant capacity of 1,050 m^3/hr and hydraulic capacity of 1,400 m^3/hr would result in some five mine discharge events occurring during the modelled 25 year period, including a simulated 1 in 200 year storm event, which may necessitate bypassing the WTP due to it being over its hydraulic capacity[2] (Figure 6). Such bypassing of the WTP would be managed using controls to be built into the plant's systems that would allow pH adjustment of the effluent (by lime addition) to increase pH of the combined treated/untreated mine discharge water to precipitate metals prior to discharge to the deep water outfall. With a projected 10% of the mine inflow being diverted, the modelling indicated that bypass events could be mitigated, as would the possibility of overtopping of the reservoir (uncontrolled discharge) from the 3250 Level portal[3].

[2] 'Design Capacity' is the maximum throughput of the plant whereby the design specifications for effluent water quality can be achieved consistently, ie reactor vessel retention times, clarifier velocities etc are within design parameters. 'Hydraulic Capacity' is the maximum throughput of the plant that is possible due to physical constraints of the reactor vessels, pipes, clarifier etc. Further increase in throughput is not possible due to overtopping or other plant malfunction. It may be possible to achieve the desired discharge parameters at the Hydraulic Capacity, however, the plant is more susceptible to upset conditions impacting discharge water quality.

[3] The 3250 Level is the next-highest entry into the mine above the 4100 Level and was demonstrated to be the overflow point from the reservoir. Untreated ARD discharge from this portal would enter Mineral Creek, a tributary of Britannia Creek and then into Howe Sound.

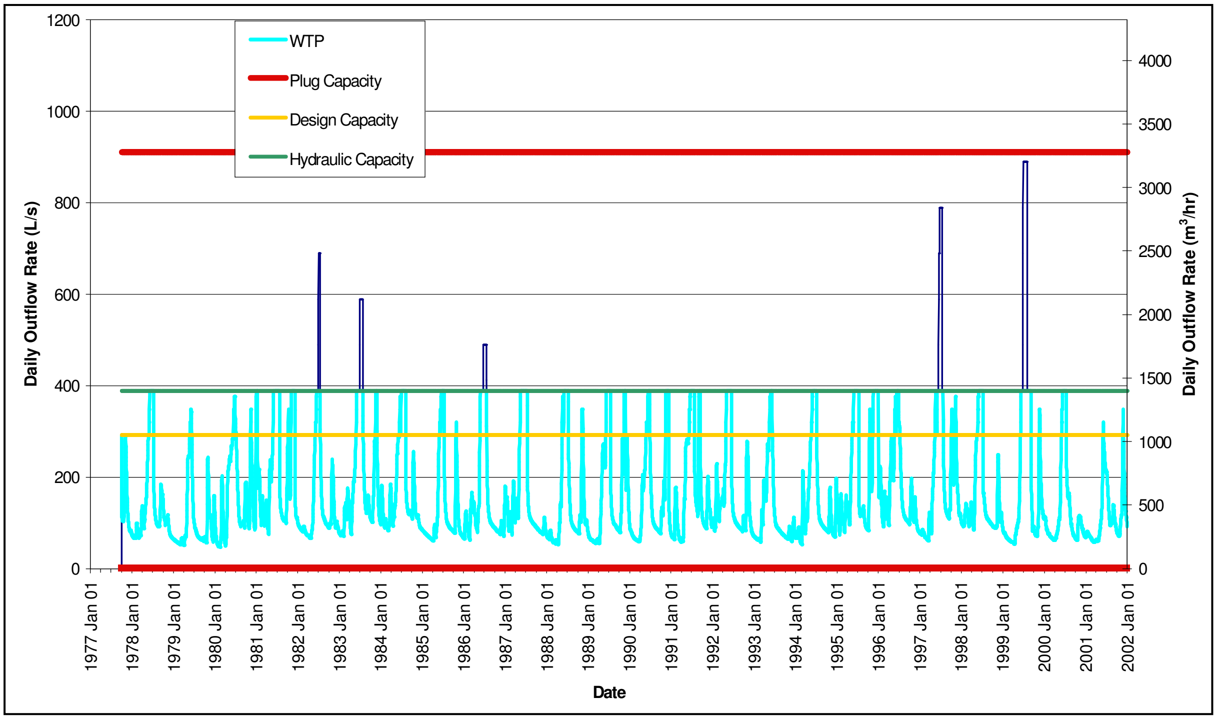

Figure 6. 25-year hydrograph of mine discharge (modified UBC WaterShed Model) showing design and hydraulic WTP capacities and also the capacity of the 4100 Level plug (pipes): in this particular model run, the peak flows over the hydraulic capacity show potentially five WTP bypass events (note: no surface water diversions accounted for in this run)

SRK's investigations of the 4100 Level plug concluded that the plug, its interface with the host rock and the pipework through the plug were all in very good condition and suitable to be brought into service as the primary control device for the mine reservoir. Golder assessed requirements for rehabilitation of the 4100 Level tunnel, which was in a dilapidated condition, having received no maintenance since the mine was closed in 1974. It was therefore decided that the tunnel must be rehabilitated to a standard that would allow safe and reliable personnel entry and equipment installation in the tunnel.

Plant location

Finding the most suitable location for the WTP was problematic. Logic was that it would best be placed close to the source of the mine water (i.e., near to the 4100 Level portal). However, a number of considerations had to be taken into account and various options explored.

Considerations included physical constraints, land ownership/access, flood risk, seismic stability/geotechnics and community expectations/concerns over visual impact, noise and (shared) access issues. Four primary locations were evaluated against these considerations: the Crown-owned shoreline ('Concentrate Wharf'), the Makin gravel pit area to the south of the mine site, the alluvial fan area (Fan Area) of Britannia Creek adjacent to the (then named) BC Museum of Mining and on the 4100 Level bench close to the 4100 Level portal. Complex access, infrastructure and land ownership issues struck-off the Makin property, seismic stability and visual concerns prevented the Concentrate Wharf from further consideration, and flood risk was a concern for locations within the Fan Area, leaving the 4100 Level bench as the prime candidate.

Further evaluation of the 4100 Level location found that it was suitable geotechnically (glacial sand overlying bedrock), was in the ownership of the Province and also had the advantage of close proximity to the 4100 Level portal, minimizing the length of influent piping to the WTP. This location also had the benefit of having a concrete-lined pond nearby (part of the old mine infrastructure) that could be re-deployed as a temporary sludge holding area if needed. However, this location, being some 60 m above sea level would make the plant visible from the highway and, possibly, parts of Britannia Beach village. This, together with potential noise of operation and emissions became issues for discussion at public meetings chaired by the Province. Also, following various investigations, the expected location of the new deep-water outfall was likely over 1 km to the southwest of this site, potentially adding significantly to the outfall infrastructure cost. Finally, access to a plant located at the 4100 Level would need to be through the Britannia Beach community and would necessitate construction of a road having suitable width, surface and acceptable grades for traffic servicing the plant (e.g., lime delivery trucks, cranes). On balance, this location was finally selected as being the most appropriate compromise of the potential sites, it being on Province-owned land, seismically stable, outside the potential flooding zone of the Fan Area and close to the 4100 Level portal.

Ancillary facilities

As noted above, the 4100 Level tunnel was assessed to be in a dilapidated condition and the (then) BC Ministry of Energy, Mines and Petroleum Resources required that the condition of the tunnel be raised to a 'civil standard', such that inspections of the plug and maintenance of pipes, valves, sensors and electrical installations installed within it could be undertaken in safety without special precautions.

Rehabilitation work within the 4100 Level tunnel included the installation of a low-density concrete bulkhead at the junction of a Y-tunnel, capping two ore chutes (raises to the 4150 Level), capping several minor ore chutes at surface, extensive rockbolting of the tunnel roof and walls, and treatment of the roof and walls along the entire 400 m length of the tunnel with steel fibre-reinforced shotcrete. This work was concurrent with WTP construction and undertaken in advance of the WTP contractor taking possession of the tunnel to install pipework, valves, instrumentation and an energy dissipater. Additional rehabilitation works subsequently undertaken by the WTP contractor included installation of a drainage pipe and gravel floor to the tunnel, replacement of electrical and data lines to the plug facilities (including lights, phone, webcam, remote-operated valves, flowmeters and pressure sensors), a ventilation system, stainless steel penstock[4] and low-pressure water discharge line (Figure 7).

[4] EPCOR, the WTP contractor, included a microhydro plant as part of their proposal. This necessitated installation of a stainless steel penstock to feed the microhydro plant under the mine head, plus an energy dissipater and low pressure discharge line to carry the mine discharge to the WTP when the microhydro plant was not operating (mine head below around 70m)

Figure 7. Installation of pipework and energy dissipater at the 4100 Level plug, some 400 metres from the portal

Investigations connected with siting of the new deep-water outfall undertaken as part of the investigation phase of the project indicated that the optimum location would be around 1km south of Britannia Beach on an area of relatively stable sediments (Figure 8). In addition, dispersion modelling had confirmed that the outfall should be at 50 m depth and be fitted with a multi-port diffuser. It was decided by the BMRP to procure the outfall as part of the same contract as the WTP.

Figure 8. New deep-water outfall being floated into position offshore, some 1 km south of Britannia Beach

Another remedial component that was identified as being linked to the water treatment facility was the groundwater management system (GMS). The GMS is needed to intercept metal-contaminated groundwater flowing through the south Fan Area before it discharges to the environmentally-sensitive shallow intertidal zone in Howe Sound. This is effected by a number of groundwater pumping wells located in a north-south line just inland of the shore. The close proximity of these wells to the shoreline is needed to maximise the capture. However, this proximity also results in the wells being susceptible to salt water intrusion from the shore. The balance of groundwater pumped from these wells is controlled automatically by an algorithm developed to maximise pumping of fresh water whilst adhering to constraints imposed by the WTP on maximum conductivity (as a surrogate for chlorides) and total volume (Figure 9). The conceptual design of the GMS was undertaken by Golder; however, it was identified that the detailed design and construction of this system would best be undertaken by the future operator of the GMS (and WTP if possible), so procurement would be rolled in with the WTP and outfall contract.

Figure 9. Flow meters and conductivity sensors in the groundwater management system (GMS) pump house

WTP Residual

HDS water treatment plants generate waste (residual) material that must be handled and disposed of appropriately, in compliance with applicable laws, regulations, and permits. As noted above, HDS treatment generates a filter cake that comprises a gypsum matrix with the extracted metals bond into its matrix – these metals are not released through expelled water or as a leachate. Planning for the WTP therefore included consideration of how the residual was to be handled and disposed (or even utilized). Consideration was given to disposing of the material on site (at various locations), disposal off-site and/or use in products (such as cement, bricks or pavers). Finding a potential use for the material was problematic particularly without having firm physical and chemical properties of the filter cake in advance of full-scale production by the WTP. Assessment of the pilot HDS plant data indicated that the full-scale WTP would generate between 3,000 and 5,000 m^3 of residual (sludge) per year.

It was therefore necessary to plan for the management and disposal of the residual. Assessment of off-site options indicated that handling, haulage and disposal fees would be significantly more expensive than an on-site disposal facility. Assessment of two locations on site were undertaken by SRK and Golder: close to the 2200 Level of the mine, around 5.5 km inland along a backcountry road and approximately 500 m asl; and at Jane Basin, 11 km along that road and at an elevation of 1,000 m asl. The 2200 Level location had the advantage of a shorter haul route and longer seasonal access, but was susceptible to debris flows and would require construction and maintenance of retaining structures, caps etc., as well as some form of leachate monitoring and/or control. The Jane Basin location was twice as far to haul and would not be open in the winter months due to snow accumulations at the higher elevations; however, Jane Basin included two glory holes (pits) that could accommodate over 130,000 m^3 of sludge without any construction and minimal maintenance effort and had the additional advantage that any leachate from the residual would drain back into the mine and report (eventually) to the WTP. The decision was made therefore to permit Jane Basin as a permanent storage location for the WTP residuals (Figure 10).

Figure 10. Filter cake disposal site in Jane Basin (East Bluff Glory Hole)

Closure

The second part of this paper deals with procurement aspects of the WTP, including detailed design, form of procurement selected, plant (and ancillary facility) construction, operation and lessons learned in the first six years of operation.

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Acronymns

asl	above sea level
BCMoE	BC Ministry of Environment
BMRP	Britannia Mine Remediation Project
CSR	Contaminated Sites Regulation
DBFO	design-build-finance-operate
EEM	environmental effects monitoring
EPCOR	EPCOR Water Services Ltd
GMS	groundwater management system
HDS	High-Density Sludge
LDS	Low-Density Sludge
MDC	Macdonald Development Corporation
MFLNRO	BC Ministry of Forests, Lands and Natural Resource Operations

NRCAN	Geological Survey of Canada
SWDs	surface water diversions
TAC	Technical Advisory Committee
WTP	water treatment plant