A SURVEY OF IN SITU OXYGEN CONSUMPTION RATES ON SULPHIDE TAILINGS: INVESTIGATIONS ON EXPOSED AND COVERED TAILINGS

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Falconbridge Limited - Kidd Creek Division
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A Survey of In Situ Oxygen Consumption Rates on Sulphide Tailings: Investigations on Exposed and Covered Tailings

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EXECUTIVE SUMMARY

Water quality impact predictions related to sulphide mine wastes involves ongoing research and technology development. Investigations of existing sulphide tailings have shown the types of water quality problems that can result from sulphide mineral oxidation and leaching of acidic and/or metal-bearing drainage into the environment. The rate of sulphide oxidation is the primary controller of the quality of drainage in many types of mine waste. Geochemical reactions can alter the characteristics of water generated in zones of oxidation but these are secondary after acid generation and dissolution of metals. Although water quality issues have been studied extensively for sulphide tailings, for example, there have been few attempts to quantify rates of oxidation in-situ. The Oxygen Consumption Method, that is a recent technological development, has been shown to provide a quantitative assessment of in-situ oxidation rates in tailings. The measurements clearly and rapidly show the reactivity of tailings. The results provide immediate feedback on the oxidation status of a tailings impoundment and can be used to calibrate models that require reaction rates as input. The method is relatively new and measurements were, until recently, available at only a few field sites where research was conducted during method development.

This study was conducted to initiate a data base of measurements at a variety of tailings impoundments. Sites were selected to represent different conditions such as sulphide minerals (pyrite or pyrrhotite), sulphide content, acidic versus neutral conditions, age since deposition and sites with oxygen barrier covers over existing tailings. This report presents the results of that study and presents an interpretation of the data including several types of information that can be extracted from the data.

In situ sulphide tailings oxidation rates were measured at six field sites using the Oxygen Consumption Method. Results were examined to evaluate the rate of *in situ* oxidation at each site and to examine possible trends in oxygen

consumption rates with other physical site characteristics including age of tailings, moisture content, sulphide content, and the effectiveness of different cover scenarios.

Overall, the results indicated that the Oxygen Consumption Method can provide useful information at a wide variety of tailings facilities. Measured rates were observed to be related to sulphide content, moisture content and climatic conditions. Significant reduction of rates was noted for tailings that were covered by oxygen barrier layers (or soil covers) with variable effectiveness exhibited by different types of cover materials and method of construction.

Oxygen consumption rates ranging from less than 1 mol O_2 m^{-2} a^{-1} to over 5000 mol O_2 m^{-2} a^{-1} were measured during this investigation. A strong trend of increasing oxygen consumption rate with increasing sulphide content was observed. This is attributed to the influence of diffusion depths that increse significantly in the near-surface zone of active oxidation. A trend of lower oxygen consumption rates was observed for cooler, wetter climatic conditions than for dryer, warm conditions. Oxygen consumption rates measured in early May were approximately 25% of rates measured during the warmer and dryer summer months.

A trend of decreasing oxygen consumption rates with tailings exposure time was also observed. This is attributed to the downward migration of the zone of oxidation that increases the diffusion path length with increased moisture content at depth over time. Higher moisture at depth further acts to lower the effective gas diffusion coefficient (D_e) within the zone of active oxidation. Oxygen consumption rates measured on highly saturated tailings were notably lower than for similar tailings where a developed vadose zone existed. Oxygen consumption rates measured on freshly deposited, fully saturated tailings and on tailings that were highly saturated were non-trivial and represent potentially significant loadings to receiving waters.

Measurements of oxygen consumption rates to evaluate the effectiveness of various cover scenarios at full-scale, test plot and *in situ* column scale revealed that the addition of a layer of non-reactive material can substantially reduce the flux of oxygen to the tailings. Simple covers constructed of local materials such as gravel or till were observed to reduce the oxygen consumption rate as much as one order-of-magnitude. A more complex, multi-layer engineered cover reduced the oxygen consumption rate by as much as two orders-of-magnitude. However, improper design can compromise the efficiency of multi-layer covers. Many of the covers investigated were sensitive to potential drying out which could greatly reduce their effectiveness.

Results from the oxygen consumption rate measurements can also be used to address issues such potential required neutralization, potential pore water loadings, rate of depletion of sulphide inventory, and depletion rates for neutralization potential. These quantities and the timing involved can be used to optimize management of reactive tailings. An example of originally neutral tailings that will eventually generate acidic leachate was assessed to determine the timing available for rehabilitation activity and budget timing.

This study clearly showed that the oxygen consumption method provides a rapid and cost effective assessment technique that can provide useful and critical data for a wide variety of sulphide tailings sites. The data can be used for waste management planning and evaluation of covers from test-plot to full-scale. The data can also be used to calibrate predictive models without the complications of decoupling highly variable hydrology from geochemistry.

RÉSUMÉ

Pour prévenir l'impact des résidus miniers sulfurés sur la qualité de l'eau, il est nécessaire d'effectuer des recherches de façon continue et de développer de nouvelles technologies. Les résultats d'investigations de résidus sulfurés existants ont démontré que le type de problèmes liés à la qualité de l'eau peut découler de l'oxydation sulfureuse des minéraux et de la lixiviation dans l'environnement de drainage acide et/ou de drainage contenant des métaux. La vitesse d'oxydation sulfureuse est le régulateur primaire de la qualité du drainage provenant de plusieurs types de déchets miniers. Les réactions géochimiques peuvent modifier les caractéristiques de l'eau dans des zones d'oxydation mais ces réactions ne se produisent qu'après la production d'acide et la dissolution des métaux. Dans le cas des résidus sulfurés, les questions liées à la qualité de l'eau ont fait l'objet d'études exhaustives mais peu d'efforts ont été déployés pour établir la vitesse d'oxydation *in-situ.* La méthode de consommation d'oxygène, un développement technologique récent, a permis d'évaluer quantitativement les vitesses d'oxydation in-situ des résidus. Les mesures indiquent clairement et rapidement le taux de réactivité des résidus. Les résultats fournissent des renseignements immédiats sur le taux d'oxydation des parcs à résidus et peuvent être utilisés pour étalonner des modèles servant à analyser les données relatives aux vitesses de réaction. La méthode, qui est relativement nouvelle, et les résultats de mesure n'étaient jusqu'à récemment disponibles que sur quelques sites où se poursuivaient les travaux de recherche lorsqu'elles étaient encore en développement.

La présente étude a pour objet d'établir une base de données des mesures prises à divers parcs à résidus. Les sites ont été sélectionnés de façon à représenter diverses conditions telles les minéraux sulfurés (pyrite ou pyrrhotine), la teneur en sulfates, l'acidité par rapport à la neutralité, l’âge du parc à résidus et les sites dotés de couvertures sèches contre l'oxygèn. Le présent rapport fait état des résultats des travaux et présente une interprétation des données, y compris divers renseignements qui en ont été extraits.

Les vitesses d'oxydation *in situ* des résidus sulfurés ont été mesurées sur place sur six sites au moyen de la méthode de consommation d'oxygène. Les résultats ont été étudiés en vue d'évaluer la vitesse d'oxydation *in situ* des résidus sur chacun des sites et d'examiner les tendances possibles en matière de vitesses de consommation d'oxygène et autres caractéristiques physiques des sites y compris l'âge des résidus, leur teneur en eau et en sulfures ainsi que l'efficacité de diverses couvertures.

Dans l'ensemble, les résultats démontrent que la méthode de consommation d'oxygène peut fournir des renseignements utiles au sujet d'une vaste gamme de parcs à résidus. D'après les observations, les taux de consommation mesurés sont liés à la teneur en sulfures et en eau des résidus ainsi qu'aux conditions climatiques. Une réduction importante des vitesses de consommation d'oxygène a été observée dans le cas des résidus munis de couvertures contre l'oxygène (ou de couvertures de sol) et l'efficacité variait en fonction de la méthode de construction des divers matériaux utilisés pour la construction des couvertures.

Les vitesses de consommation d'oxygène mesurées au cours de cette étude ont varié de moins 1 mol O_2 m^{-2} a^{-1} jusqu'à plus de 5 000 mol O_2 m^{-2} a^{-1}. On a observé que la vitesse de consommation d'oxygène tendait à augmenter en fonction de l'augmentation de la teneur en sulfures. Ce phénomène est attribuable à l'effet des profondeurs de diffusion qui augmentent considérablement au voisinage de la surface de la zone d'oxydation active. On a observé que les vitesses de consommation d'oxygène avaient tendance à être moins élevées dans des conditions climatiques plus fraîches et plus humides que dans des conditions climatiques moins humides et plus chaudes. Les vitesses de consommation d'oxygène mesurées au début de mai s'élevaient à approximativement 25% des vitesses mesurées au cours des mois d'été lorsque le climat était plus chaud et plus sec.

On a également observé que les vitesses de consommation d'oxygène diminuaient avec la durée d'exposition des résidus, ce qui peut découler de la migration vers le bas de la zone d'oxydation qui, avec le temps, augmente la longueur de la voie de diffusion et du taux d'humidité en profondeur. Plus d'humidité en profondeur ralentit la diffusion efficace du coefficient de diffusion de l'oxygène (D_e) à l'intérieur de la zone d'oxydation active. Les vitesses de consommation d'oxygène mesurées dans des résidus hautement saturés étaient notamment plus basses que dans le cas de résidus semblables où une zone vadose avait été développée. Les vitesses de consommation d'oxygène mesurées dans des résidus totalement saturés et fraîchement déposés, et dans des résidus hautement saturés étaient non-négligeable et représentaient possiblement des charges importantes dans les eaux réceptrices.

La mesure des vitesses de consommation d'oxygène utilisée pour évaluer l'efficacité de divers scénarios en matière de couverture à grandeur réelle, de parcelles d'essai et d'essais *in situ* sur colonnes a révélé que l'ajout d'une couche de matériel non réactif peut réduire considérablement le flux d'oxygène dans les résidus. D'après les observations, des couvertures simples, fabriquées à partir de matériaux locaux tel le gravier ou le till, peuvent réduire d'un ordre de grandeur les vitesses de consommation d'oxygène. Une couverture multicouches a réduit la vitesse de consommation d'oxygène de plus de deux ordres de grandeur. Toutefois, une conception inappropriée des couvertures multicouches peut compromettre leur efficacité. Plusieurs des couvertures étudiées sont sujettes à un assèchement éventuel, ce qui peut considérablement réduire leur efficacité.

Les résultats obtenus à partir de la mesure des taux de consommation d'oxygène peuvent également servir à résoudre des problèmes tels le potentiel de neutralisation requis, les charges potentielles d'eau interstitielle, le taux d'épuisement de l'inventaire de sulfures et le taux d'épuisement pour le potentiel de neutralisation. Les quantités et le facteur temps peuvent être utilisés pour optimiser la gestion des résidus réactifs. Une évaluation d'un cas où des résidus, bien que neutres au départ, produiront éventuellement un lixiviat acide a été effectuée afin de déterminer le temps disponible pour les activités de réhabilitation et de budgétisation.

La présente étude démontre clairement que la méthode de consommation d'oxygène constitue une technique d'évaluation rapide et rentable par rapport aux coûts permettant d'obtenir des données utiles et précieuses relativement à une vaste gamme de sites qui contiennent des résidus sulfurés. Les données peuvent servir pour la planification de la gestion des déchets et pour l'évaluation des couvertures à partir de parcelles d'essai jusqu'à leur installation à grande échelle. Elles peuvent aussi être utilisées pour étalonner des modèles de prévision tout en évitant les questions de découplage de l'hydrologie qui est très variable, de la géochimie.

Table of Contents

List of Figures

List of Tables

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1. Introduction

1.1 General

Mining and processing of base metal, uranium and gold ores can result in the production of large quantities of sulphide tailings as a waste material. Tailings are the fine grained, typically less than 200µm, material that remains after the mineral extraction from the ore. Tailings are commonly deposited as a high water-content slurry in to subaerial impoundments near the mine or mill complex. The subsequent exposure of these wastes to atmospheric oxygen and moisture can lead to the production of acidic leachate referred to as acid mine drainage or AMD.

Acid mine drainage is typified by elevated concentration of sulphide oxidation products including iron, sulphate, and low pH conditions. In addition, AMD leachate often contains elevated concentrations of trace metals such as zinc, copper, and nickel that are mobile under the low pH conditions. This leachate can have undesirable impacts on the quality of surrounding surface and sub-surface waters affecting wetlands ecology, lake and river environments, and contamination of potable water supplies.

Methods attempting to limit oxidation in mine tailings focus on segregating the main reactants in the oxidation reaction, namely the sulphide material, water and oxygen. Placing material on the tailings surface, as a cover, that will act to prevent oxygen transport to the tailings is one such method. These constructed covers range from single layers of locally available tills or gravel to multi-layer systems of materials specifically chosen to perform as a barrier to oxygen transport. Other approaches to AMD prevention may include placing the reactive material (tailings) under saturated conditions or under some depth of water. Water is effective at limiting oxygen transport due to the low diffusion coefficent of oxygen in water.

The understanding of the oxidation process and the ability to quantify this process is fundamental to the management of the problem, the evaluation of remediation efforts and the prevention or management of AMD development at new sites.

1.2 Objectives

The objectives of this study were four fold: 1) to develop a data base of *in situ* measurements of oxidation rates across a variety of tailings impoundments; 2) to investigate and comment of the effectiveness of selected remediation strategies; 3) to examine major trends that may be common to more than one site; and 4) to discuss the implications of the measured oxidation rates with respect to sulphide depletion rates, loadings of oxidation products, and the potential depletion rates of buffering minerals.

1.3 Scope of work

This report presents the results of oxidation rate measurements from six field sites in terms of oxygen flux as measured by the oxygen consumption test method and as expressed as equivalent mass of $CaCO_3$ required for the neutralization of the acidity generated from the oxidation of the sulphide minerals. For field sites where remediation activities have been employed, discussions on the effectiveness of the measures are presented and implications on long-term impacts are discussed. The data and results presented here provide insight into *in situ* rates and implications for oxidation of sulphide mine tailings for the specific sites examined.

2. BACKGROUND

2.1 Estimating sulphide oxidation rates

The understanding of the sulphide oxidation process and the ability to quantify this process is fundamental to the management of the problem, the evaluation of remediation efforts and the prevention or management of AMD development at new sites. The effects of sulphide mineral oxidation on the pore water quality in tailings has been recognized for some time (Dubrovsky *et al.,* 1985, Blowes, 1990 and others).

Pore water associated with sulphide oxidation is typified by elevated concentrations of sulphate, iron, and heavy metals. The acidity generated by the oxidation reaction can lead to low pH values. This can impact receiving water bodies as runoff or discharge and have adverse effects on flora and fauna or contaminate aquifers making them unsuitable for potable water.

The theoretical basis for control of oxidation rates in tailings by diffusion of oxygen from the atmosphere into the pore spaces was also understood (Nicholson, 1984, Davies and Ritchie, 1986, Nicholson *et al.,* 1995). The rate of oxidation is controlled by oxygen diffusion from the tailings surface to the depth of oxidation.

Laboratory studies have been conducted to gain insight into the mechanisms controlling the oxidation reactions and rate determining steps. Laboratory studies have also aided in understanding of the important variables such as the influence of temperature, grainsize, and bacterial catalysis. Laboratory studies have also shown the role of surface-controlled kinetics on the rate of oxidation for conditions where oxygen is not limiting (see the review by Nicholson, 1994). One of the challenges that was not addressed until more recently was the measurement of oxidation rates in tailings impoundments.

Management strategies and reclamation efforts are commonly developed without a strong understanding of the rate of sulphide oxidation that is occurring at a site. The ability to quantify oxidation rates would provide a strong understanding of the spatial and temporal distribution of the oxidation rates that significantly influence the quality of the water associated with sulphide mine wastes.

A knowledge of the rate of oxidation in a tailings impoundment is useful in several ways. Measurement of in-situ oxidation rates in the field can provide insight into potential pore water loadings of oxidation products based on an understanding of the stochiometry of the oxidation reactions and products. Knowledge of chemical loadings coupled with environmental data such as infiltration rates and the physical hydrogeology of the site can be used to assess potential discharge rates and AMD product loadings for receiving water bodies. Such information is also useful for first order assessment of treatment requirements. The measurement of oxygen consumption rates prior to commencing remediation efforts such as construction of covers or raising the water table compared to rates measured after such efforts can allow for rapid assessment of the effectiveness of the remediation. Having a database of oxygen consumption rates over time on a site can reveal major seasonal trends. This may include lower rates during periods of cold temperature or increased saturation on the tailings. Clearly, such information is useful. However, few *in situ* rates have been reported to date.

2.2 Evaluation of Sulphide Oxidation in the Field

There are several methods by which the rate of sulphide oxidation can be investigated in the field. Most methods to date have relied on mass-balance approaches for the water, solid, of gaseous phase.

One of the more innovative methods used for estimating *in situ* oxidation rates in sulphide waste rock piles involves the measurement of temperature within the pile and the calculation of oxidation rates based on the exothermic nature of the oxidation reactions (Harris and Ritchie, 1980). While this method has met with some success for waste rock environments the method is generally inappropriate for tailings oxidation applications. The method is not applicable because oxidation is limited to the near surface in tailing impoundments compared to waste rock impoudments. The higher moisture content in tailings is also problematic as the high heat capacity of water will result in errors in the calculations by diminishing the temperature response. The most significant problem in applying this measurement method to a tailings impoundment is that the temperature in the zone of active oxidation within tailings is controlled by the ground surface temperature rather than the exothermic oxidation reactions.

Historically, large data sets of pore water chemistry are collected though sampling of piezometer networks or pore water chemistry from squeezing of core samples to characterize the oxidation status of sulphide tailings impoundments (Dubrovsky *et al.* 1984; Dubrovsky *et al.* 1985; Blowes, 1990 and others). The chemical analysis of the pore water is used to infer the location and extent of the oxidation process based on the presence of elevated concentrations of oxidation products such as SO_4, Fe^{2+}, Fe^{3+}, trace metals, acidity, as well as low pH. The zone of active oxidation has also been delineated though the examination of oxygen profiles in the pore gas. (Symth, 1981; and Dubrovsky *et al.*, 1985). In this method, point measurements of the oxygen content in the pore gas are made at selected depths. This can be done by installing a sampling tube to a specific depth, sampling the gas and driving the device deeper, to the next sample depth (David, 1993; and David and Nicholson, 1995). As an alternative to this method some researchers have installed permanent gas sampling probes (Yanful et al., 1994 and Woyshner and Swarbrick, 1997). Re-sampling is possible. However, this method is more appropriate for installation into constructed covers where the simple 'push and measure' method might create undesirable conduits for oxygen transport.

As an alternative to installing and sampling peizometer networks some research efforts have focused on the collection of the pore water displaced by the infiltration of natural precipitation events over a limited surface area by installing lysimeters. This usually involves significant perturbation to the tailings for the installation of the collection system. Reworking may have implications on the moisture profiles, and hydraulic properties of the tailings due to the destruction of the *in situ* tailings texture. In addition, natural hydraulic conditions are disrupted with new boundary conditions, the water collection drain for the lysimeter is most often not at the level of the water table. This can result in poor drainage. Any development of an actively oxidizing zone in the tailings profile would also be destroyed and the disrupted geochemistry of the system may take a considerable amount of time to re-establish. Despite such concerns, lysimeters have been used to examine the effectiveness of constructed covers by observing the quantity of oxidation products in the leachate.

A detailed investigation on the performance of the engineered test covers installed at the Waite Amulet tailings site by Yanful et al. (1994) utilized oxygen profile measurements, lysimeters for collecting drainage water, and oxygen diffusion modeling. Computer modelling of oxygen flux was used to estimate cover efficiency based on the cover design characteristics. Field measurements of oxygen profiles in and below the covers demonstrated that the covers were acting as a diffusive barrier to the transport of oxygen into the tailings. While insightful as to the relative effectiveness of the cover as a diffusion barrier the oxygen profiles were not used to calculate oxygen flux through the cover and hence were not useful in quantifying the oxidation rates of the tailings and did not provide information of the potential reductions, in absolute terms, of oxidation products or oxidation rates.

Determination of oxidation rates in the field has relied mainly on geochemical models that incorporate reaction kinetics, thermodynamic data and empirical parameters, measured or estimated (Jaynes et al., 1984; Davis et al., 1986; Elberling et al., 1994; and Scharer et al., 1994) for example. While such approaches may be useful predictive tools, their usefulness is limited by the data required. To date mainly indirect data such as water chemistry was available. The reliability of water chemistry is complicated (or compromised) by complex hydrogeologic conditions and the many secondary geochemical reactions that may occur. *In situ* oxidation rates can be useful for model calibration or validation.

David and Nicholson (1995) compared oxidation rates based on mass balance of oxidation products in pore water and flux of oxygen into the tailings based on Fickian diffusion and measured oxygen gradients and estimated diffusion coefficients in shallow tailings. Estimation of oxidation rates from pore water geochemistry can be complicated by issues such as secondary reactions, mineral precipitation, displacement of oxidation products by existing flow field dynamics, and fluctuation in the water table and infiltration histories. However, these two rate estimation methods provided rates that were comparable, in relative terms, over a four order-of-magnitude range. It was recognized that the mass balance approach involved much imprecision and the oxygen gradient method provided more reasonable estimates of in-situ oxidation rates. The oxygen gradient method is, however, time consuming and is an indirect estimate because it is based on gravimetric moisture content measurements that are used to calculate gas diffusion coefficients using semi-empirical relationships such as that reported by Elberling and Nicholson (1996). The gravimetric moisture content measurements are prone to error due to difficulties in collecting a representative sample. Diffusion coefficients are strongly influenced by moisture content and the most resistive (or highest moisture content) layers may be on the order of millimeters to a few centimeters in thickness (Elberling et al, 1994). This can result in an inaccurate moisture content measurement and a potential propagation of large errors in oxidation rate calculation can result.

A more direct measurement of oxidation rates in tailings was reported by Williams (1993) and Elberling *et al.,* (1994) in the laboratory and by Nicholson *et al.,* (1995) and Elberling and Nicholson (1996) in the field. This method is referred to as the Oxygen Consumption Method and is based on the direct measurement of oxygen uptake at the tailings surface. The method has been shown to provide rates that correlate well with sulphate production rates and therefore, can also be used to estimate water quality in tailings. Although the methodology is established, there is a scarcity of measurements at tailings facilities. This research uses the oxygen consumption method in the investigation of *in situ* sulphide tailings oxidation rates measured at six field locations representing a variety of physical, chemical and seasonal conditions.

2.3 Understanding the Measurement Technique

The Oxygen Consumption Method is a measurement of the depletion rate of oxygen in a fixed volume reservoir due to oxygen transport into the tailings and its consumption by sulphide oxidation. An understanding of both the oxygen transport and consumption processes are necessary to relate this measured flux to the actual oxidation rate.

2.3.1 Oxygen Transport

Oxygen can cross the tailings/atmosphere boundary by several methods, including advective transport as dissolved oxygen in infiltrating water, volume displacement by infiltrating waters, wind action, barometric pumping, and diffusion in the gas and liquid phases.

The advective transport of dissolved oxygen by water infiltrating from precipitation events is limited to the saturation value of dissolved oxygen (D.O.) in the infiltrating waters. The D.O. saturation level at 25^{O}C and is 5^{O}C, is 8.26 mg l^{-1} and 12.8 mg l^{-1} respectively (Appelo et al., 1994). With an estimated yearly infiltration rates in the range of 60 - 280mm for tailings impoundments in northern Ontario Canada (Woyshner, 1994 and Coggans, 1992) the maximum flux of oxygen into the tailings is on the order of 0.1 mol O_2 m^{-2} a^{-1}. While non-trivial, this amount can be considered to represent the lower limit for most tailings impoundments containing sulphide minerals in temperate to humid environments.

Oxygen transport by barometric pumping may result from changes in atmospheric pressure but barometric fluctuations over the course of a day would cause a negligible amount of net transport for most tailings impoundments (Elberling et al., 1994). For tailings impoundments the dominant mechanism for oxygen transport is diffusion. Oxygen diffuses through both the gas and water phases within the soil (or tailings) profile. However, the diffusion coefficient for oxygen in water is approximately five orders-of-magnitude lower than for air,

$1.78X10^{-5}$ m^2 s^{-1} and $2.2X10^{-9}$ m^2 s^{-1} (Weast, 1984). These values differ slightly in their meaning. The diffusion coefficient of oxygen in water is based on the concentration of oxygen in the water phase that is lower than that for air. This means that the actual difference in diffusion coefficients is in excess of four orders-of-magnitude. At equilibrium, the concentration in the water phase in related to the concentration in the gas phase by Henry's Law constant. This value shows that for consistent concentration units [M L^{-3}] that the concentration of oxygen in the air phase is about 30 times that in the water phase. The mass transport of oxygen into tailings is therefore strongly influenced by the water content or degree of saturation of the tailings.

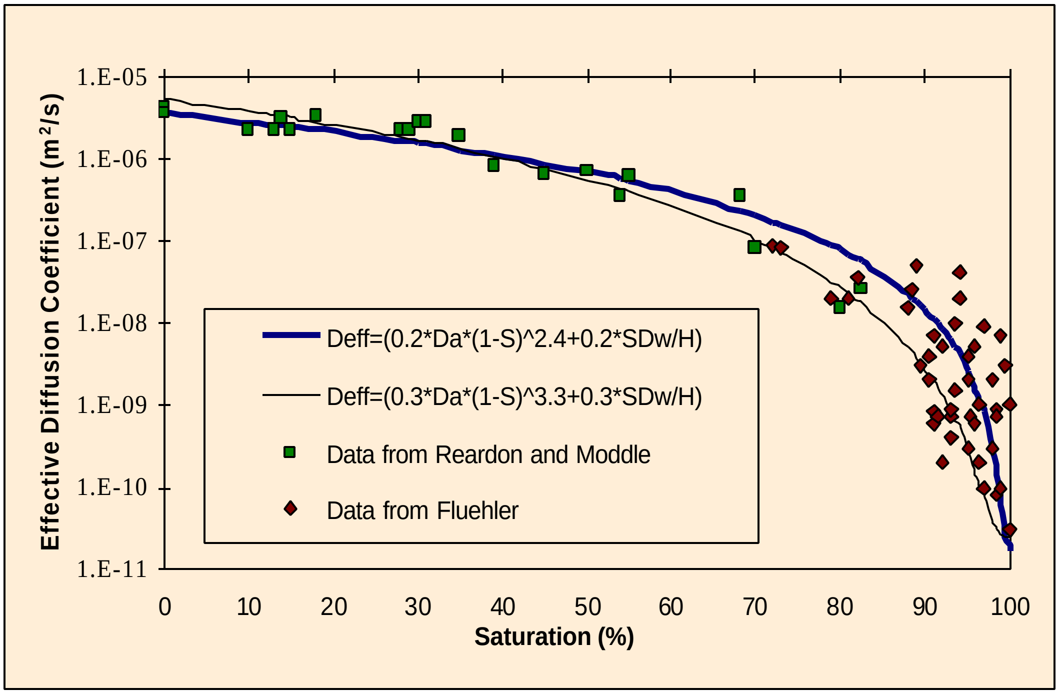
2.3.2 Diffusion vs. degree of saturation

Diffusion in homogeneous media is straight forward and diffusion coefficients for various substances are readily available (Weast, 1984; Levine, 1978) for example . Variation of diffusion coefficients in one medium is small, usually within a range of a factor of 2 to 5. Diffusion of a gas in a variably-saturated porous media is complex and the coefficient varies over orders of magnitude. Many studies have attempted to develop methods of estimating the diffusion coefficient of a gas in porous media (Millington and Quirk, 1961; Shearer et al., 1973 and Collin and Rasmuson, 1988). Most attempts have resulted in semi-empirical methods based on moisture content or combinations of moisture content and porosity. Elberling et al., (1994) proposed an equation, modified from David (1993) with data from Reardon and Moddle (1985), to determine D_e as a function of water saturation (S);

$$D_e = \tau\, D_a^o (1-S)^{\alpha} + \frac{\tau\, S D_w^o}{H} \qquad (2\text{-}1)$$

where D_a^o is the diffusion coefficient of oxygen in air, D_w^o is the diffusion coefficient of oxygen in water, and H is the unitless modified Henry's law constant and is defined as the concentration of oxygen in the gas phase divided by the concentration of oxygen in the water phase at equilibrium. The equilibrium liquid-vapor partitioning coefficient H has a value of 29.7 (mol m^{-3} in air per mol m^{-3} in water) at 20 ^oC. The parameters τ and α are dimensionless fitting parameters obtained from nonlinear regression analysis of experimental data and are equal to 0.27 " 0.08 and 3.23 " 0.4, respectively, for data on tailings samples. More recent measurements conducted on other sites showed good agreement with this relationship and it is anticipated that equation (3-5) would apply to many fine sandy to silty materials (Elberling et al, 1994). An alternate regression was calculated incorporating data from Flühler (1974) that included measurements in highly saturated natural soils. For this case the values of τ and α are approximately .2 and 2.4 respectively. Figure 2-1 shows plots of measured effective diffusion coefficient (D_e) against the degree of saturation of the media and two regression equations; one, including and one excluding the Flühler data.

Figure 2-1. Effective diffusion coefficient versus percent saturation.



The good correlation between the measured values and those predicted from the empirical equation (2-1) over a large range suggests that this equation is a reasonable method for estimating D_e. More importantly, in the context of this work, Figure 2-1 provides understanding of the importance of the degree of saturation in influencing D_e. Figure 2-1 also shows that from completely dry material up to a degree of saturation of 70% there is only a change of approximately one order-of-magnitude in the effective diffusion coefficient. However, for the range of saturation between 70% to 100% (full saturation) the diffusion coefficient varies by about 4 orders-of-magnitude.

Oxidation rates in tailings are controlled by a combination of the diffusion limited transport of oxygen and the chemical reaction rate of the sulphide oxidation. In systems with high degrees of saturation the dominante factor controlling the rate at which the oxidation can proceed is diffusion. Conversely, in systems were the water saturation is minimal the effect of diffusion on the oxidation rate is diminished (Elberling et al., 1994 and Richie, 1994).

2.3.3 The Theory of Oxygen Consumption

The process of diffusion can be described as molecular transport as a result of random, independent molecular motion that results in the net transport from regions of high concentration to regions of lower concentrations. At steadystate, oxygen diffusion in one dimension can be described by Fick's First Law:

$$F = - D_e \, dC/dz \qquad (2\text{-}2)$$

Where F is the oxygen flux [$ML^{-2}T^{-1}$], the rate of oxygen transport per unit cross-sectional area, D_e is the diffusion coefficient of the media [L^2T^{-1}], C is oxygen concentration [ML^{-3}], and z is depth [L]. The driving force for diffusive transport into the tailings is the oxygen concentration gradient (dC/dz) established in the tailings by oxygen consumption through sulphide oxidation. Conservation of mass and Fick's first law can be applied to a unit volume of the tailings where the change in concentration over time is equal to the net transport of oxygen into the tailings plus the mass of oxygen consumed within the unit volume to give;

$$\partial C/\partial t = D_e\, \partial^2 C/\partial z^2 + R \qquad (2\text{-}3)$$

This assumes vertical, one-dimensional diffusion into the tailings. The development of the complete continuity equation requires that R, the oxygen consumption term be expressed more explicitly. In this case, R is a kinetic term that relates the depletion of oxygen to the rate of oxidation of sulphide minerals in the tailings.

2.3.4 Oxygen Consumption in Sulphide Mine Tailings

The continuity equation developed above includes a transport term, and a kinetic term that incorporates the oxidation of the sulphide minerals present in the tailings. This term requires the consideration of chemical kinetics and stoichiometry of sulphide mineral oxidation.

The most common sulphide minerals in mine tailings are pyrite and pyrrhotite. Other sulphide minerals including chalcopyrite, sphalerite, and arsenopyrtie are often present in small quantities but contribute minimally to oxygen consumption for the majority of impoundments (Jambor 1994) and specifically for the impoundments featured in this investigation. While this work concentrates on the oxidation processes pertaining to pyrite and pyrrhotite, similar calculations could be applied to the oxidation of other sulphide minerals.

The oxidation of pyrite can be described by the following equation (Stumm and Morgan, 1981);

$$FeS_2 + {}^{7}/_{2}O_{2(g)} + H_2O \longrightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad (2\text{-}4)$$

Similarly the oxidation of pyrrhotite can be described as;

$$Fe_{(1-x)}S + (2-({}^{x}/_{2}))O_{2(g)} + xH_2O \longrightarrow 2SO_4^{2-} + (1-x)Fe^{2+} + 2xH^+ \quad (2\text{-}5)$$

Where x varies between 0 and 0.125 depending on the crystallographic structure (Nicholson and Scharer, 1994). A simpler stoichiometry for equation 2-5 can be used to approximate pyrrhotite oxidation as follows;

$$FeS + 2O_{2(g)} \longrightarrow SO_4^{2-} + Fe^{2+} \quad (2\text{-}6)$$

In which it is assumed that x=0.

The Fe^{2+} produced in equations (2-4) and (2-6) can be further oxidized as described by the reaction;

$$Fe^{2+} + {}^{1}/_{4}\,O_{2(g)} + {}^{5}/_{2}\,H_2O \longrightarrow Fe(OH)_3 + 2H^+ \quad (2\text{-}7)$$

Thus, the compete oxidation of pyrite can be written as:

$$FeS_2 + {}^{15}/_{4}O_{2(g)} + {}^{7}/_{2}H_2O \longrightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \quad (2\text{-}8)$$

And similarly, the complete oxidation of pyrrhotite can be written as:

$$FeS + {}^{9}/_{4}O_2 + {}^{5}/_{2}H_2O \longrightarrow SO_4^{2-} + Fe(OH)_3 + 2H^+ \qquad (2\text{-}9)$$

This stoichiometric treatment of the oxidation process allows the measurement of the oxygen consumption rate to be related to sulphide oxidation and the formation of oxidation products. The implications of the stoichiometry are addressed in more detail in the Discussion section of this document.

A reaction rate equation relating oxygen consumption by sulphide oxidation to the concentration of oxygen present can be expressed as;

$$dC/dt = -kC^n \qquad (2\text{-}10)$$

Where k is the chemical rate constant [T^{-1}] for the reaction, C [ML^{-3}] is the concentration of oxygen at time (t) and n is the rate order with respect to oxygen. The range for n has been reported to vary between 0 to 1 inclusive by Lowson (1982). Nicholson (1984) showed that applying zero or first-order kinetics does not significantly affect oxygen flux calculations. For ease of solution of the partial differential equations that describe the oxygen flux into the tailings, n will be assumed to be equal to 1. This results in a simplification of equation 2-10 to give;

$$dC/dt = -kC \qquad (2\text{-}11)$$

This rate equation can now be substituted back into equation 2-3 in place of R.

2.3.5 Combining the Diffusion and Consumption Transport of Oxygen

Combining the equations for the diffusive transport of oxygen into the tailings (2-3) and the consumption of oxygen in the tailings by sulphide oxidation (2-11) yields (Nicholson et al., 1989);

$$\partial C/\partial t = D_e\, \partial^2 C/\partial z^2 - kC \qquad (2\text{-}12)$$

Assuming steady state, dc/dt=0, and applying the boundary conditions, C(0)=Co and C(∞)=0, the solution to equation 2-12 becomes;

$$C/C_o = \exp(-z(k/D_e)^{0.5}) \qquad (2\text{-}13)$$

Equation 2-13 describes the concentration of oxygen as a function of distance (z) from the tailings surface (Nicholson et al, 1989). The oxygen flux into the tailings may be obtained by differentiating equation 2-13 with respect to ‘t’ and multiplying by De to yield;

$$\partial C/\partial t = C_o(k/D_e)^{0.5} \exp(-z\, (k/D_e)^{0.5}) \qquad (2\text{-}14)$$

At z=0 (the tailings-atmosphere interface) the flux is given by;

$$F=C_o(kD_e)^{0.5} \quad (2\text{-}15)$$

Where F is the mass of oxygen crossing a unit area (A) of the interface in a unit time (t). If a reservoir with an initial fixed mass of atmospheric gas is placed over the tailings surface the concentration of oxygen will decrease over time as it is consumed by sulphide oxidation within the tailings. A continuity equation for the reservoir can be expressed as;

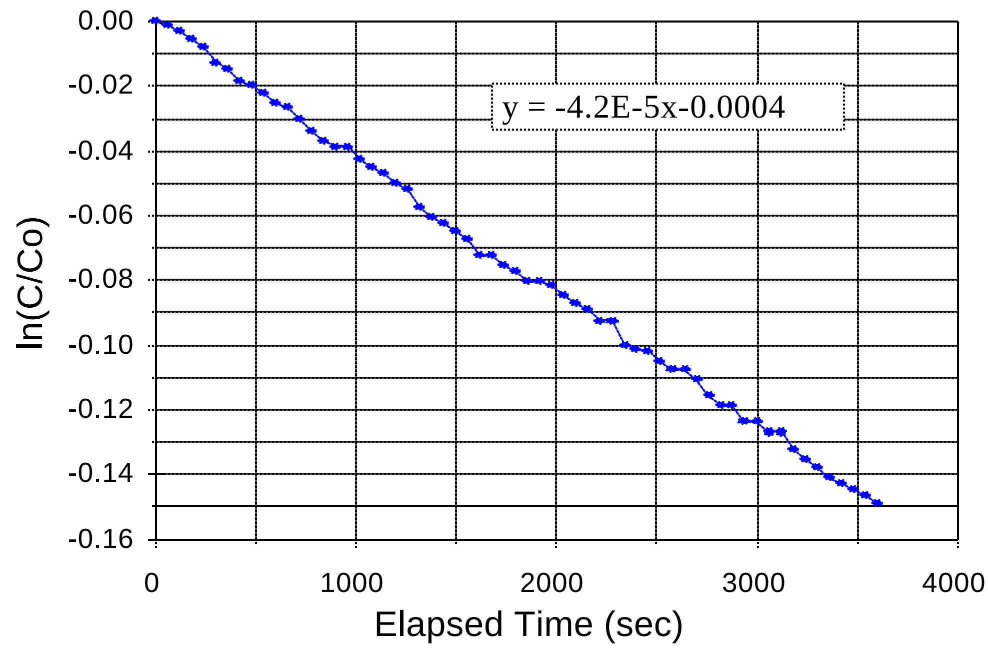
$$V\, dC/dt = AC_o(kD_e)^{0.5} \quad (2\text{-}16)$$

Where V is the volume of the reservoir and A is the surface area of the interface between the tailings and the atmosphere. The solution to (2-16) for the initial conditions $C=C_o$ at t=0 is (Elberling et al., 1994);

$$\ln(C/Co) = -{}^{A}/_{V}(kD_e)^{0.5}t \quad (2\text{-}17)$$

Where $-{}^{A}/_{V}(kD_e)^{0.5}$ is the slope of the plot of ln(C/Co) vs. time plot as shown in Figure 2-2. The value $(kD_e)^{0.5}$ can be substituted back into Equation (2-14) to calculate the flux of oxygen at the tailing surface. This flux is referred to as the oxygen consumption rate in this study.

Figure 2-2: Example plot of oxygen consumption rate test data



The decrease in oxygen concentration within the reservoir is around 1 to 2 % absolute during a typical test. The duration of a typical test was 30 to 60 minutes for exposed tailings and 60 to 120 minutes for covered tailings where consumption rates were usually much lower than those observed on exposed tailings.

2.3.6 Relating Oxygen Consumption and Oxidation Products

The oxygen consumption rates measured by the Oxygen Consumption Method can be related to the oxidation of the sulphide minerals and also to the oxidation products , acidity and sulphate. From Equations 2-4 and 2-8 it can be seen that the consumption of 1 mole of O_2 through pyrite oxidation can generate between 0.57 and1.07 moles of acid. Similarly one mole of O_2 consumed through pyrrhotite oxidation can generate between 0.0 and 0.89 moles of acid, equations 2-6 and 2-9 . The buffering of the acid generated from the above equations is usually reported as the mass of equivalent calcite ($CaCO_3$) required for neutralization. The equation that governs this buffering can be expressed as:

$$\mathbf{CaCO_3 + H^+ \longrightarrow Ca^{2+} + HCO_3^-} \qquad (2\text{-}17)$$

One mole of H^+ is assumed to be neutralized for each mole of $CaCO_3$ if the pH remains in the neutral range of 6 to 7.

This is a very conservative assumption and applies to a closed system. In systems open to the atmosphere (or gas phase with a waste pile) where a constant partial pressure of carbon dioxide (CO_2) can occur, one mole of $CaCO_3$ solid will consume 2 moles of H^+ as CO_2 degasses from the water as in the following reaction:

$$\mathbf{CaCO_3 + 2H^+ \longrightarrow Ca^{2+} + CO_2 - + H_2O} \qquad (2\text{-}18)$$

Most wastes will behave as open systems and the ratio of $CaCO_3$: H^+ will approximate 1:2 even though there will be transient periods in which this ratio approaches 1:1. For purposes of this report, the standard 1:2 ratio will be used.

Values obtained using the oxygen consumption method can be reported as a flux with the units of moles O_2 consumed per unit area of tailings surface per unit time. This can also be converted to a mass flux of products per area per time based on the oxidation equations for the sulphide minerals present, and further converted into an equivalent mass of $CaCO_3$ required for neutralization. Sample conversions are listed in Table 2-1.

Table 2-1. Sample conversions of oxygen consumption rate to equivalent mass of $CaCO_3$ consumed and SO_4 produced.

	Pyrite			**Pyrrhotite**		
Oxygen Consumption Rate Mol O_2 m^{-2} a^{-1}	Equiv. $CaCO_3$ Consumption Kg $CaCO_3$ m^{-2} a^{-1}		Potential Sulphate Production kg SO_4 m^{-2} a^{-1}	Equiv. $CaCO_3$ Consumption kg $CaCO_3$ m^{-2} a^{-1}		Potential Sulphate Production kg SO_4 m^{-2} a^{-1}
	Min	Max		Min	Max	
1	0.03	0.06	0.06	0.00	0.05	0.05
25	0.71	1.34	1.38	0.00	1.11	1.18
50	1.43	2.68	2.75	0.00	2.22	2.35
100	2.85	5.35	5.50	0.00	4.44	4.70

The values reported under the headings of minimum equivalent $CaCO_3$ consumption reflect the oxidation of pyrite as described in equation 2-4, and the oxidation of pyrrhotite as described in equation 2-6. In these reactions, Fe^{2+} is the final iron species produced (unoxidized). The maximum equivalent $CaCO_3$ consumption values in Table 2-1 include the oxidation of the Fe^{2+} as described in equations 2-8 and 2-9. The oxidation product, $Fe(OH)_3$ is easily recognized and is commonly observed in the field as reddish-brown stains. However, dissolved Fe^{2+} is also a major component in tailings pore water as shown by Duborvsky *et al.,* (1985). It is evident, therefore, that the actual amount of acid produced, or equivalent $CaCO_3$ consumed at most tailings facilities, will almost always be intermediate between the stated minimum and maximum values. The potential sulphate production rates in Table 2-1 represent average values based on stoichiometric ratios in equations 2-4 and 2-6 for pyrite and equations 2-5 and 2-6 for pyrrhotite. Differences in sulphate production are small and are not reported as ranges for these reactions. Laboratory (Elberling. et al., 1993) and field (Elberling and Nicholson 1996) studies report good correlation between measured oxygen consumption rate and sulphate loading in tailings pore water.

Conversion of the measured oxygen consumption rate from mol O_2 m^{-2} a^{-1} to kg $CaCO_3$ m^{-2} a^{-1} provides an estimate of neutralization required to counter the acidity produced from the oxidation of the sulphide minerals. The units kg $CaCO_3$ equivalent are units that are more familiar to those dealing with the impacts of acidic drainage than units of mol O_2 m^{-2} a^{-1}.

3. MEASUREMENTS AND METHODS

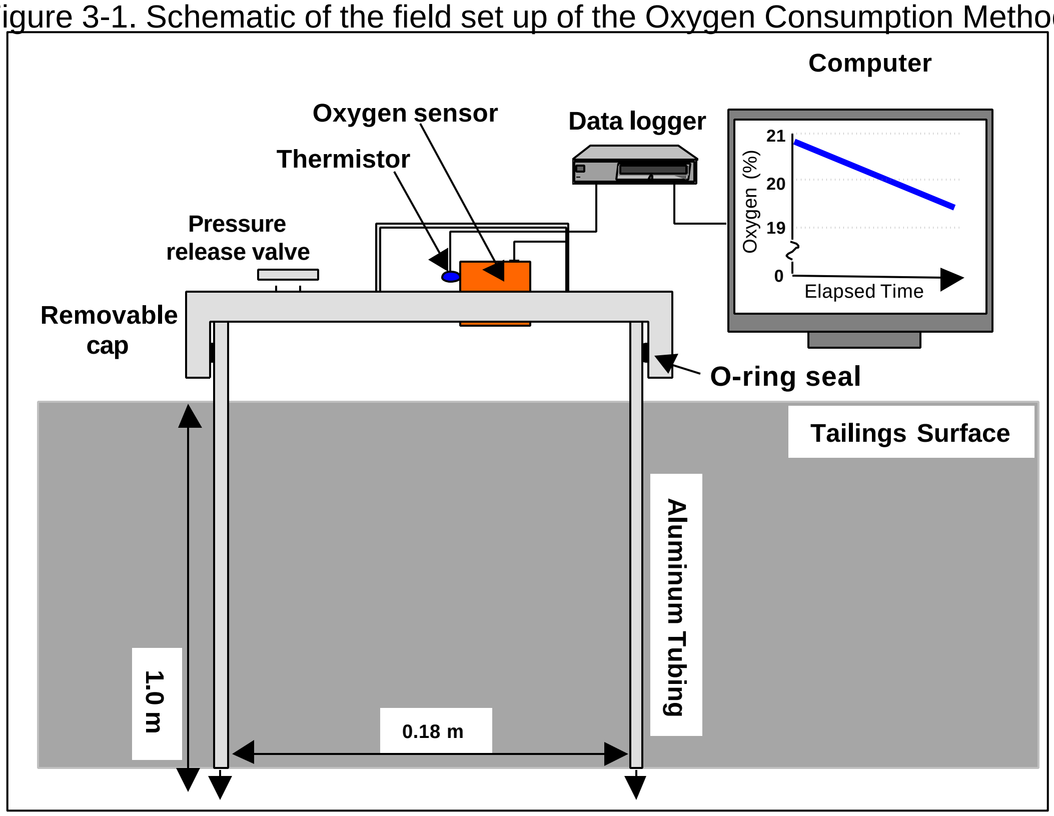
The Oxygen Consumption Method is a relatively new method that measures the rate of oxygen consumption by sulphide tailings. This method was first used in the laboratory by Williams (1993) and Elberling et al., (1994) and applied to the field by Williams (1993) and Elberling and Nicholson (1996). The Oxygen Consumption Method was modified for greater reliability in the field. Automated data-logging systems were developed to conduct measurements at several testing points at one time. Refinements for this investigation included developing methodology to minimize temperature variations and the derivation of a correction factor to decrease errors introduced into the measurement by fluctuating ambient temperatures during the test. The derivation of the temperature correction factor is presented in Appendix A.

3.1 Testing Methodology

3.1.1 Equipment Installation and Data Collection

The Oxygen Consumption Method involves the installation of 17.8cm (7") O.D., thin-wall aluminum tubing vertically into the tailings. For this research the tube length was 0.6m and 1.0m. The length of the tube is selected so that when installed it penetrates to a depth where high saturation conditions exists. This establishes a well-defined testing area on the tailings and a vertical boundary condition to prevent horizontal gas migration during the test. It has been shown that a period of up to approximately 48 hours can be required to re-establish steady-state oxygen profiles in tailings material (Elberling *et al*, 1994) and this was the waiting period observed prior to making measurements. A small headspace (0.01-0.02m) above the cover or tailings surface was maintained in each tube. This headspace is temporarily sealed during the test with a gas tight cap to measure the depletion of oxygen in the headspace. (Figure 3-1). The finite quantity of oxygen in the sealed headspace is decreased by the oxidation of the sulphide minerals in the tailings. Sensors located in the cap measure gaseous oxygen content in the sealed headspace of the tube as well as temperature.

Figure 3-1. Schematic of the field set up of the Oxygen Consumption Method.



The oxygen sensor used in these tests was the GC33-200 manufactured by GC Industries. The sensor is a galvanic electrochemical cell using the Pb-PbOOH half-cell to reduce oxygen. The voltage produced by this reduction reaction is directly proportional to the partial pressure of oxygen in the gas phase. The voltage from the sensor was measured using a Fluke Hydra 2620A data acquisition unit and recorded by a computer data-logging program developed at the University of Waterloo (Redman 1995) or measured and recorded using an Ultra-Logger Data Storage Unit R-X (Lakewood Systems LTD.).

Temperature was measured by a 10 kΩ thermistor that was monitored against a reference resistor in the case of the Ultra-Logger or the measured resistance converted to temperature based on a 3rd order polynomial conversion equation (Redman 1995) for the Fluke Hydra 2620A. The temperature sensor was located in the cap assembly to measure temperature fluctuations in the vicinity of the sensor body (Figure 3-1). Each oxygen consumption rate test measurement was conducted over a 1 to 2 hour period with readings recorded every minute. The typical decrease in the oxygen content in the sealed headspace during the test was from 20.9% (atmospheric) to about 19%. The resultant time series of oxygen content values were reduced to provide a value corresponding to flux of oxygen across the air-tailings boundary across an area of tailings (that within the tube) over a period of time. This results in a oxygen consumption rate, or flux, expressed as mol O_2 consumed m^{-2} a^{-1}.

3.1.2 Correction of Errors Resulting from Temperature Fluctuations

Early in the development of the field testing equipment it was observed that the oxygen sensor measurement was affected by temperature fluctuations.

Fluctuations in temperature during the 1-2 hour test period could potentially lead to inaccurate oxygen consumption rate measurements. A correction factor was developed to aid in limiting errors associated with temperature fluctuations (Appendix A). Temperature variation in the cap assembly was minimised by insulating the volume around the sensor and by providing protective insulated covers that were placed over the tube during the oxygen consumption rate test.

3.2 Field Sites

Measurements of the oxygen consumption rate were carried out at six field sites. Field sites were located in Northern Ontario, Northern Quebec, and the North West Territories, Canada. Locations of the field sites can be seen in Figure 3-2.

Oxygen consumption rates are influenced by a variety of parameters. Sites were selected for the investigation of the role and effect of several of these parameters on the oxygen consumption rate of the tailings. The parameters investigated were;

1) sulphide content
2) time of exposure (age of tailings)
3) remediation efforts
   a) covers
      - single layer
      - multi-layer
   b) raised water table

Figure 3-2. Location of studied Field sites

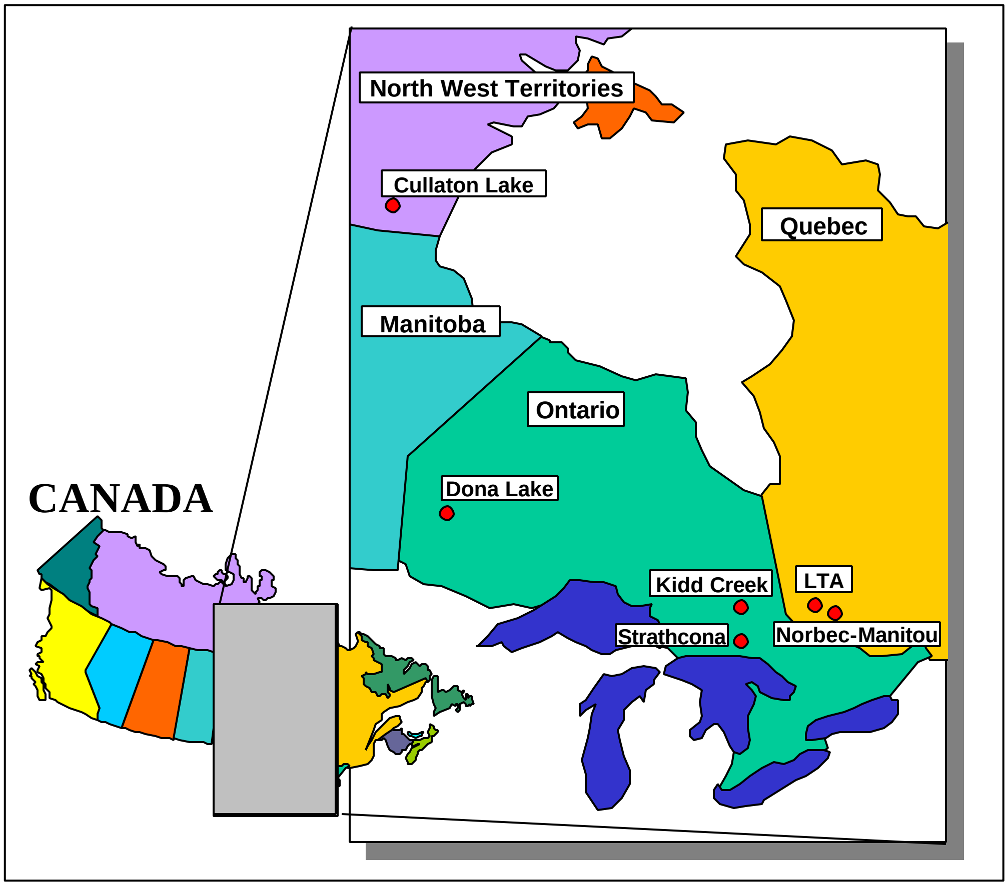


Table 3-1 lists the field site and information on the nature of the tailings as well as the parameter of specific interest at each site.

Table 3-1. Field sites and major parameters investigated

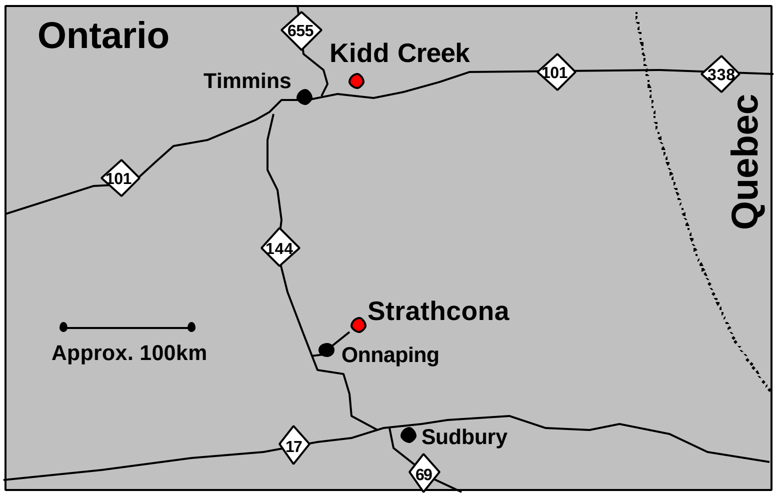
Site	Location	Sulphide	%S Content	Parameter(s) Investigated
Strathcona	N. Ontario	Pyrrhotite	1%, 15%, 30%	Sulphide content
Kidd Creek	N. Ontario	Pyrite	13%	Exposure Time/Moisture
Dona Lake	N. Ontario	Pyrrhotite/Pyrite	5% / 2%	Raised water table/Neutral pH
Cullaton Lake	N.W.T.	Pyrite	0.5% & 2.3%	Till cover/Permafrost
LTA	N. Quebec	Pyrite	5%	Multi-layer cover
Norbec-Manitou	N. Quebec	Pyrite	3%	Multi-layer cover Test Plots

The field portion of this investigation was conducted during the period of October 1995 to June, 1997. Some sites were visited on more than one occasion.

3.2.1 Strathcona, Ont.

The Strathcona tailings site is located approximately 2 km north of the town of Onaping Falls, Ontario (Figure 3-3).

Figure 3-3. Map of the Sudbury and Timmins region.



Ore from 5 mines in the vicinity is milled at the strathcona mill and the resulting tailings deposited in impoundments adjacent to Moose Lake. The property is owned and operated by Falconbridge Limited.

The mine contributing to the Strathcona tailings impoundments produce nickel-copper ore typical of mines located in the Sudbury Basin. The predominate sulphide mineral in the tailings is pyrrhotite. Separation of pyrrhotite from the main tailings is conducted in the mill by a modified flotation circuit. The segregated, high sulphide tailings are discharged to separate impoundments at the site. The high pyrrhotite tailings consists of approximately 30% S as pyrrhotite. The desulphurized portion of the tailings consists of approximately 1% S as pyrrhotite. The tailings are transported from the mill and deposited at the Strathcona Moose Lake site by liquid slurry.

The testing objectives for this site were two-fold; to measure oxygen consumption rates on impoundments of differing, yet known sulphide contents; and to obtain a first-order evaluation of the effectiveness of three proposed gravel cover scenarios. The scenarios investigated involved 0.5 to 1.0m of gravel as potential cover material. The gravel was placed in the tube and manually compacted.

Aluminum tubes were installed in the 30%S, 15%S, and 1%S as pyrrhotite tailings impoundments. The impoundment referred to as the 15%S impoundment contained tailings that had not undergone sulphide content segregation. Two testing stations were installed in both the 15%S and the 30%S impoundments. Locations for these testing stations were selected based on accessibility and are shown in Figure 3-4. All testing stations consisting of four tubes each were installed in the 30% and 15% impoundments. Four testing stations were installed in the 1%S impoundment on a transect running approximately NW-SE within the impoundment with stations spaced at 20m intervals. Each testing station consisted of a control tube, used to measure oxygen consumption rates of the tailings as currently exposed, and three tubes to evaluate the gravel cover scenarios as shown in Figure 3-5.

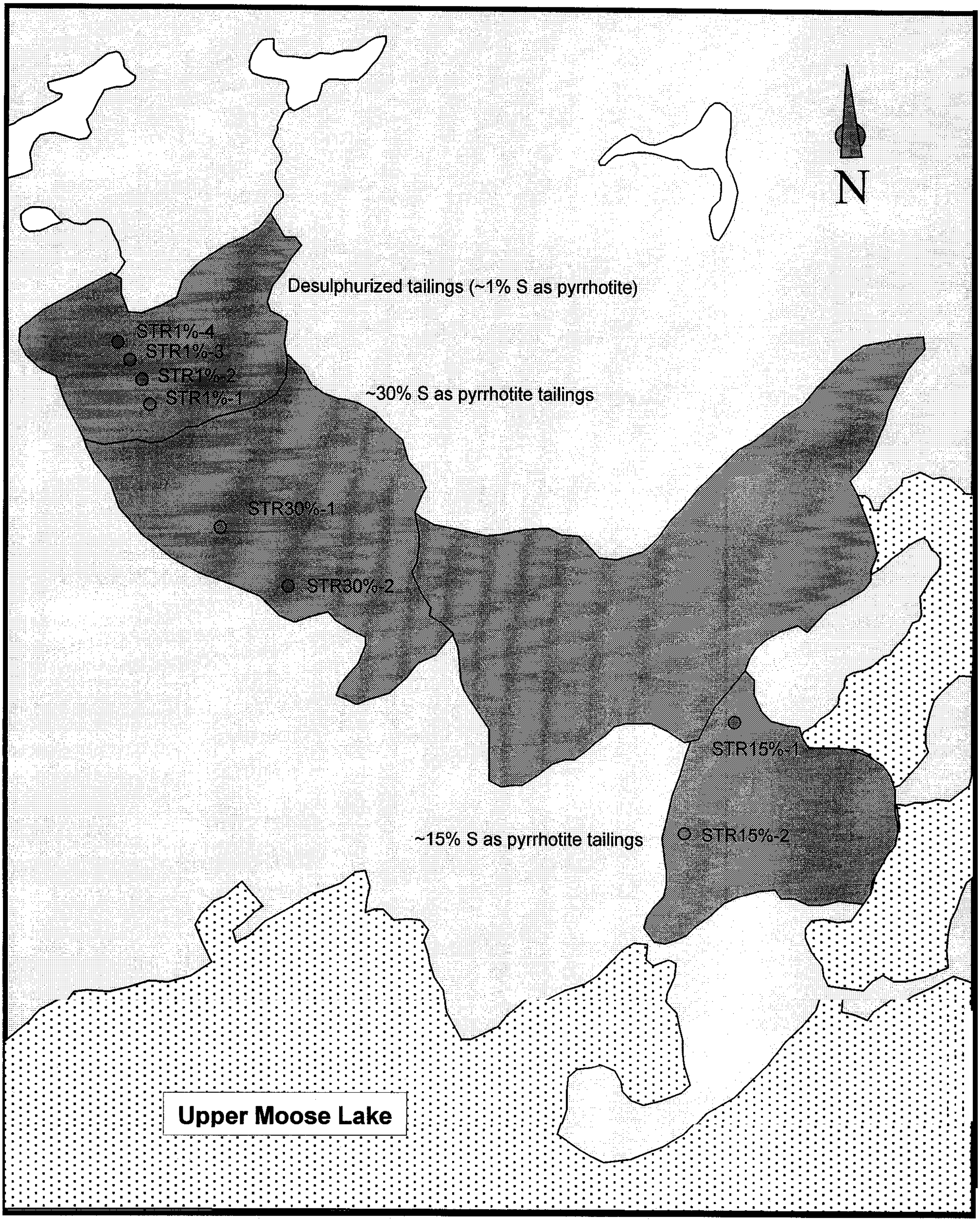
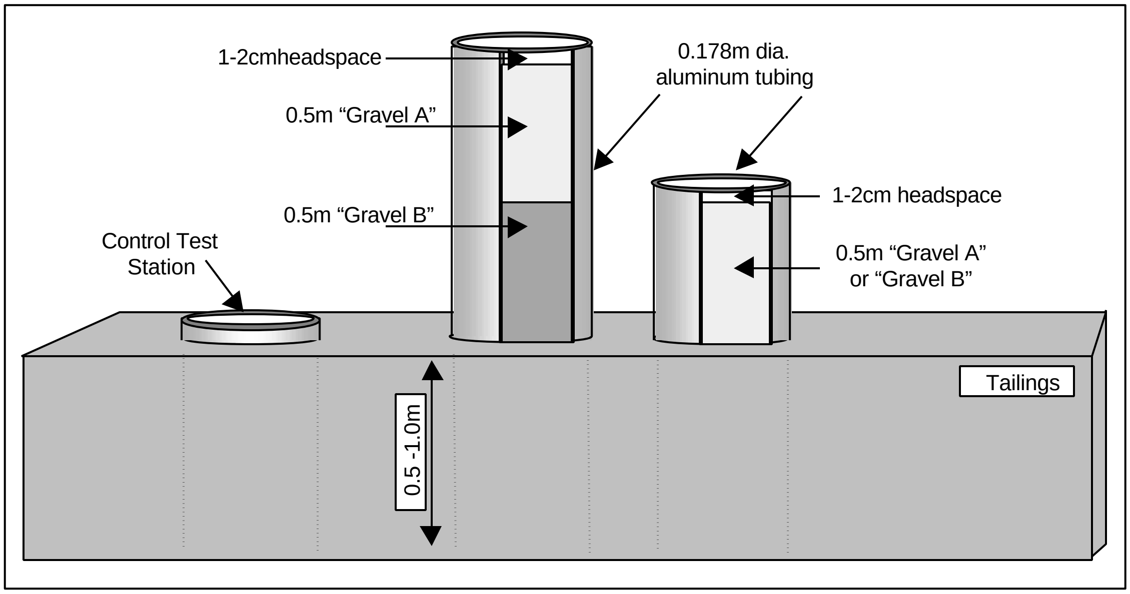


Figure 3-4. Approximate locations of testing stations (Strathcona)

Figure 3-5. Testing set-up for Strathcona tailings and cover evaluation.



Oxygen consumption rate tests were conducted during the period of May 29th to June 2nd 1996.

3.2.2 Kidd Creek, Ont.

The Kidd Creek Tailings impoundment is located approximately 15km north east of Timmins, Ontario (Figure 3-3). The impoundment is located adjacent to the mill complex. The site is owned and operated by Falconbridge Limited, Kidd Creek Division. The Kidd Creek Cu-Zn ore deposit consists of mainly Chalcopyrite, sphalerite, galena, and pyrite. The mine began production in 1966 with current production rates beginning approximately 10000 tonnes per day (tpd). Tailings are deposited as a thickened slurry to a 1200ha impoundment (Robinsky et al. 1991). The thickened tailings disposal method results in a conical impoundment with slopes in the order of 1 to 3%. The thickened tailings method results in a homogeneous, non-segregated tailings compared to most tailings impoudments. The tailings consist of 10–25 wt % pyrite, 1–2 wt % pyrrhotite, 1–2 wt % combined sphalerite and chalcopyrite, 75–85 wt % gangue minerals, 1–5 wt % carbonate minerals and trace amounts of numerous other minerals (Al et al., 1994).

The testing objectives for the Kidd Creek site were to investigate the relationship between exposure time of the tailings and the oxygen consumption rate. It was hypothesized that a trend in decreasing oxygen consumption rates with increased tailings exposure time would be observed. It was anticipated that as oxidation proceeds, consuming the sulphide, the zone of active oxidation will migrate downward. The overlying, sulphide depleted, material will than act to retard diffusion, resulting in a reduction in oxygen consumption rates. The Kidd Creek impoundment was well suited to investigating this issue due to the homogeneous nature of the thickened tailings and a well recorded depositional history. A second objective was to investigate seasonal trends in oxidation rate over the spring, summer, and autumn. Oxygen consumption rates measured near the cone centre were compared to rates measured nearer to the impoundment's perimeter. This was to ascertain if oxygen consumption rates where the vadose zone extended approximately 1m below the surface, differed significantly from rates measured near the impoundment perimeter, where the vadose zone was minimal and the tailings were considerably more saturated.

Initial installation of the testing equipment and the measurement of the oxygen consumption rates occurred during the period of September 11th to 22nd,

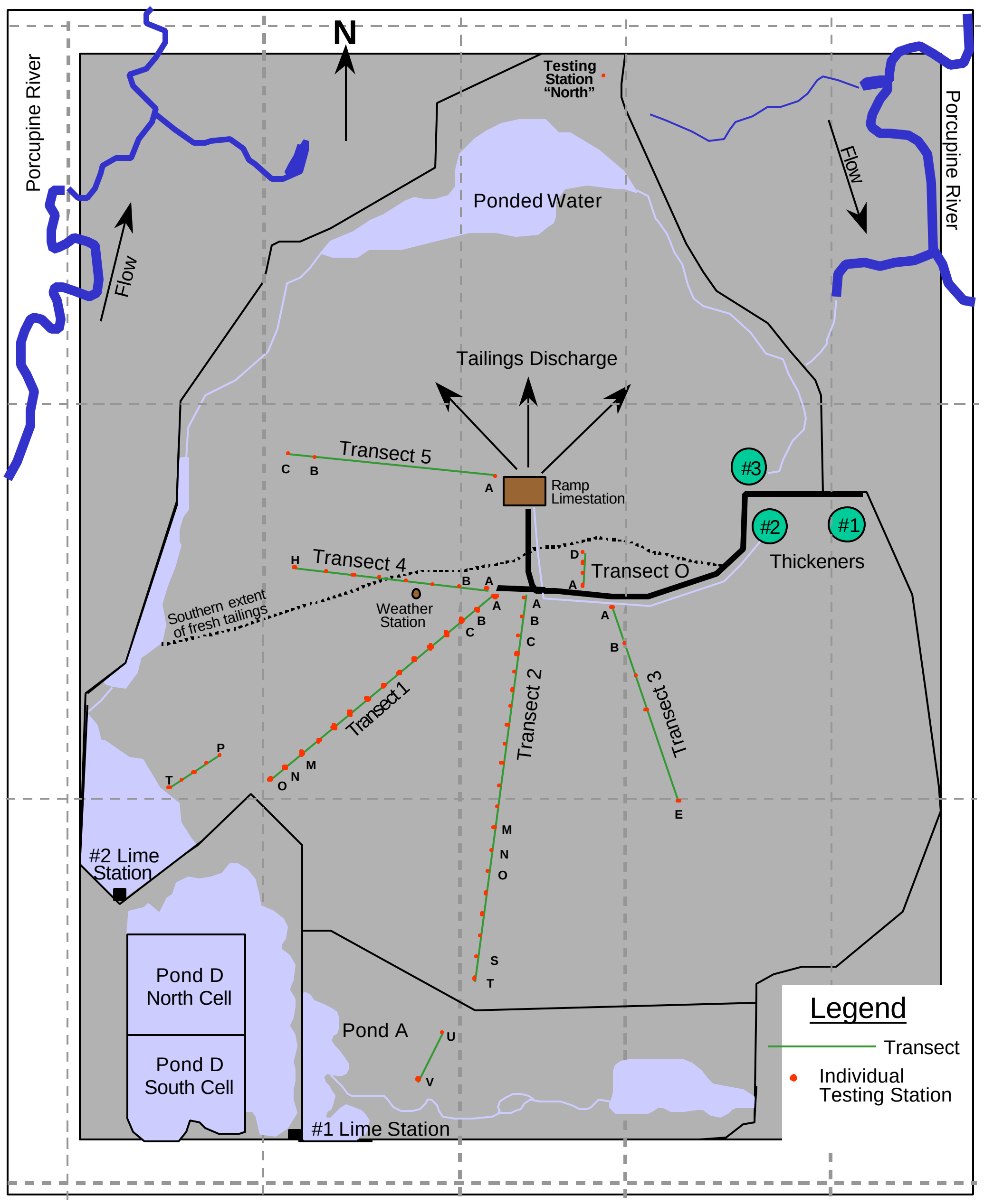
1996. Testing stations at the Kidd Creek consisted of a single aluminum tube (17.8cm (7") O.D. X 1.0m X 0.65’’’) driven manually into the tailings such that only 1-2 cm of stick-up remained. A total of 60 testing stations were installed at the site during the September , 1996 field visit. Most testing locations were configured as transects radiating from the centre of the cone towards the perimeter. Orientations were selected in an attempt to survey tailings that had been deposited up to 10 years ago and as recent as one year ago. The orientation of transects and approximate position of individual testing stations can be seen in Figure 3-6 and detailed in Table 3-2. The centre portion of the cone has a slightly greater slope than the more distal areas. Based on this and the observed condition of the tailings several zones were delineated for purposes of comparing the measured oxygen consumption rates.

Table 3-2. Testing station locations and tailings description.

Transect	Station(s)	Age of Tailings (yrs)	Zone (based on observation)	Approx. Slope of Cone	Tailings Conditions
O	A-D	10	Upper cone	$>2^o$	Well drained[1].
1	A-F	3-4	Upper cone	$>2^o$	Well drained.
	G-O	3-4	Middle cone	$<2^o$	Well drained.
	P-U	3-4	Perimeter	$<2^o$	Near saturation.
2	A-F	5-6	Upper cone	$>2^o$	Well drained.
	G-N	5-6	Middle cone	$<2^o$	Well drained.
	O-T	5-6	Lower-middle cone	$<2^o$	Poorly drained.
	U-V	5-6	Perimeter	$<<2^o$	Near saturation.
3	A-C	5-6	Upper cone	$>2^o$	Well drained.
	D-E	5-6	Middle cone	$<2^o$	Partially Saturated.
4	A-D	3-4	Upper cone	$>2^o$	Well drained[1].
	E-H	<2	Middle cone	$<2^o$	Saturated, poorly consolidated.
5	A	1	Near active spigot	$>2^o$	Saturated, poorly consolidated.
	B-C	<2	Middle cone	$<2^o$	Saturated, poorly consolidated.
	North	<2	Perimeter	$<<2^o$	Near saturation, consolidated.

Approximately 50% of the tailings impoundment was insufficiently drained and consolidated to allow for safe access. This zone consists of fresh tailings (less than 2 years old) that have been deposited since the discharge spigot was moved to its present location. On Figure 3-6, this area is located from the current tailings discharge area northward. The southern extent of this newer tailings deposit is indicated by a dashed line. Despite the unfavorable conditions on the fresher tailings, several testing stations were installed as indicated in Table 3-2, and on Figure 3-6.

Figure 3-6. Approximate location of installed testing stations.



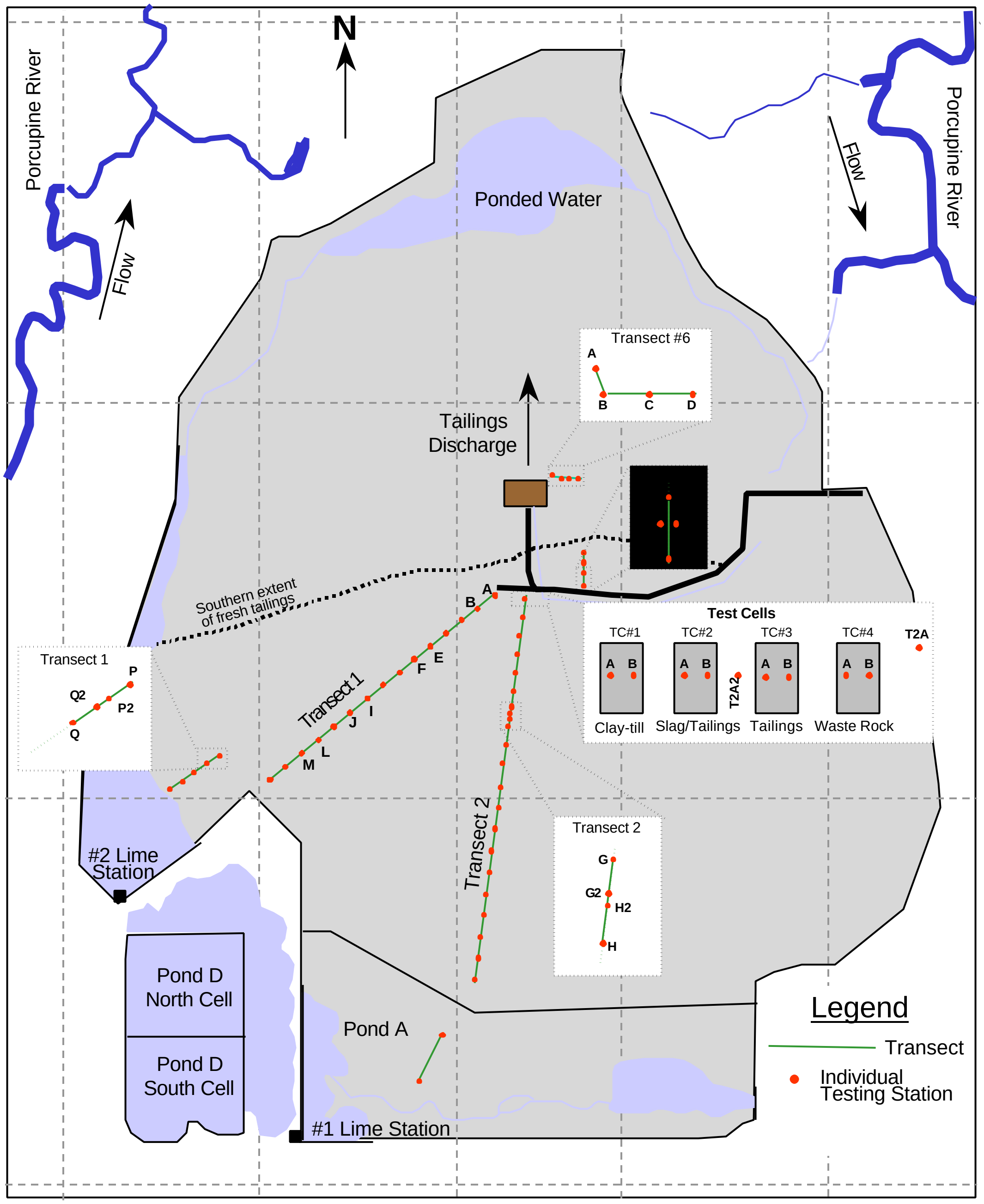
The Kidd Creek site was visited again during the month of May, 1997. The objectives of the May, 1997 visit were to install additional tubes at select locations and to measure the oxygen consumption rate at these locations in order to assess the rate of sulphide oxidation that was occurring at the site during the cooler and wetter spring season. Locations for additional tube installations and for oxygen consumption rate measurements were selected to enable rapid characterization of the impoundment during this and subsequent visits based on the overall oxygen consumption measured in the September, 1996 investigation. Selected measurement locations and the location of additional installed tubes are presented in Table 3-3, and Figure 3-7.

Table 3-3. Selected measurement locations and installation dates (Kidd Creek).

Location	Tubes	Installation Date
Transect #1	A, B, E, F, I, J, L, M, P, Q	Sept. 1996
Transect #2	A1, A2, G, H	Sept. 1996
Old Tailings	A, B	Sept. 1996
Test Plots	1A, 1B, 2A, 2B, 3A, 3B, 4A, 4B	Sept. 1996
Transect #1	P2, Q2	May, 1997
Transect #2	G2, H2	May, 1997
Fresh Tailings	A, B, C, D	May, 1997
Old Tailings	A2, B2	May, 1997

The second visit of the 1997 work plan occurred during the month of June, 1997. No further Oxygen Consumption Method tubes were installed at this time. Oxygen consumption rate measurements were conducted on the select group of tubes measured in May, 1997.

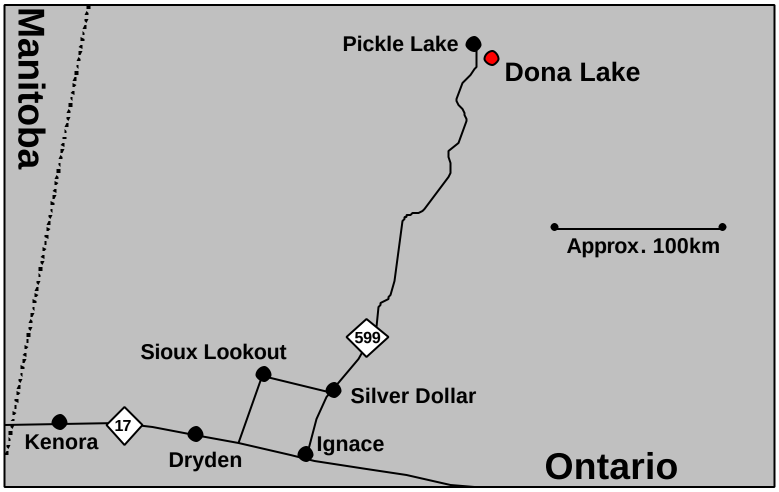
Figure 3-7. Selected measurement locations and Sept. 97 added stations



3.2.3 Dona Lake, Ont.

The Dona Lake tailings impoundment is located approximately 10km south west of Pickle Lake, Ontario (Figure 3-8). The Dona Lake tailings impoundment is under care and maintenance of Placer Dome Canada.

Figure 3-8. Map of the Pickle Lake Region.



Approximately two thirds of the tailings impoundment area was flooded in the spring of 1995 (Ferguson, Pers. Comm., 1997) to minimize the exposed tailings surface area and hence reduce the oxidation of sulphide minerals and subsequent chemical loadings to the pore water and surrounding environment. The exposed tailings area is approximately 14 hectares. This area is bounded to the southeast by a Dyke 3, and to the northwest by Sika Pond (Figure 3-9). The exposed tailings area was the focus of this study. Based on available information (from solids testing) the sulphide component of the Dona Lake tailings was a combination of 18 wt % pyrrhotite and 6 wt % pyrite (Ferguson Pers. Comm., 1996).

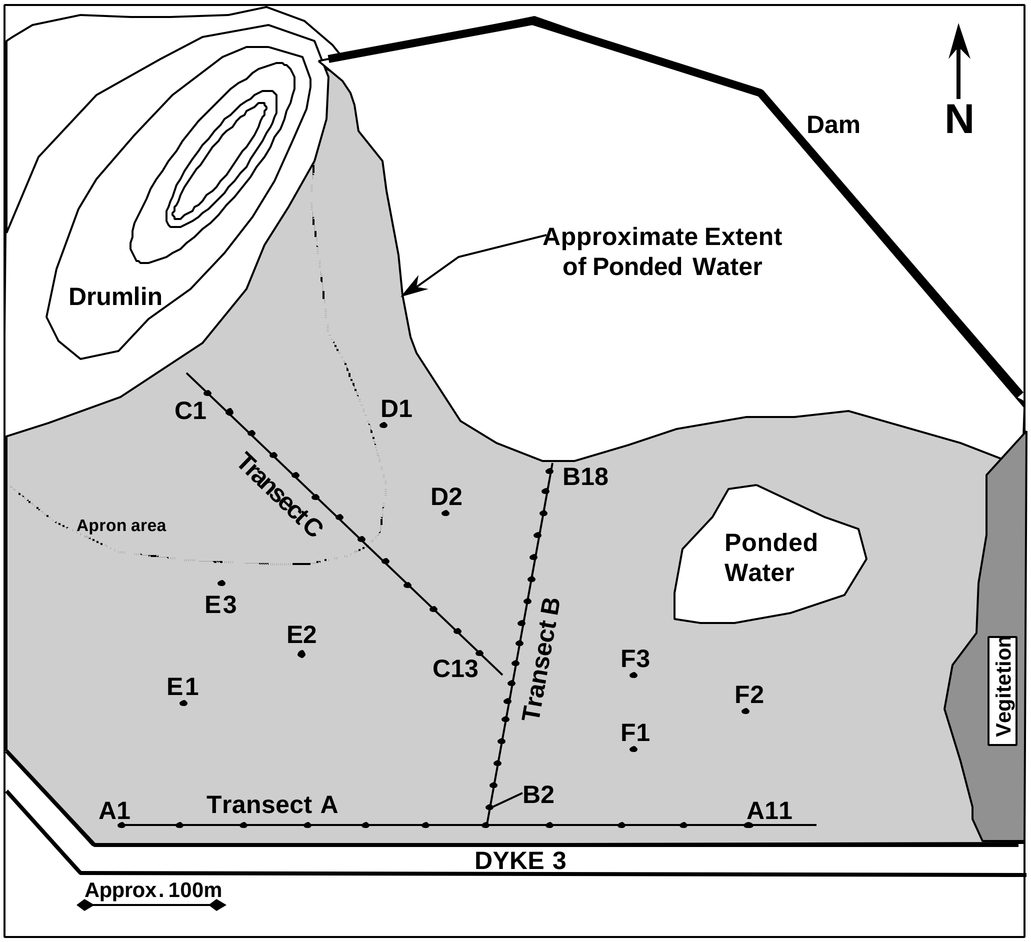
The objectives for the investigation at the Dona Lake impoundment were to assess the overall oxygen consumption rate for the site in general and to investigate the effect of the depth to the water table on the oxygen consumption rate.

The goal of raising the water table, or flooding an impoundment is to minimize the sulphide material in contact with atmospheric conditions, namely gaseous oxygen. With diffusion of oxygen through water being approximately 4 orders-of-magnitude lower than that of oxygen through air, availability of oxygen to oxidize the sulphide material will be greatly reduced. Consequently the oxygen consumption rate and the development of oxidation products will be greatly reduced.

Testing stations at the Dona Lake impoundment consisted of a single aluminum tube 1m in length installed in the tailings with only 1–2 cm remaining above the tailings surface. Three main transects and several discrete testing points were instrumented at the Dona Lake tailings site. Transect A is parallel to Dyke 3 and located approximately 18 m from the dyke. Transect A consists of 11 testing points with a spacing of approximately 45 m between testing points. These stations were referred to as A1 through A11. The depth to the water table along Transect A was approximately 1 meter. The orientation of transect B was selected to coincide with the cross-section 2 used in the SEEP/W modelling simulations carried out of the Dona Lake tailings site by workers at the University of Saskatchewan (Bews. et al., 1994). Transect B is oriented approximately NW-SE, perpendicular to Dyke 3. Transect B consist of 17 testing points at a spacing of approximately 18 m. These testing points are referred to as B2 through B18. Transect A and Transect B intersect at testing point A7. Only one measurement was made at this point.

A drumlin-like feature has been identified at the southeast side of the tailings impoundment. Tailings were deposited on the flank of this topographic feature and on visual inspection appear as dark brown in colour with a deeper water table than in areas in the central tailings area. The third transect (C) was oriented to coincide approximately with cross-section 1 used by Bews. et al. (1994). It was suspected that the area of tailings located on the slightly elevated flank of the drumlin might be experiencing higher oxidation rates due to the thicker vadose zone in that area. Transect C consisted of 14 testing points at a spacing of approximately 20m. These testing points are identified as C1-C13 with testing point C1 being located highest on the drumlin's flank. The locations of these three main transects and all individual testing points are shown in Figure 3-9. Installation of field equipment and measurement of oxygen consumption rates were competed during the period of August 9th through 17th, 1996.

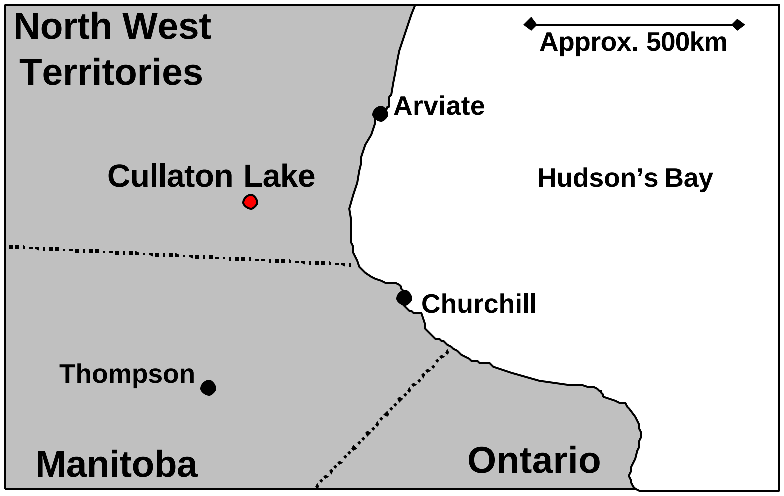
Figure 3-9. Location of oxygen consumption transects and testing points.



3.2.4 Cullaton Lake, NWT

The Cullaton Lake tailings impoundment is located at the former Cullaton Lake Gold Mines LTD. Location in the district of Nunavut, Keewaitin Sub-District of the Northwest Territories. The property is located approximately 620km north of Thompson, Manitoba and 416km northwest of Churchill, Manitoba (Figure 3-10). The site is underlain by continuous permafrost that develops an active zone during the summer season.

Figure 3-10. Map of the Cullaton Lake Region



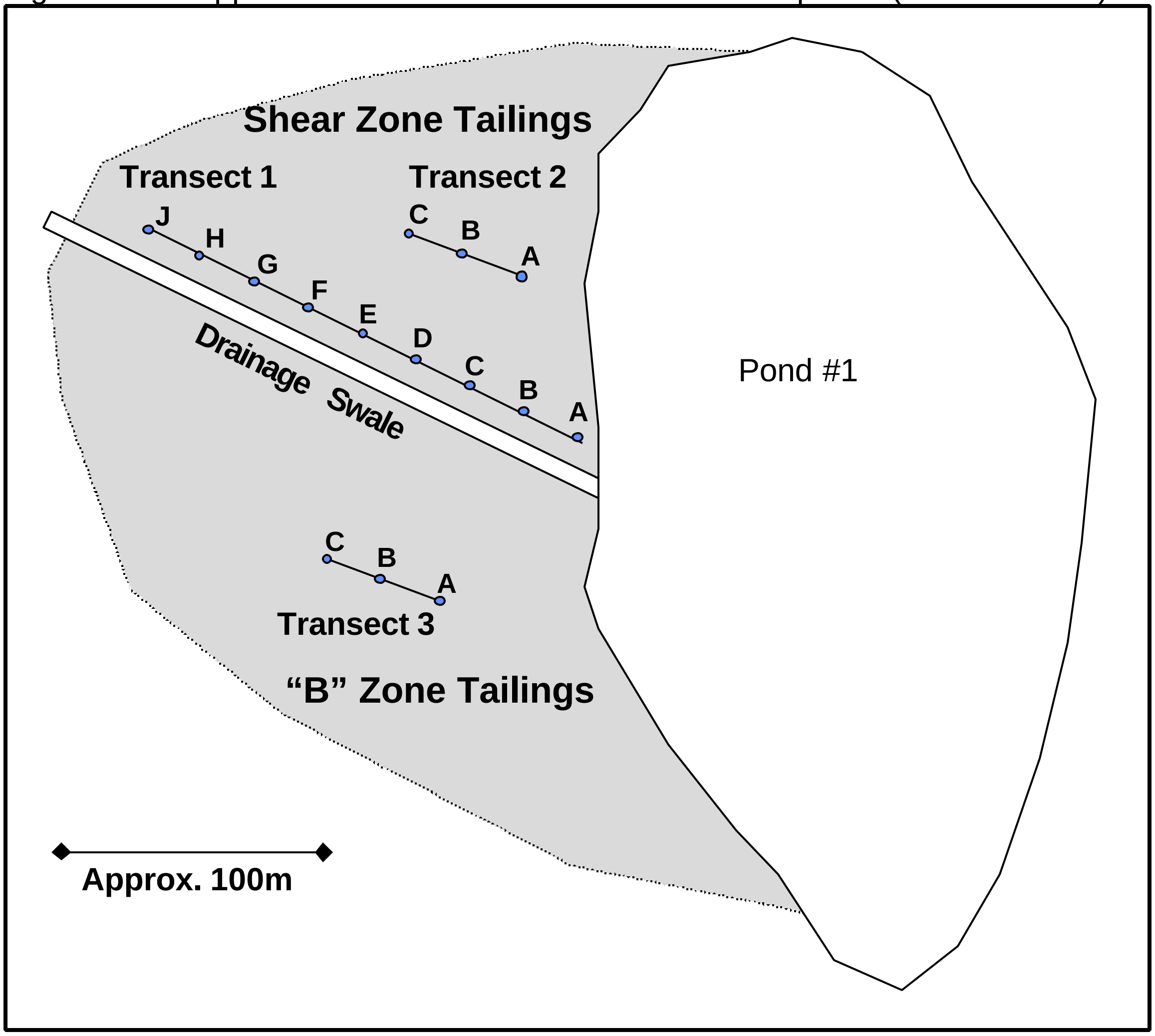
The property is owned by Homestake Canada Ltd. and has been under care and maintenance since September 1985 when production ceased. The tailings impoundment was covered with a waste rock and overburden cover to promote the development of permafrost conditions in the tailings and subsequently limit sulphide mineral oxidation. The tailings impoundment consists of two tailings derived from two distinct ore bodies, the Shear Zone and the "B" Zone ores. The "B" Zone deposit is a gold bearing iron formation located in a turbiditic sedimentary basin that forms part of the Rankin Inlet - Ennadi Archean greenstone belt . Pyrrhotite and pyrite are the dominant sulphide minerals present with minor amounts of arsenopyrite and chalcopyrite. The Shear Zone is a discontinuous ridge of orthoquartzite with gold mineralization found in altered shears, breccias, pyritic shears, pyritic sericitic, and impure quartzite. The dominant sulphide mineral in the Shear Zone is pyrite (Clulow 1996).

The objectives of investigating the oxygen consumption rates at the Cullaton Lake impoundment were to evaluate the effectiveness of the applied till cover. The cover may act as a diffusion barrier, limiting the availability of oxygen in contact with tailings, as a thermal barrier to promote upward development of the permafrost zone to further limit oxidation, and also to maintain high moisture conditions in the tailings by minimizing evaporation. The material selected for the cover was a till and waste-rock mixture locally available.

The three transects were installed on the Cullaton Lake tailings impoundment and are shown in Figure 3-11.

Transect #1 is parallel to the drainage swale that bisects the impoundment. Transect #1 is located on Shear Lake tailings covered by cobbley till cover and consists of 9 testing points at a 15m spacing. These are labeled 1A-1J (to prevent possible confusion the letter "i" was not used). Tube 1A is located 3m from the shore of Pond #1.

Figure 3-11. Approximate location of transects and test points (Cullaton Lake).



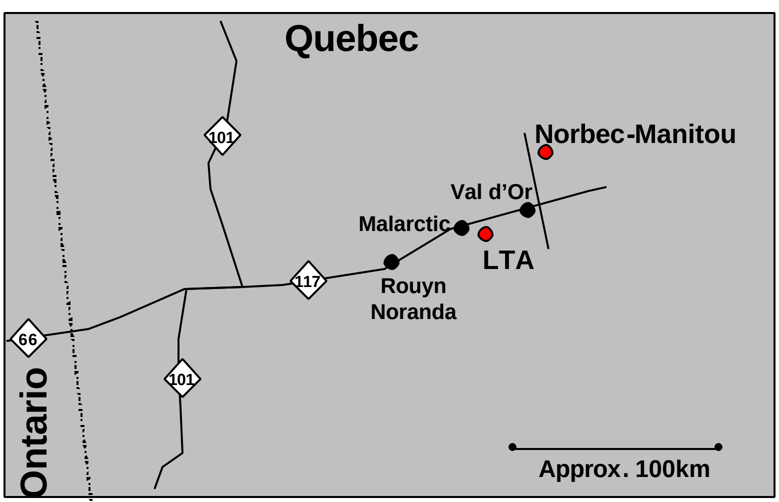
Transect #2 is also located on the covered Shear Lake tailings. This transect consists of three testing points with a spacing of 15m. These are identified as 2A, 2B, and 2C. Tube 2A is 25 m from the shore of pond #1. Transect #2 is parallel to Transect #1 at a distance of approximately 100 m.

Transect #3 is located on the covered "B" Zone tailings. This transect also consists of three testing points with a spacing of 15m. These are identified as 3A, 3B, and 3C. Tube 3A is approximately 50 m from the shore of pond #1. Transect #3 is also parallel to the drainage swale and is located approximately 200 m from Transect #1. In addition to the three transects two tests were performed on Shear Zone tailings without cover. One of these tests was conducted on the area of exposed tailings with minor water ponding. This testing point is referred to as the control for Transect 1 and was located near testing point F. The second test on uncovered Shear Zone tailings was conducted by the manual removal of the cover and the installation of a testing point. This testing point is referred to as the control of Transect 2 and was located at Transect 2 testing point C. Installation of the field testing equipment and oxygen consumption rate measurements were conducted over the period of July 25th through July 31st, 1996.

3.2.5 LTA, PQ.

The Les Terrains Auriferes (LTA) tailings impoundment is located approximately 8.5km Southeast of Malartic, Quebec (Figure 3-12). The site is on claims now owned by Barrick Gold Corporation.

Figure 3-12. Map of the Rouyn-Noranda and Val d'Or region



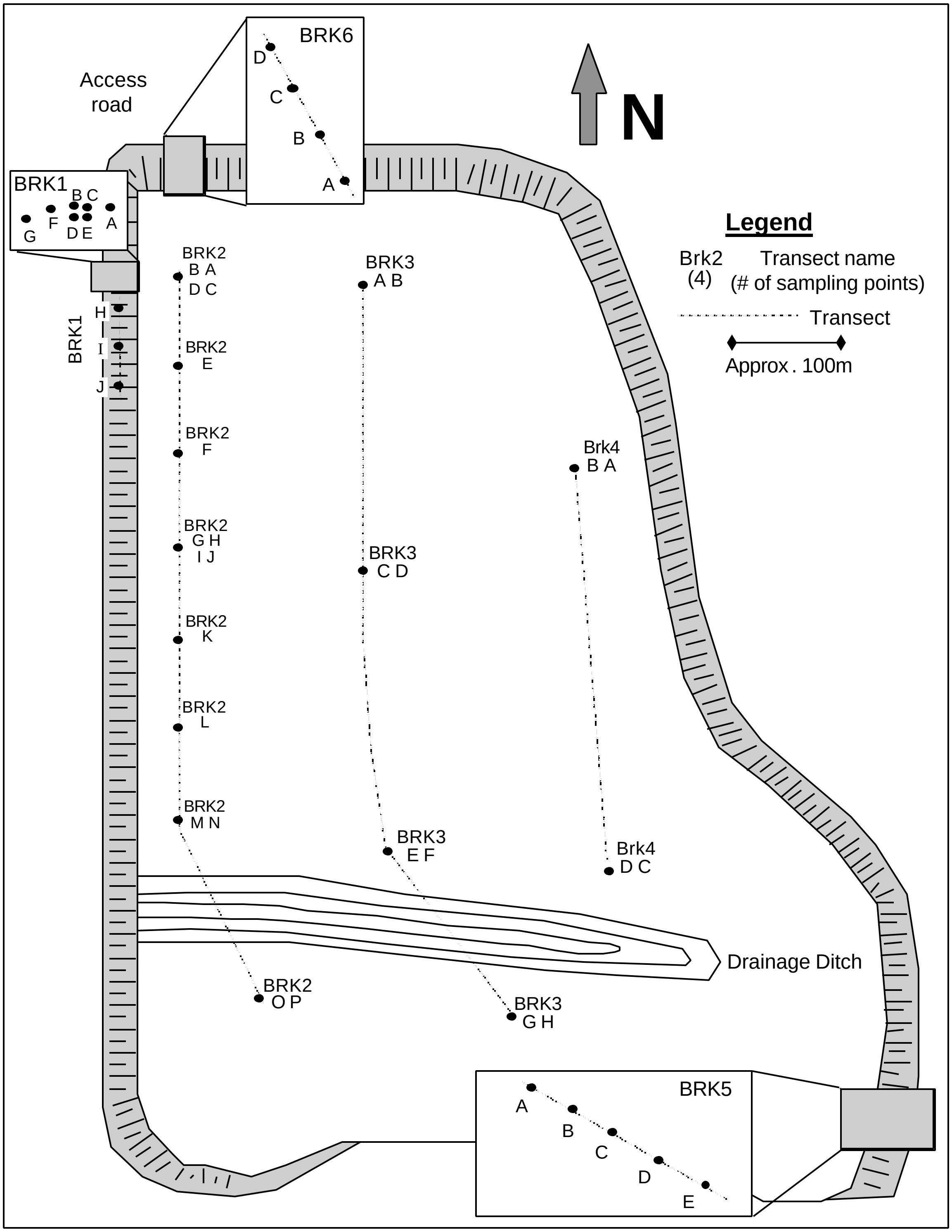
The LTA impoundment consists of approximately 8 million tonnes of sulphidic tailings with an aerial extent of 60 hectares and a depth of 10m to 12m.

These tailings sit on an older tailings deposit of non-sulphidic tailings that are approximately 5m thick and cover approximately 100ha (Ricard et al. 1996). The sulphidic tailings located at the LTA impoundment contain approximately 6 wt % sulphide minerals. The predominant sulphide mineral is pyrite. Pyrrhotite, chalcopyrite, sphalerite and arsenopyrite are also present in smaller amounts. The LTA tailings impoundment is confined to the south by a topographic rise and to the north, east and west by stack dykes.

The objective of this portion of the study was to investigate the reduction in oxygen consumption rates for the reactive tailings resulting from the construction of a multi-layer cover, designed as an oxygen diffusion barrier. The oxygen consumption method was used to measure rates of oxygen uptake through the cover. Measurements on exposed or uncovered tailings were also conducted prior to cover construction in selected areas.

Tubes were installed at testing locations on the Barrick LTA site between June 11th to June 16th, 1996. Measurements were taken at this time and during a second testing round in early October 1996. During the June field visit 26 testing stations comprising in total 43 tubes were successfully installed. Of these, 10 tubes were in the uncovered tailings located on the west slope of the impoundment (Figure 3-13). During the second field visit in October an additional 4 tubes were installed. This transect referred to as BRK6 was located on the north-west slope. Measurements were conducted on an uncovered portion of the

Figure 3-13. Approximate location of transects and testing points (LTA)



tailings prior to re-contouring and cover installation. The position of sampling stations located on the cover were chosen to coincide with the Water-Mark and TDR monitoring stations installed by Golder Associates personnel in June, 1996. The over all layout of sampling stations is described as 5 transects; 3 located on the cover over the tailings impoundment, 2 on the completed cover on the tailings dam slope, and 1 one on the reactive, uncovered tailings (prior to cover construction). Figure 3-13 shows approximate positions of sampling Stations and the number of tubes located at each testing station.

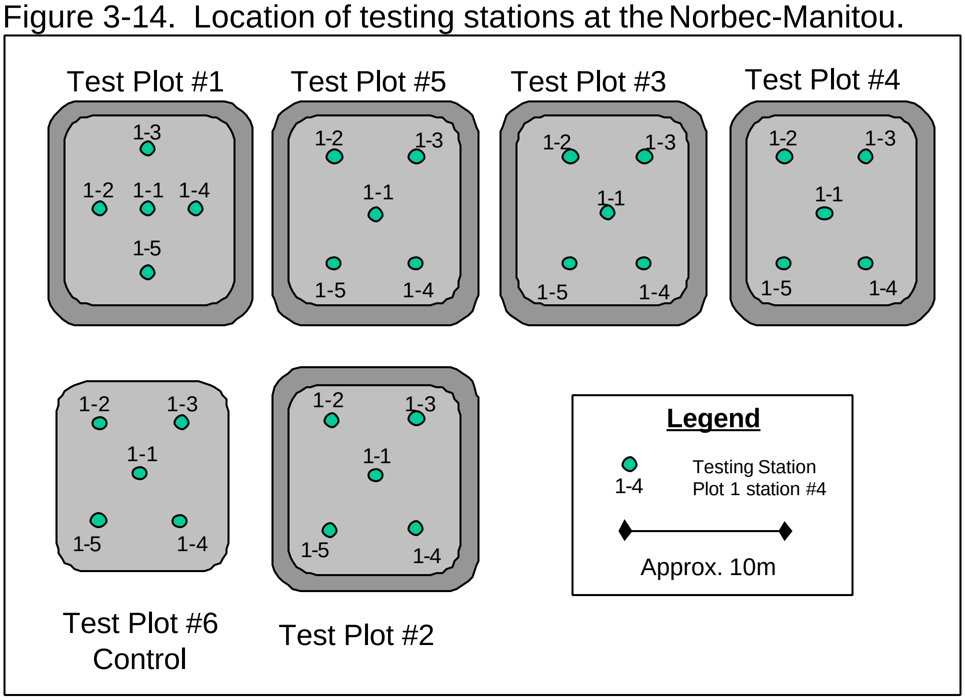
3.2.6 Norbec-Manitou, PQ.

The Norbec-Manitou field site was located approximately 5 km northeast of the town of Val d'Or P.Q. (Figure 3-11). The site consisted of six test plots with dimensions of 10m X 10m. The test plots were designed to evaluate the effectiveness of five different multi-layered cover scenarios using low-sulphur content tailings and soils as part of a Ph.D. research project by B. Bussiere at Unité de Recherche et de Service en Technologie Minérale (USTRM). The sixth test plot was the control location consisting of exposed tailings. The design criteria and research and results specific to the Ph.D work is not within the scope of this investigation. For further details on the layer components, design methodology, and preliminary results the reader is referred to Aubertin et al., 1997a&b and Bussiere et al., 1997. The reactive tailings positioned beneath the five test plots and that comprised the control test plot consisted of approximately 5.5% pyrite (Bernier, 1997).

The objectives of this portion of the investigation were to attempt to evaluate the efficiency of the individual test plot covers in comparison to the non-covered control plot. In a more general sense the investigation also hoped to comment on the relative efficiency of engineered, multi-level covers in general.

Five testing stations were installed in each of the six test plots. The arrangement of the test plots and the positions of the Oxygen Consumption Method testing stations are shown in Figure 3-14. Testing stations were installed in early October, 1995. Oxygen consumption rate measurements were conducted at this time and on two subsequent visits in June, 1996 and October, 1996.

Figure 3-14. Location of testing stations at the Norbec-Manitou.



4. RESULTS

Results from the investigations at the six field sites are presented by field site. Interpretation of the data is developed in the Discussion section of this document

4.1 Strathcona, ON.

The investigation at the Strathcona site involved oxygen consumption rate measurements on tailings impoundments containing 1%S, 15%S, and 30%S (as pyrrhotite) as well as first order evaluation of 3 proposed gravel cover scenarios.

The range of oxygen consumption rate measured at the Strathcona site spanned a range of over three orders-of-magnitude. The lower values were those measured on the 1%S and on the test-cover scenarios. The highest oxygen consumption rates were measured on the exposed 30%S tailings. Table 4-1 lists the oxygen consumption rates measured on the initial site visit in May, 1996. The average oxygen consumption rate for the three control stations located on the 1%S was 29 mol O_2 m^{-2} a^{-1}. Control test station 1-1, located closest to the retaining weir, yielded an oxygen consumption rate that was an order-of-magnitude higher than other controls testing stations in the 1%S impoundment. This rate was similar to rates measured on the non-segregated tailings (15%S). It is strongly suspected that some of the 15%S tailings overflowed and impacted this testing station. Due to this uncertainty the rate is not included in the calculated average.

Table 4-1. Strathcona oxygen consumption rates (May, 1996).

Pyrrhotite Content (%S)	Testing Station	Control	Gravel A (0.5m)	Gravel B (0.5m)	Gravel A+B (0.5m / 0.5m)
		Oxygen Consumption Rate (mol O2 m-2 a-1)			
1	1-1	479*	27	21	36
	1-2	37	13	54	29
	1-3	32	*NA*	9	10
	1-4	19	5	19	6
	Average	**29**	**15**	**26**	**20**
15	15-1	460	*NA*	127	26
	15-2	427	69	65	47
	Average	**444**	**69**	**96**	**36**
30	30-1	4071	385	502	221
	30-2	6131	263	422	291
	Average	**5101**	**324**	**462**	**256**

** Possible contamination with non 1%S tailings. Value not used in calculations*
NA – Not available

The oxygen consumption rates measured on the three gravel test covers were slightly lower than the rates measured at the nearby control stations. However the differences in oxygen consumption rates among the three gravel covers and between the covers and the control are minimal.

Oxygen consumption rates measured at the non-covered testing station located on the 15%S tailings impoundment were approximately an order-of-magnitude higher than those measured on the 1%S impoundment. The average oxygen consumption rate for the two control stations was 444 mol O_2 m^{-2} a^{-1}.

The oxygen consumption rates measured on the three tubes containing the gravel test covers were consistently much lower than rates from the 15%S control stations. On average the rates measured on the gravel filled tubes were a factor of 4.5 to 12 lower. Of the three scenarios, the tube filled with 0.5m of ‘Gravel A’ and 0.5m of ‘Gravel B’ yielded the lowest oxygen consumption rate (36 mol O_2 m^{-2} a^{-1}). Of the two tubes filled with only 0.5m of gravel, the one containing ‘Gravel A’ yielded the lower rate (69 mol O_2 m^{-2} a^{-1}). The oxygen consumption rate for the tube containing ‘Gravel B’ was 96 mol O_2 m^{-2} a^{-1}.

The highest rates measured were those from the 30%S impoundment. These rates ranged from 4000 to 6000 mol O_2 m^{-2} a^{-1}. The average oxygen consumption rate for the 30%S testing stations was 5101 mol O_2 m^{-2} a^{-1}.

In contrast, the oxygen consumption rates measured on the tubes containing the gravel test covers were over an order-of-magnitude lower than the rates yielded by the adjacent control stations. The oxygen consumption rate for the tube containing the 1.0m thick layer of gravel composite cover was the lowest of the three (256 mol O_2 m^{-2} a^{-1}). Similarly to the trend in rates from the gravel filled tubes at the 15%S impoundment, the tube containing ‘Gravel B’ was higher than the rate measured for the tube containing ‘Gravel A’ (462 mol O_2 m^{-2} a^{-1} and 324 mol O_2 m^{-2} a^{-1} respectively).

The Strathcona site was visited again in September, 1996. All testing stations located in the 1%S impoundment were lost prior to the second site visit of September, 1996. Unsegregated (15%S) tailings discharge from the mill breached the 1%S tailings enclosure and buried the testing stations. No further oxygen consumption rate measurements were made on 1%S tailings. Table 4-2 lists oxygen consumption rates measured during the September site visit.

The average oxygen consumption rate measured on the 15%S control stations for the September, 1996 site visit was 341 mol O_2 m^{-2} a^{-1}. This rate is approximately 30% lower that the average rate measured during the previous

May visit. The oxygen consumption rates measured for the three gravel filled tubes were very similar to the corresponding rates measured during the previous visit.

Table 4-2. Strathcona oxygen consumption rates (September, 1996).

Pyrrhotite Content (%S)	Testing Station	Control	Gravel A (0.5m)	Gravel B (0.5m)	Gravel A+B (0.5m / 0.5m)
		Oxygen Consumption Rate (mol O_2 m^{-2} a^{-1})			
15	15-1	403	37	34	40
	15-2	279	97	159	118
	Average	**341**	**67**	**97**	**79**
30	30%-1	L	184	199	233
	30%-2	863	408	303	168
	Average	**863**	**296**	**251**	**201**

L – lost due to hardpan formation

The intense oxidation occurring at the 30% impoundment caused the development of a cemented layer of tailings and secondary oxidation products (hardpan) approximately 0.1m in thickness. The development of the hardpan caused damage to one of the two control test stations in the 30%S impoundment that precluded oxygen consumption rate measurements. The oxygen consumption rate measured at the remaining 30%S control was 863 mol O_2 m^{-2} a^{-1}. This oxygen consumption rate is considerably lower than the 5101 mol O_2 m^{-2} a^{-1} average measured during the May, 1996 visit.

The oxygen consumption rates measured on the gravel filled tubes were significantly lower than the control values. The rates measured in September were 10 to 55% lower than the oxygen consumption rates measured during the May site visit. The tube containing the 1.0m composite gravel cover again yielded the lowest rate of the three gravel filled tubes. The oxygen consumption rates for the two tubes containing 0.5m of gravel were similar, with the oxygen consumption rate for the tube containing ‘Gravel B’ being slightly lower than the rate for the tube containing ‘Gravel A’ (251 mol O_2 m^{-2} a^{-1} and 296 mol O_2 m^{-2} a^{-1} respectively).

The site was visited for a third time in October, 1996. Table 4-3 lists the oxygen consumption rates measured in October for the remaining intact testing stations.

Table 4-3. Strathcona oxygen consumption rates (October, 1996).

Pyrrhotite Content (%S)	Testing Station	Control	Gravel A (0.5m)	Gravel B (0.5m)	Gravel A+B (0.5m / 0.5m)
		Oxygen Consumption Rate (mol O2 m-2 a-1)			
30	30-1	*L*	66	112	43
	30-2	*L*	115		27
	Average		**91**	**112**	**35**

L – lost due to hardpan formation

It was observed that the control stations at the 15%S impoundment were beginning to exhibit corrosion from oxidation that were earlier observed at the 30% impoundment. The control tubes usefulness was also diminished by deposits of surface run-off that had deposited a layer of very fine grained tailings within the control test stations. In addition to problems with the control test stations the above-ground portion of the stations containing the gravel was being damaged by the oxidation of the tailings piled around them. It is suspected that oxygen was now entering these tubes at points along the side-wall.

The second control station located on the 30%S impoundment was observed to be severely damaged by tailings oxidation and hardpan formation during the October visit. It was not possible to conduct a measurement at this station.

Although the number of test stations diminished over time, the results are still usefull to assess temporal trends. The oxygen consumption rates measured for the three tubes filled with gravel were consistently lower than the corresponding rates measured in either September or May. Oxygen consumption rates were generally 2 to 6 times lower than those measured in September. Remaining consistent to the trend, the tube containing the 1.0m composite gravel yielded the lowest rate of the three (35 mol O_2 m^{-2} a^{-1}). Tubes containing 'Gravel A' and 'Gravel B' yielded oxygen consumption rates of (91 mol O_2 m^{-2} a^{-1} and 112 mol O_2 m^{-2} a^{-1} respectively).

4.2 Kidd Creek, ON.

The tailings impoundment at the Kidd Creek site was instrumented in September, 1996. Initial oxygen consumption rate measurements were taken at that time. The site was revisited in May, 1997, and again in June 1997 at which time oxygen consumption rate measurements were taken at select locations on the 1996 installations and on additional tubes installed during the May visit. The results for oxygen consumption rate measurements conducted in September, 1996 are listed in Table 4-4. The average oxygen consumption rate measured in September, 1996 on the exposed tailings was 195 mol O_2 m^{-2} a^{-1}. This value considers all tests conducted on the exposed tailings, both the well drained, older tailings and the poorly drained, fresh tailings. The range of values measured was 1 to 1617 mol O_2 m^{-2} a^{-1}. The lowest measured values were generally located around the perimeter of the impoundment in areas of higher water content. While the majority of measurements were less than 500 mol O_2 m^{-2} a^{-1} two tests yielded oxidation rates in excess of 1500 mol O_2 m^{-2} a^{-1}.

Table 4-4. Kidd Creek oxygen consumption rates (September, 1996).

Transect 1		**Transect 2**		**Transect 3**	
Testing Station	Oxygen Consumption Rate mol/m2/a	Testing Station	Oxygen Consumption Rate mol O_2 m^{-2} a^{-1}	Testing Station	Oxygen Consumption Rate mol O_2 m^{-2} a^{-1}
A	218	A1	264	A	105
B	87	A2	168	B	84
C	145	B	193	C	334
D	40	C	121	D	267
E	169	D	332	E	178
F	141	E	316	**Transect 4**	
G	221	F	88	A	180
H	390	G	483	B	24
I	365	H	209	C	5
J	294	I	518	D	19
K	104	J	322	E	7
L	1525	K	134	F	29
M	1617	L	222	G	26
N	237	M	195	H	26
O	318	N	170	**Transect 5** (fresh tailings)	
P	107	O	86	A	56
Q	119	P	255	B	49
R	54	Q	155	C	2
S	88	R	1	North	67
T	97	S	71		
		T	75	**Transect O** (old tailings)	
		U	6	A	107
		V	25	B	156
				C	44
				D	17

The exposed tailings at the Kidd Creek site can be divided into two categories, relatively young fresh gray tailings that have a high water content and are poorly drained, and tailings that were deposited several years prior to this study that are consolidated, have a developed vadose zone and are orange-brown in colour at the surface as a result of prolonged oxidation. The young tailings are those to the north that have been deposited since the discharge spigot was moved to its present location to the north of the impoundment. This tailings area is visibly well defined in the field and delineated on Figures 3-6, and 3-7 by a dashed line running approximately W-E across the impoundment just north of the spigot access road.

Oxygen consumption rates measured in September, 1996 at the 8 testing stations located on the fresh tailings ranged from 2 to 67 mol O_2 m^{-2} a^{-1} with an average oxygen consumption rate of 33 mol O_2 m^{-2} a^{-1}.

Measured oxygen consumption rates for the selected testing locations along transect #1 are listed in Table 4-5. Measured oxygen consumption rates from the September, 1997 field work reaveled two locations with unusually high rates compared to all other site measurements (tubes L and M). Since rates at these locations did not show similarly high values for June, separate averages for the September measurements are listed, the first being the average of all measurements, the second with rates from tubes L and M excluded.

Table 4-5. Oxygen consumption rates for Kidd Creek Transect #1.

	Sept 96	**May 97**	**June 97**
Testing Station	**Oxygen Consumption Rates mol O^2 m^{-2} a^{-1}**		
A	218	77	121
B	87	23	325
E	169	15	206
F	141	19	276
I	365	77	233
J	294	67	179
L	1525	*NM*	28
M	1617	*NM*	271
P	107	6	223
P2	X	*NM*	*NM*
Q2	*X*	*NM*	95
Q	119	10	252
Average	**464**	**37**	**201**
Average[1]	**187**		

X – tube not installed at this time
NM – not measured
Average[1] – excluding L and M

The overall trend in oxygen consumption rate for the three visits is similar to that observed across other areas of the impoundment. Moderately high rates measured in September, lower rates for May (approximately 20% of September values), and rates equal to or in excess of September measured in June, 1997.

Oxygen consumption rates measured at the selected testing locations on transect #2 are presented in Table 4-6. The average oxygen consumption rate as measured in September, 1996 and in June, 1997 are similar with the June average being slightly higher. However, the average oxygen consumption rate measured in May, 1997 for this area is considerably lower. Measurements conducted on G2 and H2 in May are suspected to be an underestimate due to water content perturbation caused by installation. Re-establishment of steady state conditions may not have occurred within the time between tube installation and oxygen consumption rate measurement. If these two measurements are excluded from the May average the average oxygen consumption rate is still much lower than that measured during the previous September visit and in the June, 1997 visit.

Table 4-6. Oxygen consumption rates for Kidd Creek Transect #2.

	Sept 96	**May 97**	**June 97**
Testing Station	**Oxygen Consumption Rates mol O_2 m^{-2} a^{-1}**		
A1	168	*NM*	631
A2	264	98	*NM*
G	483	107	151
G2	*X*	7	173
H2	*X*	18	551
H	209	60	167
Average	**281**	**58**	**335**
	Average[1]	**88**	

X – tube not installed at this time
NM – not measured
Average[1] – excluding G2 and H2

September measurements of oxygen consumption rates on the 'fresh tailings' were conducted at locations on what is referred to as Transect #5 This consisted of one tube, 'T5A', located to the immediate west of the discharge point, two tubes. 'T5B' and 'T5C', located approximately 1km west of the discharge station, and at a testing station located in the extreme north portion of the impoundment referred to as 'T5north' (Figure 3-6). Unfortunately tube 'T5A' was lost due to redirection of the discharge spigott during early spring 1997 and could not be re-tested. During the May, 1997 visit, tubes 'T5B' and 'T5C' were inaccessible due to surface wetness. It was decided that the installation of a new set of tubes for the characterization of the oxygen consumption rates for the 'fresh tailings' was necessary. A set of four tubes was installed to the immediate east of the discharge station in May, 1997. This testing location is referred to as transect #6 with the individual tubes labeled 'A', 'B', 'C', and 'D' (Figure 3-7). Measurements of the oxygen consumption rates at this location were conducted in May and again in June, 1997. The measured oxygen consumption rates for 'fresh tailings' are reported in Table 4-7.

Table 4-7. Oxygen consumption rates for Kidd Creek 'fresh tailings'.

	Testing Station	Sept 96	May 97	June 97
		Oxygen Consumption Rates mol O_2 m^{-2} a^{-1}		
Installed Sept. 96	T5-A	56	*Lost*	*Lost*
	T5-B	49	*NM*	*NM*
	T5-C	*NA*	*NM*	*NM*
	T5-north	67	*NM*	*NM*
Installed May 97	T6-A	X	71	63
	T6-B	*X*	57	85
	T6-C	*X*	60	119
	T6-D	*X*	86	124
	Average	**57**	**68**	**98**

X – tube not installed at this time
NM – not measured
Lost – tube buried by redirected discharge

The oxygen consumption rates measured in September and in May are similar but a notable increase in the measured rate was observed for the June, 1997 results. Oxygen consumption rates measured in June, 1996 were approximately 40% larger than those measured in May, 1996.

The results from the oxygen consumption rate measurements conducted on transect 'O' (the 'old tailings') are listed in Table 4-8.

Table 4-8. Oxygen consumption rates measured on Kidd Creek 'old tailings'

Testing Station	Sept 96	May 97	June 97
	Oxygen Consumption Rates mol O_2 m^{-2} a^{-1}		
A	107	28	3
A2	X	60	76
B2	*X*	*NM*	36
B	156	35	15
C	105	*NM*	*NM*
D	124	*NM*	*NM*
Average	**123**	**41**	**32**
Average[1]			**56**

X – tube not installed at this time
NM – not measured
Average[1] – excluding A and B

Oxygen consumption rates measured in May, 1997 are approximately 25% of those measured in September, 1996. The average oxygen consumption rate shows only a slight increase from the measurements in May to June when the values from tubes A and B are excluded. The headspace of tubes A and B were partially filled with fine material from overland flow and erosion between the May and June measurements. The presence of this thin layer of fine material with a high water content resulted in diminished oxygen consumption rates.

Two tubes were installed in each of the four test cells during the September, 1996 visit to the site. Oxygen consumption rate measurements were conducted at all test cell stations and the two control tubes installed in the adjacent tailings during the September, May and June visits. Results of the three sampling rounds are listed in Table 4-9. The average oxygen consumption rate measured on the control stations located adjacent the Test Cells shows a similar trend as seen for other areas of the impoundment. Rates measured in May, 1997 are significantly lower than rates measured during the previous September or during the June, 1997 measurement round. The oxygen consumption rates measured on the control for June are notably higher than those measured during the previous September.

Table 4-9. Oxygen consumption rates for Kidd Creek Test Cells.

	Testing Station	Sept 96	May 97	June 97
		Oxygen Consumption Rates mol O_2 m^{-2} a^{-1}		
Control	T2-A1	201	NM	631
	T2-A2	409	99	NM
Control average		**307**	**99**	**631**
Clay	TC1-A	55	54	187
	TC1-B	29	42	188
Tailings with Slag	TC2-A	23	23	30
	TC2-B	28	41	74
Tailings	TC3-A	51	27	53
	TC3-B	50	26	39
Rock	TC4-A	26	16	54
	TC4-B	21	5	54

The oxygen consumption rates measured through the test covers were consistently much lower than the rates obtained from the control measurements conducted on nearby exposed tailings. The oxygen consumption rates measured on the covers during September, 1996 were, in general, an order-of-magnitude lower than rates measured on the adjacent control stations. Of the four test covers, the waste rock and the crushed slag overlain by low-sulphur gold tailings yielded the lowest oxygen consumption rates. In contrast the covers constructed of low-sulphur gold tailings only and of clay-till yielded oxygen consumption rates that were 40 to 100% higher than the other two test covers.

Oxygen consumption rates measured in May, 1996 for the clay-till and the crushed slag overlain by desulphurized tailings covers were similar to but slightly in excess of the rates measured during the previous September. The oxygen consumption rates measured on the low-sulphur gold tailings cover and the waste rock cover did exhibit a reduction in measured rates on the order of 50% to 75%, similar to the reduction in rates observed for the control stations.

4.3 Dona Lake, ON.

The Dona Lake tailings impoundment has been partially flooded as a remediation effort. The near-surface pore water at this site was at neutral pH values indicating that any acidity resulting from sulphide oxidation was currently being buffered by carbonate minerals in the tailings (Ferguson Pers. Comm., 1996). Testing stations were installed in transects as described in the Methods chapter. The oxygen consumption rates from the tests conducted at Dona Lake are listed in Table 4-10.

The average oxygen consumption rate measured on the Dona Lake tailings impoundment was 194 mol O_2 m^{-2} a^{-1}. Oxygen consumption rates ranged from a low of 10 mol O_2 m^{-2} a^{-1} to high 924 mol O_2 m^{-2} a^{-1} with a standard deviation of approximately 200 mol O_2 m^{-2} a^{-1}.

Transect 'A' was oriented parallel to Dyke 3 with stations positioned approximately 20m north of the dyke at a spacing of approximately 45m. The measured oxygen consumption rates are listed in Table 4-10 and shown graphically in Figure 4-1.

Table 4-10. Oxygen consumption rate results, Dona Lake.

Testing Station	Oxygen Consumption Rate mol O_2 m^{-2} a^{-1}
A1	88
A2	44
A3	109
A4	220
A5	137
A6	120
A7	77
A8	NA
A9	28
A10	48
A11	35
Average	**82**

B2	107
B3	326
B4	219
B5	75
B6	292
B7	375
B8	925
B9	34
B10	NA
B11	69
B12	39
B13	116
B14	50
B15	175
B16	30
B17	89
B18	10
Average	**172**

Testing Station	Oxygen Consumption Rate mol O_2 m^{-2} a^{-1}
C1	281
C2	236
C3	365
C4	73
C5	505
C6	244
C7	879
C8	NA
C9	84
C10	260
C11	155
C12	108
C13	263
Average	**266**

D1	190
D2	194
Average	**192**

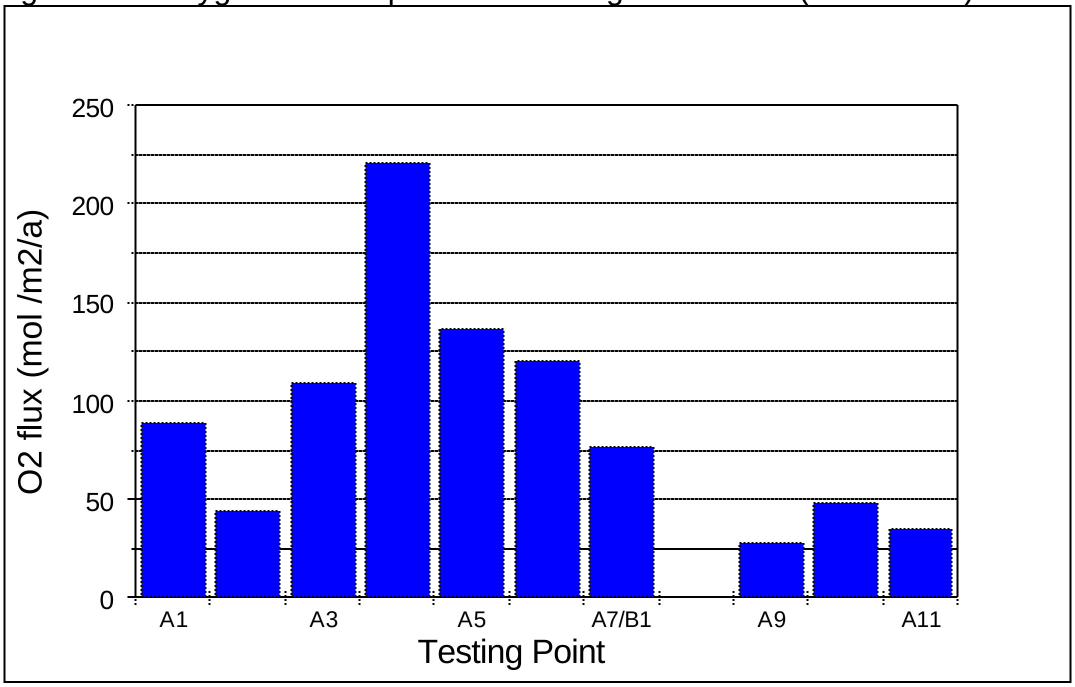
E1	175
E2	616
E3	58
Average	**283**

F1	252
F2	115
F3	59
Average	**142**

NA-not available

The average oxygen consumption rate for all testing stations on transect ‘A’ was 82 mol O_2 m^{-2} a^{-1}. Some variation in the measured rates was observed along the transect with the lower rates associated with the testing stations located near the west and east ends of the dyke.

Figure 4-1. Oxygen consumption rates along transect ‘A’ (Dona Lake).



The average oxygen consumption rate measured along transect ‘B’ was 183 mol O_2 m^{-2} a^{-1}. Oxygen consumption rates measured along this transect included both the lower and upper values recorded over the entire site. The standard deviation within the rates measured along transect ‘B’ was 228 mol O_2 m^{-2} a^{-1}.

Transect ‘C’ was oriented to bisect the apron area located in the northwest area of the impoundment. Transect ‘C’ intersected Transect ‘B’ at testing stations ‘B8’. The average oxygen consumption rate along transect ‘C’ was 266 mol O_2 m^{-2} a^{-1}. This oxygen consumption rate is considerably higher than the average rates measured along transect ‘A’ or ’B’ and also considerably above the average oxygen consumption rate for the site. Tailings in this area were visibly different from the rest of the impoundment. Qualitatively the tailings on the apron area were slightly coarser and had a orange-brown colouration, in contrast with the dark gray tailings in other areas.

Testing stations located in areas ‘D’ and ‘F’ of the impoundment yielded values that were similar to the average rate for the site. One test station located in area ‘E’ yielded an oxygen consumption rate of 616 mol O_2 m^{-2} a^{-1} which was in sharp contrast to the other two testing stations located in this area. Stations ‘E1’ and ‘E3’ yielded oxygen consumption rates of 175 mol O_2 m^{-2} a^{-1}, and 58 mol O_2 m^{-2} a^{-1} respectively.

4.4 Cullaton Lake, NWT.

The Cullaton Lake site was instrumented and tested in order to gain insight into the effectiveness of a cover of locally available till at minimizing oxygen flux into the tailings. Table 4-11 details the cover thickness at the testing locations.

Table 4-11. Cover thickness at testing locations (Cullaton Lake)

Transect 1	Thickness (cm)
A	61
B	89
C	71
D	70
E	62
F	68
G	69
H	58
J	62
average	**68**

Transect 2	Thickness (cm)
A	72
B	67
C	60
Average	**76**

Transect 3	Thickness (cm)
A	90
B	90
C	88
Average	**89**

Two small areas located on the tailings impoundment exhibited bare tailings with no cover. One area was comprised of exposed tailings with partially established vegetation. This area was located on the ‘B Zone’ tailings. The second area was located on the 'Shear Zone' tailings and was comprised of exposed tailings with minor water ponding.

The results of the oxygen consumption rate measurements are listed in Table 4-12 ('B Zone' tailings) and Table 4-13 ('Shear Zone' tailings).

Table 4-12. Oxygen consumption rates 'B Zone' tailings (Cullaton Lake)

Testing Station	Oxygen Consumption Rate mol O_2 m^{-2} a^{-1}
Control-1	128
1A	33
1B	22
1C	14
1D	12
1E	3
1G	7
1H	3
Average	**13**

Testing Station	Oxygen Consumption Rate mol O_2 m^{-2} a^{-1}
Control-2	82
2A	2
2B	< 1
2C	7
Average	**3**

Table 4-13. Oxygen consumption rates the 'Shear Zone' tailings (Cullaton Lake)

Testing Station	Oxygen Consumption Rate mol O2 m-2 a-1
A	9
B	9
C	12
Average	**10**

The overall oxygen consumption rate for the testing stations located on the covered 'Shear Zone' tailings was 9 mol O_2 m^{-2} a^{-1}.

This oxygen consumption rate is approximately an order-of-magnitude lower than the 105 mol O_2 m^{-2} a^{-1} average oxygen consumption rate measured on the non-covered portions of the 'Shear Zone' tailings.

The average oxygen consumption rate was 13 mol O_2 m^{-2} a^{-1} along transect #1 which was oriented parallel to the drainage ditch (Figure 3-11). Oxygen consumption rates measured along Transect 2, also located on the 'Shear Zone' tailings portion of the impoundment, exhibited an average oxygen consumption rate of approximately 3 mol O_2 m^{-2} a^{-1}. The oxygen consumption rates for the testing stations located on the non-covered portions on the 'Shear Zone' tailings were 128 mol O_2 m^{-2} a^{-1} and 82 mol O_2 m^{-2} a^{-1} for transects #1 and #2 respectively.

Measurements were not conducted on non-covered portions of the 'B Zone' tailings area due time constraints. The average oxygen consumption rate measured at testing stations located on the covered 'B Zone' tailings was 10 mol O_2 m^{-2} a^{-1}.

4.5 LTA, PQ.

The LTA site is a 66 hectare tailings impoundment on which a multi-layered engineered cover was installed during the winter of 1995-1996. During the June, 1996 visit to the site, one portion of the impoundment remained uncovered. This provided an opportunity to measure rates on exposed tailings. These rates are compared to those measured on the covered portion of the site to evaluate cover effectiveness. Ten tubes were installed in the exposed tailings. The results of oxygen consumption rate tests on the exposed tailings (BRK-1 tubes A-J) are listed in Table 4-14.

Table 4-14. Oxygen consumption rates on exposed tailings prior to cover installation (LTA).

Transect	Testing Station	Oxygen Consumption Rate mol (O_2 m^{-2} a^{-1})
BRK-1	A	410
	B	836
	C	503
	D	228
	E	606
	F	221
	G	223
	H	154
	I	422
	J	284
	Average	**389**

Oxygen consumption rates ranged from 154 mol O_2 m^{-2} a^{-1} to 836 mol O_2 m^{-2} a^{-1}. The average oxygen consumption rate for these testing stations was 389 mol O_2 m^{-2} a^{-1}. These testing stations were lost when the cover was constructed in this area.

During the June, 1996 visit 33 tubes were installed on the covered portion of the impoundment and oxygen consumption rates were measured. The field site was visited again in October, 1996. Only subset of the tubes installed in June, 1996, were measured in October. Also, at this time it was decided that an additional transect would be installed to aid in investigating the effect of potential drying and drainage on the covered slope of the tailings dam. This transect is referred to as transect 6 (Figure 3-13). The results for the June and October, 1996 measurements are listed in Table 4-15.

Table 4-15. Oxygen consumption rates for covered areas of the LTA tailings

JUNE 1996			OCTOBER 1996		
Transect	Testing Station	Oxygen Consumption Rate (mol O_2 m^{-2} a^{-1})	Transect	Testing Station	Oxygen Consumption Rate (mol O_2 m^{-2} a^{-1})
BRK-2	A	7	BRK-2	A	10.6
	B	16		B	*MN*
	C	2		C	*MN*
	D	*bdl*		D	*Bdl*
	E	3		E	3.9
	F	*bdl*		F	*Bdl*
	G	NA		G	14.8
	H	18		H	8.9
	I	*bdl*		I	*MN*
	J	*bdl*		J	*MN*
	K	*bdl*		K	29.6
	L	*bdl*		L	*MN*
	M	1		M	24.2
	N	9		N	16.8
	O	2		O	*MN*
	P	*bdl*		P	1.7
BRK-3	A	*bdl*	BRK-3	A	4.4
	B	*bdl*		B	5.7
	C	6		C	4.8
	D	7		D	1.3
	E	*bdl*		E	3.2
	F	4		F	4.7
	G	1		G	*Bdl*
	H	16		H	*Bdl*
BRK-4	A	1.9	BRK-4	A	*Bdl*
	B	*bdl*		B	*Bdl*
	C	2		C	*Bdl*
	D	12		D	*Bdl*
BRK-5	A	0.3	BRK-5	A	8.0
	B	*bdl*		B	2.1
	C	2		C	9.6
	D	*bdl*		D	1.8
	E	*bdl*		E	*NM*
BRK-6	A	*X*	BRK-6	A	4.2
	B	*X*		B	*Bdl*
	C	*X*		C	1.3
	D	*X*		D	4.2
	Average[1]	**6**		**Average[1]**	**7.8**
	Average[2]	**4**		**Average[3]**	**5.3**

bdl –below detection limit
X – tube not installed at this time
NM – not measured

Average[1] – Excluding all values bdl
Average[2] – Including bdl vlaue for Oct 1996
Average[3] – Including bdl vlaue for June 1996

The average oxygen consumption rate for the covered portion of the impoundment was approximately 4 to 6 mol O_2 m^{-2} a^{-1} for test conducted during the June, 1996 visit. The average oxygen consumption rates measured during the October, 1996 site visit for the Barrick LTA covered site was 5 to 8 mol O_2 m^{-2} a^{-1}, similar to the rates measured in June, 1996.

4.6 Norbec-Manitou, PQ.

The Norbec-Manitou site consisted of five engineered, multi-level test plots and one control plot of exposed tailings. Five testing stations were installed in each of the six test plots. Measurements were conducted in October, 1995, June, 1996, and again in October,1996. A selected subset of testing stations were were measured in June and October, 1996. Table 4-16 lists the results of the oxygen consumption rate measurements for the three testing rounds.

Table 4-16. Oxygen consumption rates measured on Norbec-Manitou test plots

		Date		
		Oct 1995	**June 1996**	**Oct 1996**
Test Plot	**Testing Station**	Oxygen Consumption Rate mol O_2 m^{-2} a^{-1}		
Control	C-1	89	33.5	20.0
	C-2	53	10.7	*NM*
	C-3	142	10.4	15.1
	C-4	65	20.8	27.7
	C-5	126	*NM*	10.4
	Control Average	**95**	**18.9**	**18.3**
#1	1-1	27	23.7	0.2
	1-2	14	5.8	0.6
	1-3	7	*NM*	2.0
	1-4	10	*NM*	1.4
	1-5	9	55.8	*NM*
	#1 Average	**13**	**28.4**	**1.0**
#2	2-1	18	7.1	1.0
	2-2	56	7.9	1.0
	2-3	23	*NM*	*NM*
	2-4	18	16.3	*NM*
	2-5	38	8.1	*NM*
	#2 Average	**34**	**9.8**	**1.0**
#3	3-1	42	4.0	*NM*
	3-2	*E*	9.4	*NM*
	3-3	*E*	2.6	4.5
	3-4	30	*NM*	4.2
	3-5	22	7.7	*NM*
	#3 Average	**31**	**5.9**	**4.3**
#4	4-1	*E*	8.4	*NM*
	4-2	22	5.2	0.7
	4-3	24	10.0	*NM*
	4-4	46	17.5	*NM*
	4-5	*E*	*NM*	2.6
	#4 Average	**32**	**10.3**	**1.6**
#5	5-1	39	25.8	*NM*
	5-2	46	11.4	*NM*
	5-3	30	11.3	0.2
	5-4	34	14.0	0.2
	5-5	40	*NM*	*NM*
	#5 Average	**39**	**15.6**	**0.2**

NM – Not measured
E – *Failed test*

The installation and oxygen consumption rate measurements in October, 1995 at the Norbec-Manitou site was the first attempts at measuring oxygen consumption rates through constructed covers. Short-comings in the yet unrefined testing system combined with inclement weather and below seasonal temperature resulted in many unsuccessful tests. Fortunately time permitted several tests at many of the testing stations. Successful tests on each tube were averaged to yield the single value reported for each tube. Table 4-17 lists all available results for the oxygen consumption rate test conducted in October, 1995.

The severity of precipitation events increased during the days following the tube installation and the frequency of failed tests also increased. For some of the test plots as many as five test attempts were done, for other test plots only one or two attempts were possible.

Despite some difficulties, a set of reasonably useful data was collected for October, 1995. Refinements in the testing procedure allowed for greater resolution in the measurements collected during the June and October, 1996 visits. The average value of available tests on each tube for the October, 1995 testing round is reported as the oxygen consumption rate for that tube in Table 4-16.

Table 4-17. Oxygen consumption rate test results for October, 1995 (Norbec-Manitou test plots)

	Oxygen Consumption Rate mol O_2 m^{-2} a^{-1}					
Testing Station	Measurement					
	#1	#2	#3	#4	#5	**Average**
C-1	89					**89**
C-2	53					**53**
C-3	142					**142**
C-4	65					**65**
C-5	126					**126**
1-1	27					**27**
1-2	21	6				**14**
1-3	7					**7**
1-4	9					**9**
1-5	9					**9**
2-1	18					**18**
2-2	90	21				**56**
2-3	10	36				**23**
2-4	18					**18**
2-5	35	20	69	26		**37**
3-1	45	23	36	41	64	**42**
3-2						
3-3						
3-4	18	58	33	13		**30**
3-5	22					**22**
4-1						
4-2	22					**22**
4-3	24					**24**
4-4	63	29				**46**
4-5						
5-1	44	21	53			**39**
5-2	60	58	21			**46**
5-3	42	18				**30**
5-4	43	25				**34**
5-5	40					**40**

During the June, 1996 site visit the oxygen consumption rates measured on the exposed tailings in test cell #6 (control) were significantly lower than the rates measured during the previous October. The average oxygen consumption rate was 19 mol O_2 m^{-2} a^{-1} for the control test plot. The measured rates for the five test plots also demonstrated similar reductions between the October, 1995 and June, 1996 measurement rounds, with the exception of test plot #1. Oxygen consumption rates measured on test cell #1 were on average a factor of two higher for the June measurements. Oxygen consumption rate for test plots #2 through #5 exhibited an approximate average decrease by a factor of 2 to 6. Measured oxygen consumption rate for the covered test plots were in the same range as the rates measured for the exposed control plot.

The site was visited for a third time during the October, 1996. Time constraints precluded oxygen consumption rate measurement at all testing stations. The oxygen consumption rates measured for the control plot was 18 mol O_2 m^{-2} a^{-1} , very similar to the rate determined in June. A notable decrease in oxygen consumption rates was observed for all covered test plots, with the exception of test plot #3. An average decrease of approximately one order-of-magnitude between the two sampling rounds (June and October, 1996) for test plots #1, #2, #4, and #5 was also observed.

4.7 Summary of Results

Oxygen consumption rate measurements were conducted at six different tailings impoundments. Rates were measured on exposed tailings with sulphide content ranging from 1%S to 30%S. The dominant sulphide mineral present also varied among the sites from pyrite, a mixture of pyrite and pyrrhotite to pyrrhotite. At one site the near-surface pore water was still neutral yet significant oxidation was observed. For some sites the time since tailings depostion in defined areas was well documented. At other locations the depth to the water table or relative degree of saturation could be noted. In addition to varied mineralogical and physical parameters, several remediation efforts, or experimental management scanarios had been applied. Rates measured across such diverse conditions allows for an overall appreciation of in situ tailings oxidation rates.

The overall range in oxygen consumption rates measured for this research span five orders-of-magnitude, from approximately 0.1 to over 6000 mol O_2 m^{-2} a^{-1}. The lowest rates measured were those from areas of exposed tailings at saturated conditions and rates measured through constructed cover systems. The highest oxygen consumption rates (4000 to 6000 mol O_2 m^{-2} a^{-1}) were measured on fresh, high sulphide content tailings.

Oxygen consumption rates for exposed tailings that were not water-saturated, but where the unsaturated zone ranged from a few centimeters to approximately 1 meter where in the range of 100 to 500 mol O_2 m^{-2} a^{-1} for both tailings with pyrite and pyrrhotite as the dominant sulphide mineral.

5. DISCUSSION

Six field sites were selected to investigate the relationship between oxygen consumption rates and physical site characteristics, such as sulphide content or remediation effort. In addition to discussions on the results from individual sites, results have been grouped along common themes, where appropriate. These provide a broader context for discussion of acid mine drainage issues and oxygen consumption rates.

5.1 Strathcona, ON.

Oxygen consumption rates were measured at the Strathcona site during May, September, and October, 1996. Rates were measured on three impoundments containing pyrrhotite tailings with sulphide contents of 1%S, 15%S, and 30%S. The effectiveness of three potential cover scenarios were also examined.

5.1.1 Sulphide Content and Oxygen Consumption Rate

The relationship between sulphide content (as %S) and measured oxygen consumption rate was pronounced. Table 5-1 lists the average oxygen consumption rates measured on the control test stations located on the three tailings impoundments for the three visits. Table 5-1 also lists the maximum potential neutralization requirement, expressed as the maximum equivalent mass of $CaCO_3$ m^{-2} a^{-1}.

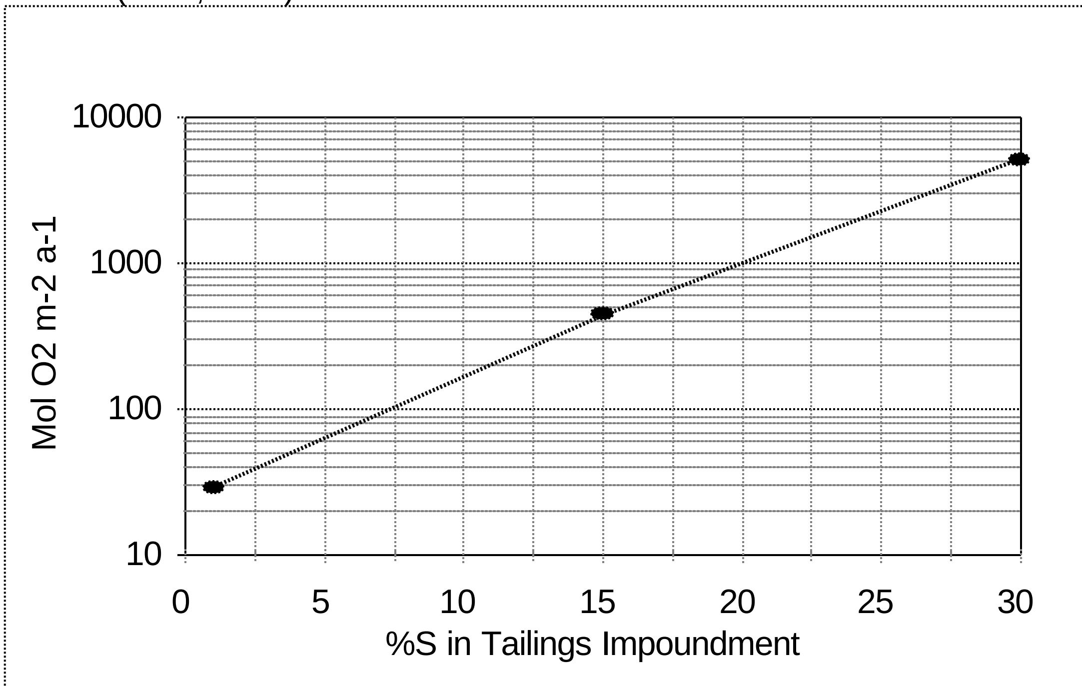
Table 5-1. Average oxygen consumption rates and potential equivalent neutralization for control test stations (Strathcona).

	Control Stations (exposed tailings)					
	Average Oxygen Consumption Rate (mol O_2 m^{-2} a^{-1})			Max. Equiv. CaCO3 Consumption (kg $CaCO_3$ m^{-2} a^{-1})		
Pyrrhotite Content	May	Sep	Oct	May	Sep	Oct
1%S	29	*L*	*L*	1.5	*L*	*L*
15%S	444	341	*L*	20	15	*L*
30%S	5101	863	*L*	226	38	*L*

L- Lost

From these data, it is clear that the sulphur content of the tailings had a strong influence on the oxygen consumption rates. The effect of sulphur content across the three impoundments was evaluated for the measurements conducted in May when the 30%S tailings were fresh and the testing stations located on the 1%S impoundment were available. The rates measured on the 15%S tailings were approximately one order-of-magnitude higher than those measured on the 1%S impoundment. The oxygen consumption rates measured on the 30% impoundment were approximately one order-of-magnitude higher than the rates on the 15%S impoundment. This log-linear relationship of the oxygen consumption rate to the sulphide content is evident in Figure 5-1.

Figure 5-1. Oxygen consumption rate versus sulphide content (%S) for control stations (MAY, 1996).



An increased sulphide content in the tailings implies that there are more potential oxidation sites. However, a doubling of the sulphide content should theoretically double the potential oxidation sites, or available reactive surface area of the sulphide mineral. This should result in a doubling of the measured oxygen consumption rate based on availability of reactive surfaces. This may be true for situations were the transport of oxygen is not limited by diffusion and the oxygen consumption rate is solely a controlled by reaction rate kinetics. However, this is not the case for field conditions.

The oxygen consumption rate measured in the field is controlled by a combination of the availability of oxygen (diffusion) in the tailings profile and the rate that it can be consumed (kinetic rate). The diffusion coefficient of the system is strongly influenced by the degree of saturation. The value of D_e for oxygen decreases with depth as moisture content increases. This means that diffusion is highest near the surface of the tailings profile. Previous studies have shown that oxygen is consumed in a shallower zone for tailings with higher sulphur contents (Nicholson, 1984 and Elberling, et al. 1994).

At the 1%S impoundment, much of the material that the oxygen encounters on its path within the tailings is non-reactive. As the oxygen diffuses to greater depths the D_e value of the tailings decreases as the moisture content increases. Moisture content is likely lower at the surface due to drainage and evaporation. The diffusion of oxygen through this material limits the rate at which it can reach potential oxidation sites.

Within the 15%S impoundment, the oxygen encounters sulphide material on a shorter travel path because more of the material is potentially reactive. The depth of the active oxidation zone is shallower and the decreasing D_e associated with increasing depth is less influential. In this case, the effect of diffusion acting as a limiting factor in the oxygen consumption rate is lessened, as the pathway, or the zone of oxidation is shortened.

The extremely high sulphide content of the 30%S impoundment implies that nearly all that oxygen comes into contact with is potentially reactive sulphide. In this case the influence of diffusion is reduced and the oxygen consumption rates are high.

A trend of increasing oxygen consumption rates with increasing sulphide content was also reported for low sulphur tailings in a laboratory column investigation (Bussiere, et al., 1997). In that study, oxygen consumption rates measured on 1%S tailings were approximately 50 times higher than those for tailings containing 0.14%S.

5.1.2 First-Order Assessment of Potential Cover Material

The importance of diffusion in influencing oxygen consumption rates is further demonstrated by the lower rates measured on testing stations where a layer of gravel was placed in the tubes above the tailings (Figure 5-2). The oxygen consumption rate as measured through the gravel covers at the 1%S impoundment was 10% to 50% lower than the rate at the nearby controls. The addition of a diffusive barrier to the 1%S impoundment had only a limited effect because diffusion within the tailings profile was already controlling the oxygen consumption rate to a great extent. The non-reactive portion (99%) of the tailings were acting as a diffusive barrier. In absolute terms the reduction in oxygen consumption rate is small because the rates are already low due to the low-sulphur content in the tailings. In contrast, the rates measured on the covered test stations at the 15%S impoundment were 80% to 92% lower than the associated controls. At this location the addition of non-reactive material constituted a greater change in the diffusion component of the system because the tailings contained a greater component of sulphide. Diffusion through the tailings was less of a controlling factor. The difference between oxygen consumption rates measured on exposed tailings and on nearby test stations with gravel layers was even more pronounced at the 30%S impoundment.

Oxygen consumption rates measured at the gravel covered test stations were more than one order-of-magnitude lower than the oxygen consumption rates for the associated control test stations.

Figure 5-2. Oxygen consumption rate versus sulphide content (%S) for control stations and gravel test covers, May, 1996 (Strathcona).

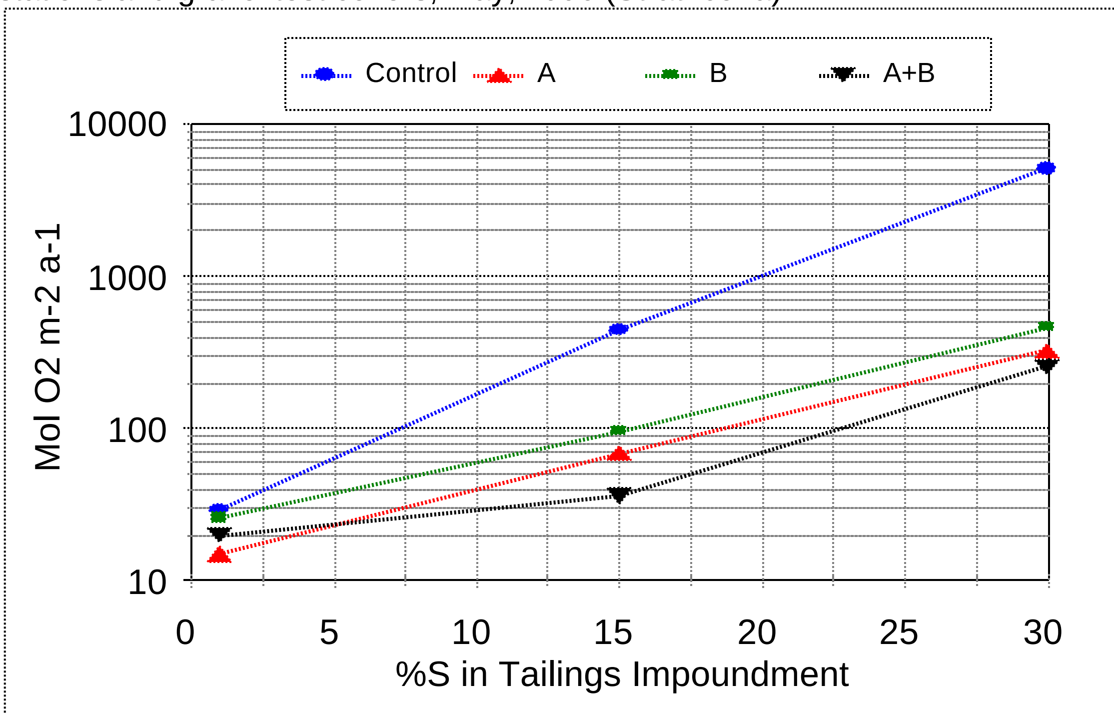


Figure 5-2 also provides an insight into the performance of the three gravel covers. Oxygen consumption rates measured for all three cover scenarios were lower than the rates for the associated controls. Results of oxygen consumption rate measurements on the three gravel covers are listed in Table 5-2.

Table 5-2. Average oxygen consumption rates measured on gravel cover test stations for May, 1996 (Strathcona).

Pyrrhotite Content	Average Oxygen Consumption Rate (mol O_2 m^{-2} a^{-1})		
	Gravel A (0.5m)	Gravel B (0.5m)	Gravel A+B (1.0m)
1%S	15	26	20
15%S	69	96	36
30%S	324	462	256

Oxygen consumption rates measured on the 1.0m cover were considerably lower than the associated rates measured on the 0.5m covers in all but one instance. Oxygen consumption rates measured on the two 0.5m gravel covers were similar. Table 5-3 lists the oxygen consumption rates for the three gravel cover scenarios that were measured during the three site visits.

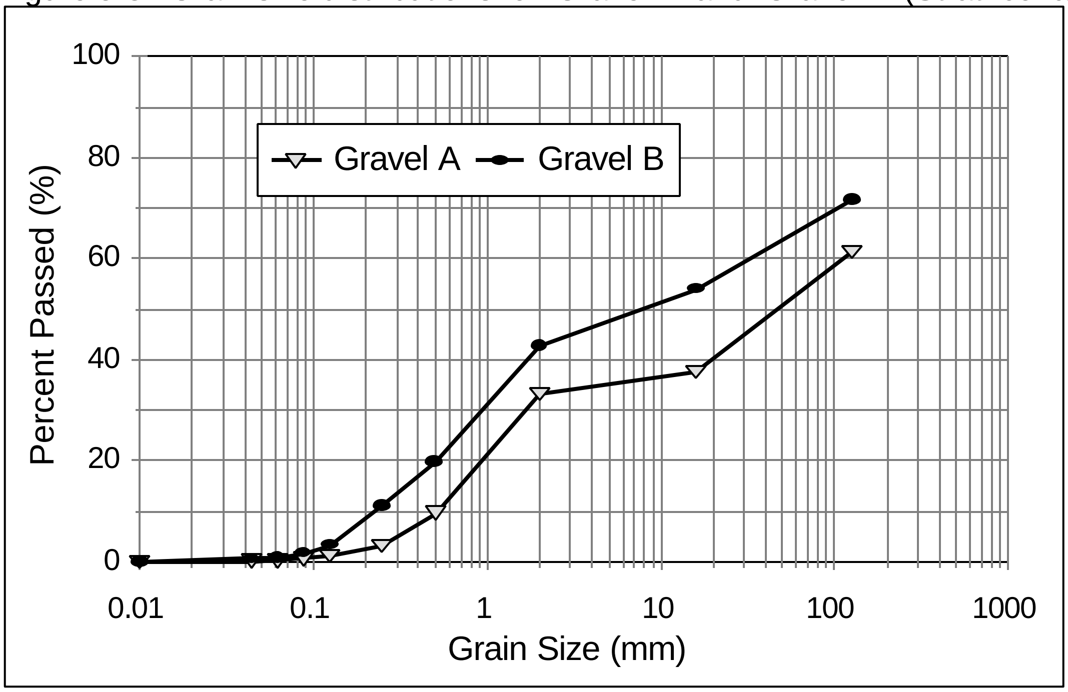
Table 5-3. Oxygen consumption rates measured on gravel cover scenarios (Strathcona).

	Average Oxygen Consumption Rate (mol O_2 m^{-2} a^{-1})					
Pyrrhotite Content	**Gravel A (0.5m)**			**Gravel B (0.5m)**		
	May	Sept	Oct	May	Sept	Oct
1%S	15	*L*	*L*	26	*L*	*L*
15%S	69	67	*L*	96	97	*L*
30%S	324	296	91	462	251	112

L - Lost

'Gravel A' had undergone a screening process to remove the medium grain portion and 'Gravel B' was pit run material. However, on inspection of the grain size distributions of the two materials this was not dramatically visible (Figure 5-3).

Figure 5-3. Grain size distributions for 'Gravel A' and 'Gravel B' (Strathcona).



Both materials contained a considerable percentage of material coarser than ½" (127mm) and the grain size distributions for both material were quite large. Nicholson et al. (1991) refers to the d_{10} of the medium as the controlling factor for the air entry value (AEV) and drainage characteristics, which in turn control diffusion. The minimal difference in the d_{10} for these two materials suggest that minimal differences in their diffusion properties as cover material may be expected. In comparison to the control rates the two gravel covers yielded similar oxygen consumption rates.

From these data and observed trends it can be concluded that sulphide content of the tailings is directly correlated to oxygen consumption rate both in absolute terms for this site and in a general relative sense. The application of a gravel layer on the tailings resulted in a reduction in oxygen consumption rate. The greater absolute and relative reduction in rates were observed for the impoundments containing the higher sulphide contents. Low oxygen consumption rates measured on the composite cover are attributed to greater diffusive retardation associated with a thicker layer of material.

5.1.3 Seasonal Variation in Oxidation Rates

The Strathcona site was visited three times over the non-frozen field season of 1996 to examine temporal trends in oxygen consumption rates at this site. Unfortunately, the testing stations located on the 1%S impoundment were lost prior to the second visit and many of the testing stations on the 15%S and 30%S impoundments were also lost over the field season due to the development of hardpan that deformed and corroded the aluminum tubes. Despite these complications, several interesting observations can be made about the effect of hardpan development on oxygen consumption rates at the 30%S impoundment. Table 5-4 lists the oxygen consumption rates measured on the 30%S control and gravel-cover test stations for the three measurement rounds.

Table 5-4. Oxygen consumption rates 30%S impoundment (Strathcona).

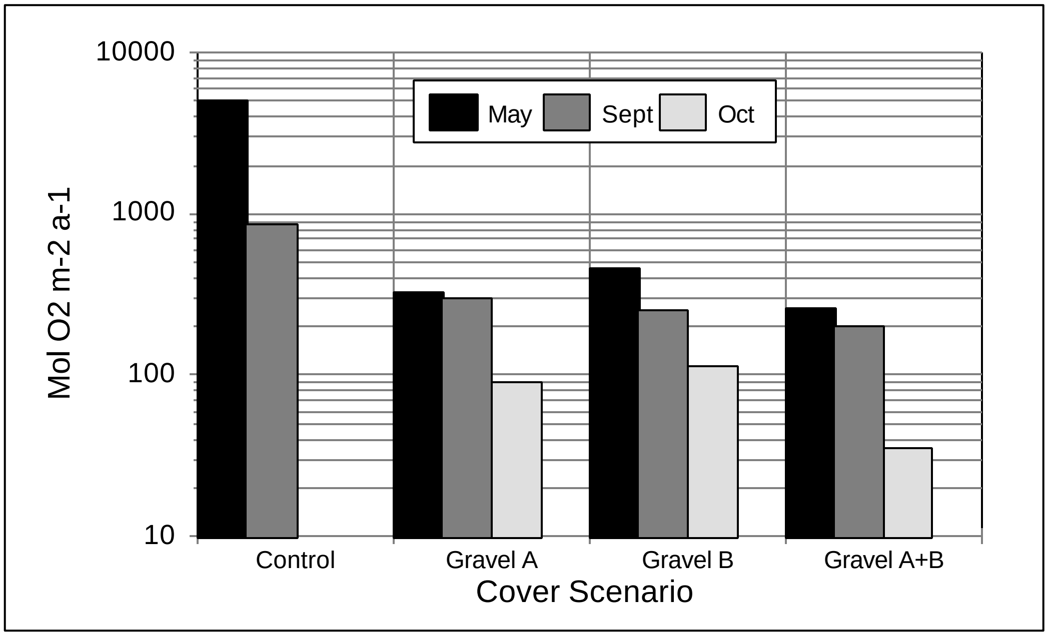
	Average Oxygen Consumption Rate ($mol\ O_2\ m^{-2}\ a^{-1}$)			
Date	Control	Gravel A	Gravel B	Gravel A+B
May	5101	324	462	256
Sep	863	296	251	201
Oct	*L*	91	112	35

L - lost

A trend of lower oxygen consumption rates over time can be observed for the control test stations as well as for the three gravel cover scenarios. Figure 5-

4, highlights the differences among the oxygen consumption rates at the 30% impoundment.

Figure 5-4. Oxygen consumption rates measured on the 30%S impoundment for May, September, and October, 1996 (Strathcona).



The average oxygen consumption rate measured in September on the control stations was approximately a factor of six lower than those measured in May 1996. In absolute terms this represents a change from 5101 mol O_2 m^{-2} a^{-1} to 863 mol O_2 m^{-2} a^{-1}. The oxygen consumption rates measured for the covered test stations were also lower in September than for May. The change in the average oxygen consumption rates for the gravel covered test stations were less than those observed at the control stations. On average the oxygen consumption rates for the covered test stations were a factor of 1.1 to 1.8. lower in September than in May.

During the same time period the oxygen consumption rate measured on the control test stations on the 15%S impoundment decreased by approximately

25%. Table 5-5 lists the average oxygen consumption rates measured at the testing stations located on the 15%S tailings impoundment.

Table 5-5. Oxygen consumption rates for 15%S impoundment (Strathcona).

	Average Oxygen Consumption Rate ($mol\ O_2\ m^{-2}\ a^{-1}$)			
Date	Control	Gravel A	Gravel B	Gravel A+B
May	444	69	96	36
Sep	341	67	97	79
Oct	*L*	*L*	*L*	*L*

L – Lost

5.1.4 Effects of Hardpan Formation

The large decrease in oxygen consumption rates observed at the 30%S testing stations may be attributed mainly to the rapid development of a zone of oxidation cemented with $Fe(OH)_3$ on the tailings surface, often referred to as hardpan. At the time of the May measurements the 30%S impoundment contained fresh tailings and no hardpan existed. During the September measurement round, significant hardpan development was observed. This hardpan layer was approximately 8-12cm in thickness, extremely hard and a dark brown-red in color. This well developed hardpan formed in less than six months. The hardpan may have acted as a physical barrier to oxygen transport due to its consolidated and cemented nature. Other researchers (Blowes, et al., 1991, and Elberling, 1995) have reported oxygen diffusion coefficients for cemented porous media that were approximately an order-of-magnitude lower than for uncemented media.

The 15%S site was already a couple of years old and some interbedded layering of oxidized layers was observed during the May measurement round. No visible increase in hardpan development was observed at the 15%S impoundment between the June and September visits. However, the 15%S tailings in the areas of the testing stations were observed to be wetter in September. Changes in the degree of saturation of the near-surface tailings may have been responsible for the lower oxygen consumption rates measured during the September visit.

Further reductions in oxygen consumption rates for the remaining testing stations were observed in the October, 1996 data (Table 5-4). By October both control testing stations located on the 30% impoundment were unusable due to deformation and corrosion from the hardpan development. Oxygen consumption rates measured in October were between a factor of 4 and 7 lower for the gravel covered testing stations than those measured in May. It is postulated that the hardpan layer formation in the testing stations containing the gravel covers was slower due to the lower oxidation rate and that by October the hardpan in the gravel filled test stations was sufficiently developed to impede oxygen transport. In addition to the hardpan formation, water content with in the gravel may have increased, resulting in a lower effective diffusion coefficient for the cover material.

The Strathcona site is perhaps unique as it consisted of segregated tailings impoundments of different sulphide contents discharged from the same mill. Oxygen consumption rates measured at this site ranged over a three order-of-magnitude scale. The 30%S impoundment yielded the highest rates measured at any of the six sites instrumented for this research. Work at this site also demonstrated the usefulness of the Oxygen Consumption Method in determining rapid, first order assessment of potential cover materials.

5.2 Kidd Creek, ON.

Hydraulic properties of the Kidd Creek thickened tailings impoundment have been well characterized (Robinsky et al., 1991). The thickened tailings deposition method used at the Kidd Creek site resulted in the development of a large (1260ha) roughly conical tailings stack, with slopes of approximately 2^o on average. The slope is slightly steeper near the centre region of the cone near the spigott and flattens somewhat distally. The tailings are homogeneous, with minimal grain size segregation with distance from the spigott (Robinsky et al., 1991). Robinsky et al also reported high air entry values (in the range of 7-10m), and low hydraulic conductivity ($1.1X10^{-7}$ m s^{-1} and lower) that were consistent on several samples from the site. Due to the low hydraulic conductivity and high AEV the Kidd Creek tailings has a high moisture content well above the water table and the zone of active oxidation is quite shallow (<1m).

The geochemistry of the Kidd Creek thickened tailings, and tailings pore water has also been the focus of detailed study (Al et al., 1994). Al et al. Reported elevated concentrations of sulphide oxidation products including sulphate, iron, and metals as well as depressed pH values in the 0m to 0.6m zone of the tailings profile. This identifies that sulphide oxidation is occurring in the near-surface zone. The zone of active oxidation was also identified by Woyshner, et al (1997) through the measurement of gaseous oxygen concentration with depth in the tailings. Woyshner reports that the oxygen concentration decreases to less than 5%O_2 within the top 0.3m of the tailings. This suggests that the zone of active oxidation is within approximately 0.3m of the tailings surface.

Sixty testing stations were installed on the exposed tailings at the Kidd Creek thickened tailings impoundment during the September, 1996 field visit. Oxygen consumption rate measurements were conducted at that time and again on two subsequent visits (May and June, 1997). Oxygen consumption rates were measured at a subset of the testing stations during the May and June visits.

Physical age of the exposed tailings at the surface ranges from less than two years to approximately ten years. Water content was also variable, with higher degrees of saturation associated with the perimeter of the cone and with the freshly deposited tailings. Physical parameters such as temperature and saturation conditions varied for the three measurement rounds. Several trends were observed between the measured oxygen consumption rates to these physical conditions at the site.

5.2.1 Trends in Oxidation Rate and Radial Distance from Centre of Cone

It was anticipated that the oxygen consumption rate rates would be highest near the centre of the cone and diminish to a considerably lower rate with distance due to a decrease in the extent of the vadose zone or an increase in the degree of saturation near the tailings surface. Examination of results from Transects #1 and #2 (Figure 3-6) show that variation along a radial line from the cone centre to perimeter is large. Variable, but significant oxidation rates were measured along the entire length of the transects. However, if the average value for the 10 testing stations located nearest to the cone center are compared to the 5 testing stations furthest from the cone centre a notable difference in oxygen consumption rates can be observed (Table 5-6).

Table 5-6. Trends in Oxidation Rate with distance from center of cone. September, 1996 data (Kidd Creek).

	Average Oxygen Consumption Rate mol O_2 m^{-2} a^{-1}	
Transect	Upper Cone	Perimeter
1	207	89
2	274	36

The most central 10 testing station were selected for averaging because they are located on the steeper, higher elevation portion of the tailings cone. The farthest 5 testing stations were selected for averaging and comparison to the central stations because of the lower elevation and proximity to ponded water. These factors would suggest higher moisture contents in the near-surface tailings around the perimeter compared to the central portion of the cone. This was noticeable in the field. The perimeter regions of Transects #1 and #2 exhibit oxidation rates approximately 60% to 80% lower than the higher elevated, better drained areas. Rates measured in the perimeter regions of Transects #1 and #2 are similar to rates measured on the fresh, poorly drained tailings located in the northern portion of the impoundment. While there was a trend of decreasing oxidation rates with distance form the centre of the tailings cone even the rates measured around the wetter perimeter of the tailings impoundment are non-trivial (40 to 90 mol O_2 m^{-2} a^{-1} or 2 to 5 kg $CaCO_3$ m^{-2} a^{-1}). These values are similar to measurements obtained on another site where the water table was shallow (purposefully raised as part of the site closure plan). At this site the raising of the water table reduced oxygen consumption rates from approximately 200 to about 70 mol-O_2 m^{-2} a^{-1}. Measurements of oxygen consumption on the older, well-drained tailings yielded an average rate of approximately 220 mol O_2 m^{-2} a^{-1} (12 kg $CaCO_3$ m^{-2} a^{-1}).

5.2.2 Trends in Oxidation Rate and Time Since Deposition

One of the objectives of this study was to evaluate temporal trends in the oxidation rate of the tailings. Because deposition had occurred in different radial directions over the last 10 years, it was possible to perform measurements on tailings that had been exposed to atmospheric conditions for between one and 10 years.

As oxidation proceeds, the sulphide component of the tailings located near the surface can be consumed and the oxidation profile can migrate to greater depths. In general, moisture content increases with depth and resistance to oxygen diffusion increases. It is hypothesized that oxygen consumption rates would decrease over time as a result of sulphide depletion at the surface. Elberling et al, 1994 presented results from a combined kinetic and diffusion model for pyrite oxidation that support this. It is not appropriate to compare the oxygen consumption rates measured on freshly deposited tailings to those measured on the other portions on the impoundment because the fresh tailings were poorly drained, and contained process water at the surface prior to consolidation. Oxygen consumption rates measured on the fresh tailings are lower than expected due to the high degrees of saturation present. Table 5-7 lists the average oxygen consumption rate measured on tailings areas of the specified ages as well as the range of oxygen consumption rates for each of the areas. The differences among the average oxygen consumption rates measured on tailings of 3, 5, and 10 years were small compared to variations within the data. However, the average values do suggest a trend of decreasing oxygen consumption rates with age of tailings. Statistically there is no significant difference in the rates measured on the tailings exposed for 3-4 and 5-6yrs. The is a significant difference between the rates for the tailings exposed for 5-6yrs and those exposed for 10 years (Appendix B).

Table 5-7. Average oxygen consumption rate on tailings exposed for different number of years. September, 1996 data (Kidd Creek)

Age of Tailings (yrs)	Number of Measurements	Range of Consumption Rate mol O_2 m^{-2} a^{-1}	Average Oxygen Consumption Rate mol O_2 m^{-2} a^{-1}
Less than 2	8	7 – 97	41
3-4	24	40-1617	273
5-6	28	1 – 518	192
10	4	17 – 156	81

These data suggest that a decrease in oxygen consumption rate may be expected with time since deposition. Rates will be highest when the material is fresh and after initial drainage and consolidation. Depletion of the sulphide minerals in the near-surface region of the tailings profile will result in lower rates due to the added diffusion resistance of the near-surface. The zone of active (or rapid) oxidation will progress downward until it reaches saturated conditions. This process may take many years, decades, or centuries. The Oxygen Consumption Method can be used to develop an approximation for this time. This is discussed further in a later section.

5.2.3 Seasonal Variation in Oxidation Rates

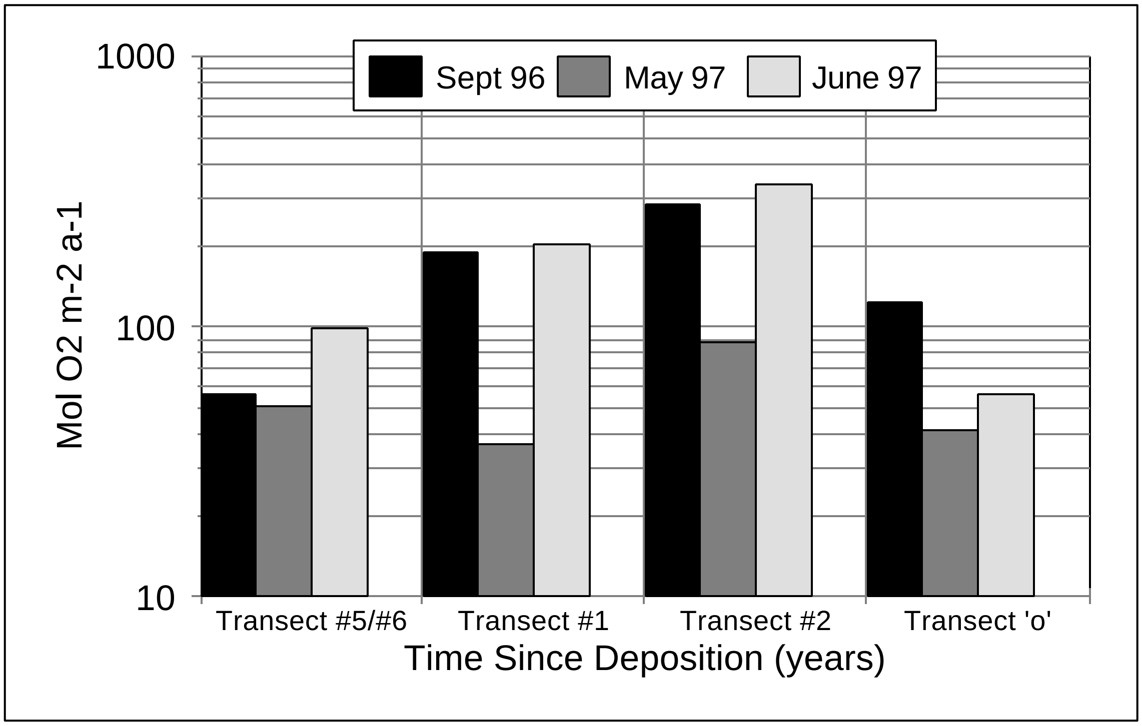
Measurement of oxygen consumption rates at a subset of the testing stations during the three site visits allows for investigation into the effects of seasonal change on oxygen consumption rates. The site was initially instrumented and oxygen consumption rates were first measured in September, 1996. Mid-September may be considered representative of late summer conditions at the site. The Temperature was in the 15 to 20^{o}C range, with moderate winds, interspersed with short periods of light rain. In contrast the temperature range for the May, 1997 visit was 0 to 15^oC. The early May visit may be considered representative of spring conditions. Occasional patches of snow were still visible in the Timmins area, water levels were high from spring run off, and a small snow fall was recorded during this visit. The June, 1996 measurements were conducted at temperatures ranging from 15 to 28^oC. Results gathered from the June visit may be considered representative of summer conditions at this site. Table 5-8 and Figure 5-5 present the oxygen consumption rates measured on the subset of testing stations where oxygen consumption rate were measured on all three site visits.

Table 5-8. Average oxygen consumption rates at Kidd Creek testing stations.

	Average Oxygen Consumption Rate ($mol\ O_2\ m^{-2}\ a^{-1}$)			
Sampling Round	Transect #5 and #6	Transect #1	Transect #2	Transect “o”
Sep 96	56	187	281	123
May 97	51	37	88	41
Jun 97	98	201	335	56

From these data a trend in oxygen consumption rates with season can be observed. In comparison to rates measured in June and in the previous September, the oxygen consumption rates from May are substantially lower for all but the freshly deposited tailings (Transects #5 and #6). Rates measured at Transect #6 during the May 1997 visit are similar to the rates measured on Transect #5 in September, 1996.

Figure 5-5. Oxygen consumption rates for September, 96, May and June, 1997 (Kidd Creek).



The lower rates measured in May are still non-trivial in terms of oxidation product loadings and acid generated. For example the average oxygen consumption rate measured for Transect #2 was 88 mol O_2 m^{-2} a^{-1}, or converted to a maximum required neutralization potential, over 4.5 kg $CaC0_3$ m^{-2} a^{-1}. Rates measured for the fresh tailings in May, 1997 were conducted at temperatures of less than 3^{o}C. It had been hypothesized that, at temperatures in this range the oxidation of sulphides in a tailings impoundment would be very low.

The rates measured in May, 1997, suggest that considerable amounts of oxidation may occur during the spring and late autumn portions of the year when temperatures are near freezing. Rates measured in May were at most 20% to 25% lower than rates measured during the visits in warmer, dryer months of September and June. Oxygen consumption rates measured in June, 1997 were very similar, and in most cases slightly higher, than the rates measured during the previous September. Statistically there was no difference in the rates measured in June and September along Transect #1. There was, however, a significant difference between June and September in comparison to May (refer to Appendix B for statistical output).

Results from the three visits can be used to qualitatively address the issue of average yearly oxidation rates at the site. If rates from June and September are representative of rates for the summer season and rates measured in May are typical of spring, and similarly, a good approximation of autumn (pre freeze-up) oxygen consumption rates, a weighted average method can be used to calculate average annual oxygen consumption rates. For various areas of the impoundment as demonstrated in Table 5-9.

Table 5-9. Calculating average annual oxygen consumption rate.

	Average Oxygen Consumption Rate ($mol\ O_2\ m^{-2}\ a^{-1}$)			
	Fresh (<2yrs)	3-4yrs old	5-6yrs old	10yrs old
May	51	37	88	41
Jun	98	201	335	56
Jul	98	201	335	56
Aug	98	201	335	56
Sep	56	187	281	123
Oct	56	187	281	123
Nov	51	37	88	41
Dec-Apr	*(assumed 0)*	*(assumed 0)*	*(assumed 0)*	*(assumed 0)*
Average	**42**	**88**	**145**	**41**

A trend in the oxygen consumption rate and the climatic conditions is evident in the oxygen consumption rates measured during the three visits. The seasonal variations in the oxygen consumption rates can be taken into account to arrive at a more appropriate estimation of annual *in situ* oxidation rates. Having oxygen consumption rates that are reasonable for several months it is possible to assess potential loading rates of oxidation products to receiving bodies, in this case possibly by flushing of the shallow pore water during rainfall events (Al and Blowes, 1995). This can aid in identifying times of discharge when concentrations may be unacceptably high due to a combination of high oxidation rates and low recharge. Further resolution of the average annual oxygen consumption rate and on the seasonal variation in oxygen consumption rates could be achieved by conducting measurements during the winter months

5.2.4 Oxygen Consumption Rates on Test Covers

In addition to the testing stations installed on the Kidd Creek thickened-tailings impoundment, four test plots representing different cover scenario designs (Noranda Technolgy Centre, 1996) were also instrumented for oxygen consumption rate measurements. This provided an alternative assessment of the different cover designs in comparison to oxygen consumption rates measured on nearby control testing stations on exposed tailings. The performance of the four different covers was also be examined over the spring and summer conditions. Table 5-10 lists the average oxygen consumption rate measured on the control stations and on the test covers for the three measurement rounds

Table 5-10. Average oxygen consumption rates for control stations and test covers (Kidd Creek).

	Sep 96	May 97	Jun 97	Average
	mol O_2 m^{-2} a^{-1}			
Control	305	99	631	345
Clay	42	48	187	93
Tailings & Slag	25	32	52	37
Tailings	51	26	46	41
Rock	24	11	54	30

Results for individual testing stations are reported in Table 4-9 in the Results chapter. The tailings used in two of the test cover designs was low-sulphur gold tailings from another mill. The relative effectiveness of the individual test covers can be observed in Table 5-11 which lists the efficiency of the covers in terms of reduction factors. These values are the calculated as the average oxygen consumption rate for the control station divided by the average oxygen consumption rate measured on each of the four test covers.

Table 5-11. Efficiency of test covers on the Kidd Creek tailings impoundment.

	Sep 96	May 97	June 97	**Average**
Cover Material	Reduction Factor in Oxygen Consumption Rates			
Clay	7.2	2.0	3.4	**4.2**
Tailings & Slag	12.0	3.1	12.1	**9.1**
Tailings	6.0	3.8	13.7	**7.8**
Rock	12.8	9.2	11.6	**11.2**

On average, over the three sampling rounds, the cover constructed from waste rock caused the greatest reduction in measured oxygen consumption rates. However, for the rates measured in June, when oxygen consumption rates at the site in general were highest, we see that the cover constructed of only tailings was the most efficient.

Oxygen consumption rate measurements conducted in June, 1997 demonstrated the response of the various covers to net evaporative, dryer, conditions. The average oxygen consumption rate of the control stations was approximately three times that which was measured in September, 1996. Oxygen consumption rate measurements taken on the clay-till cover were also approximately three times those measured in May, 1997 and in the September,

1996. The dry conditions of June lead to the partial desiccation of the clay-till test cell and the development of cracks. This observation is supported by TDR moisture content measurements showing notable dewatering of the test plot covers during the summer (Woyshner and Swarbrick, 1997). The cover constructed of waste rock also showed a dramatic increase in measured oxygen consumption rates from the May to June, 1997 measurement rounds. The oxygen consumption rate measured on the waste rock test plot increased by approximately a factor of five. While this was the largest relative increase observed amongst the test cells over the three measurement rounds, the clay-till test cover consistently yielded the highest absolute values that were, on average, a factor of three greater than any of the other test cells. Oxygen consumption rates for the test cell constructed from crushed slag and desulphurized tailings showed a doubling in rates, yielding absolute rates similar to those measured on the waste rock cover. Oxygen consumption rates measured on the cover constructed of only desulphurized tailings were the lowest for the June measurement round and the lowest relative increase from May to June. Woyshner and Swarbrick (1997) reported oxygen fluxes calculated from measured oxygen gradients that also show that oxidation continues, at a reduced rate, beneath the clay-till, tailings and slag, and tailings covers. The oxygen gradient method may be prone to over estimation (Elberling, et al., 1994). Oxygen fluxes reported by Woyshner and Swarbrick (1997) were calculated from oxygen profiles were 2 to 4 time higher than rates measured with the Oxygen Consumption Method for the tailings and slag and the tailings covers. However, as seen in the fluxes calculated by the Oxygen Consumption Method, the tailings and slag cover yielded fluxes that were also greater than those for the tailings only cover. Woyshner and Swarbrick (1997) report an oxygen flux through the clay-till cover that is considerably lower than that measured using the Oxygen Consumption Method. They do however, indicate that the flux through the clay-till cover should be effectively larger owing to the observed cracking. There is also some concern that the drying of the clay-till may have caused the development of cracks along the inside perimeter of the tube used in the Oxygen Consumption Method. This would result in preferential pathways for oxygen transport through the cover and higher oxygen consumption rates. Such cracking was not observed in the field but is worth consideration.

Several important issues are brought to light from the observations made on the oxygen consumption rate data collected from the testing stations located on the Kidd Creek test covers. The relative effectiveness of the cover material was strongly affected by the net evaporation conditions in June. During this time, and even before, we see that the clay-till cover performed poorly due to the formation of desiccation cracks that may have acted as high diffusion conduits for oxygen transport. Despite the clay-till having a fine grained texture and a high air-entry value, beneficial properties in a diffusion barrier cover, it was not highly effective as constructed. The addition of an evaporative barrier to limit desiccation may have greatly improved the ability of the clay-till cover to limit oxygen consumption rates.

The coarser grained crushed slag layer was incorporated to act as a hydraulic discontinuity, preventing drainage of pore water from the fine grained low-sulphur tailings above and thereby maintaining a high moisture content in the upper tailings layer. The high degree of saturation in the fine layer can act as an effective barrier to oxygen transport. However, the composite cover of tailings and slag was less efficient as an oxygen barrier than the cover consisting of tailings only, based on June, 1997 oxygen consumption rate measurements. It is hypothesized that the hydraulic discontinuity created by the crushed slag material worked well to prevent drainage from the overlying fines layer but also prevented upward movement of water to replenish moisture lost from the fine grained tailings through evapotransporation. In contrast, the moisture profile of the low-sulphur tailings cover was maintained to some degree by moisture transfer from the underlying Kidd Creek tailings.

The implications of this are clear. In designing a multi-layer cover, care must be taken to design for high saturation of the fine layer remembering the net evaporative loss conditions that will occur during summer conditions. Such consideration may include increased thickness of the fines layer, or the addition of a coarse grained top-most layer to minimize water loss by evapor-transporation.

5.3 Dona Lake, ON.

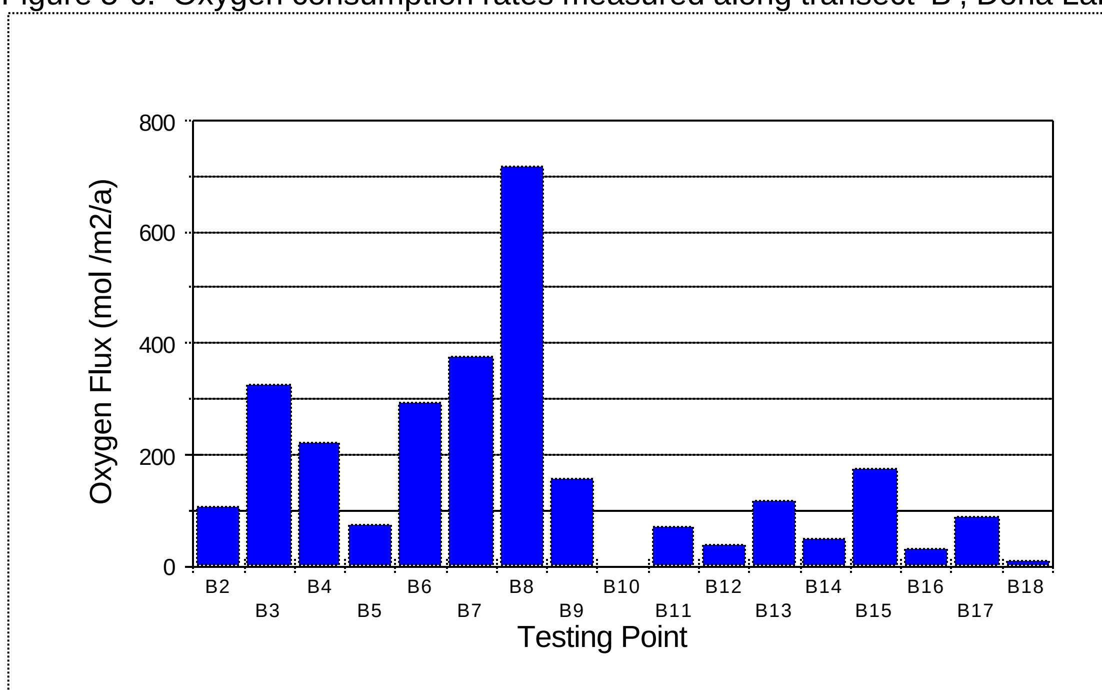
The reasons for investigating the oxygen consumption rates at the Dona Lake included advancement of the understanding of *in situ* oxidation rates by enlarging the existing data set; to investigate the effect of the raised water table on oxygen consumption rates; and to evaluate the site spatially to identify areas, that due to higher than site average oxidation rates, may require special remedial attention.

In contrast with the acidic pore water conditions seen at the Kidd Creek site the near-surface pore water in the Dona Lake tailings was at near neutral conditions, as indicated by paste pH sampling (Ferguson Pers. Comm., 1996). This suggests that carbonate minerals likely remain near the surface, and that neutralization potential has not yet been exceed in the near surface material even though the tailings, on average have a net deficit of neutralization potential (Ferguson Pers. Comm., 1996). This may suggest that the site is not currently acid generating and that remedial efforts to prevent the onset of acid drainage would be appropriate.

The objective of investigating the relationship between the depth to the water table and oxygen consumption rates was addressed by orienting transect 'B' perpendicular to the pond shore. The depth to the water table at testing station 'B2' was approximately 1m where as the water table was only 5-10cm below the tailings surface at testing station 'B18'. It would be anticipated that the lowest oxygen consumption rates would be measured at testing stations along transect ‘B’ where the depth to the water table was the smallest, and therefore only small amounts of sulphides would be available for oxidation.

A trend of increasing oxidation rate with increasing depth to the water table was reported by Elberling and Nicholson (1996). In that investigation the oxygen consumption rate increased steadily with increasing depth to the water table from 5 to 40cm. No further increase in the oxygen consumption rate was noted for test where the water table was between 40 and 70cm. The active zone of oxidation, a function of the D_e of the system and the sulphide content of the tailings was no effected by the position of the water table when it was deeper than approximately 40cm below the ground surface. The depth of oxidation zone is site specific and also can migrate downward with time as sulphide material is consumed. Results for the oxygen consumption rates measured on transect ‘B’ are listed in Table 4-10 in the Results chapter presented below in Figure 5-6.

Figure 5-6. Oxygen consumption rates measured along transect ‘B’, Dona Lake



A consistent trend in measured oxygen consumption rates was not observed along transect ‘B’. However, it can be said that oxygen consumption rates measured near the pond (stations ‘B11’ to ‘B18’) were, on average lower than rates measured on the testing stations located further from the pond (‘B2’ to ‘B9’). The average oxygen consumption rate for stations ‘B2’ to ‘B9’ and for stations ‘B11’ to ‘B18’ are listed in Table 5-12.

Table 5-12. Average oxygen consumption rates and equivalent neutralization for stations near the pond (‘B11’ to ‘B18’) and for stations far from the pond (“B2’ to ‘B9’) (Dona Lake).

Segment of Transect ‘B’	Average Oxygen Consumption Rate (mol O_2 m^{-2} a^{-1})	Max. Equiv. CaCO3 Consumption (kg $CaCO_3$ m^{-2} a^{-1})
'B2' to ‘B9’	294	16
'B11' to ‘B18’	72	4

The highest oxygen consumption rates for transect ‘B’ were measured in the vicinity of testing stations ‘B7’ and ‘B8’, where the depth to the water table was not as great as at stations nearer to Dyke 3 (‘B2’). This observation may be explained by the presence of coarser-grained material that runoff and erosion had carried down-slope from the apron area located to the northwest (Figure 3-9, Methods chapter), depositing it in the area where tubes ‘B7’ through ‘B10’. This material may have been more reactive and therefore responsible for the elevated rates measured at testing stations ‘B7’ and ‘B8’.

The average oxygen consumption rate along transect ‘C’ was 288 mol O_2 m^{-2} a^{-1}. This also suggests that material from this area my have been responsible for the high rates testing stations ‘B7’ and ‘B8’. The area characterized by Transect ‘C’ may require remedial attention to avert the development of acidic conditions in the near future. Minor amounts of the material from the apron area (Figure 3-9) were also deposited in the region where ‘B11’ through ‘B15’ were installed. However, high saturation conditions in the tailings at these locations may limit the oxidation rate of this material.

Raising the water table had an observable effect on the *in situ* sulphide oxidation rate, as seen along transect ‘B’. Oxygen consumption rates were, on average, lower in areas where the water table was very close to the tailings surface. This implies that raising the water table may result in a notable decrease in oxidation rates at the site and a reduction in oxidation product loading to receiving water bodies. However, despite the water table being within centimeters of the tailings surface, and the tailings being highly saturated, oxygen consumption rates were measurable and non-trivial. This suggests that while the rate of oxidation may be considerably reduced by raising the water table, oxidation may continue at a rate where some form of treatment may be necessary.

A far more positive effect of raising the water table is the potential reduction in long term impacts from the site due to a decrease in the available sulphide inventory above the water table. Raising the water table from 1m below the tailings surface to 0.5m below the tailings surface effectively means that 50% of the material that would have eventually undergone oxidation, at rates typical for the vadose zone, is now below the water table where oxidation rates would be limited by the low oxygen diffusion coefficient in the saturated tailings.

5.4 Cullaton lake, NWT.

The Cullaton Lake impoundment was capped with a sandy-gravel-till cover to limit oxygen availability to the sulphide tailings as a method of reducing oxidation. The cover applied at this site was comprised of locally available till that was placed on the tailings impoundment using heavy equipment. Thickness of the cover varied between 0.5m and 1m. Table 5-13 lists the oxygen consumption rates measured at the control stations and the average rate measured on the stations installed through the till cover.

Table 5-13. Oxygen consumption rates on exposed tailings and covered areas (Cullaton Lake).

	Oxygen Consumption Rates mol O_2 m^{-2} a^{-1}	
Transect	Control Station	Average on Cover Test stations
#1	128	13
#2	82	3
#3	X	10

X – No control test station available

Oxygen consumption rates measured on the covered portions of the impoundment were approximately one order-of-magnitude lower than rates measured at non-covered testing stations. The observed efficiency of this simple cover is useful information. In lieu of other materials, not available at this remote site, this sandy-gravely-till provided substantial reductions of the *in situ* oxidation rates.

The cover may be acting as a diffusion barrier and also as an evaporation barrier, maintaining relatively high moisture contents in the underlying tailings.

Cullaton Lake is located in the Eastern NWT where the amount of precipitation is considerably lower than that at tailings impoundments located in the Timmins and Sudbury areas of Northern Ontario. Conditions of net evaporation can develop during the short but intense summer season, when temperature can often reach the high 20^{o}C range. A coarse grained cover would act to minimize this moisture loss. The Cullaton Lake area is underlain by permafrost and it was hoped that the addition of the till cover would promote upward migration of the permafrost zone to encompass the tailings. To date this has not happened. The average tailings thickness is approximately 1.2m, temperatures at this depth have been measured in the range of 2 to 6oC (Meyer, Pers. Comm., 1997).

5.5 LTA, PQ.

The LTA site was a reactive tailings impoundment that had been capped with an engineered, multi-layered cover. The cover consisted of a coarse grained sand layer placed on the tailings to acts as a capillary break. The second layer consisted of a non-reactive tailings that (due to its fine grained texture) would act to retain moisture and be an effective barrier to oxygen diffusion. This layer was covered by a sandy-gravel layer to minimize evaporative loss from the non-reactive tailings layer.

The average oxidation rate measured on the non-covered LTA tailings was 339 mol O_2 m^{-2} a^{-1} (18 kg of $CaCO_3$ m^{-2} a^{-1}). Average oxygen consumption rates measured on the testing stations installed in covered areas of the impoundment were approximately 4 mol O_2 m^{-2} a^{-1} (0.1 kg $CaCO_3$ m^{-2} a^{-1}) for the June, 1996 site visit. The average oxygen consumption rate for the covered areas was approximately 8 mol O_2 m^{-2} a^{-1} (0.4 kg $CaCO_3$ m^{-2} a^{-1}.) for the October, 1996 site visit. These neutralization requirements are significantly lower than those for the non-covered areas and may represent a major potential cost saving in terms of effluent treatment cost.

Measurements exhibit consistently low values for the covered tailings. In general, the cover has resulted in a reduction in oxidation rates on the order of 100 times, or two orders-of-magnitude in comparison to values measured on the uncovered tailings prior to cover construction.

The oxygen consumption rates measured at the toe of the covered tailings dam were also similar to measurements conducted on the main body of the impoundment. This is significant because of concerns of potential drainage of the moisture retaining layer due to the elevation differences on the sloped portion of the cover where the pressure head could possibly exceeding the air entry value of the fine-grained layer (Aubertin et al., 1997). This could potentially result in the drainage of the fine layer. Measured oxidation rates suggest that the performance of the cover has not yet been affected by the slope.

Ambient temperatures during the sampling event in June 1996 were in the 30^{o}C range. Data collected during the June, 1996 visit gives some indication of cover performance during warmer temperatures and increased evaporation conditions. Measured values were not necessarily representative of an extended period of warm temperature or prolonged dry period. The results for June, 1996 were, on average, very similar to those measured in October, 1996. This suggests that the efficiency of the cover system was not adversely affected by drying due to net evaporation conditions over the summer season.

The consistency of the values, during both the June and October sampling rounds demonstrate the overall effectiveness of the cover. More than 60 individual measurements were made. Seventy-five percent of the measured rates were less than 5 mol O_2 m^{-2} a^{-1} with only fifteen percent between 10 and 30 mol O_2 m^{-2} a^{-1}. Rates measured along individual transects suggest that there are effectively no spatial patterns to the variability.

The cover was constructed during the winter of 1995-1996 with the exception of one area that was completed in early June, 1996. The melting of entrained snow and ice and settling of the cover are worth considering. It is postulated that steady-state moisture profiles may have not been fully developed during the first field season. Low saturation of the fine layer would result in reduced cover efficiency. This is a possible explanation the few anomalous high oxygen consumption rates measured on the impoundment .

5.6 Norbec-Manitou, PQ.

Oxygen consumption rates were measured on the test plots located at the Norbec-Manitou site in October, 1995, May, 1996 and again in October, 1996. Test plots #1 through #5 contained different multi-layered covers and test plot #6 represented the control scenario, consisting of exposed tailings (refer to Figure 3-

14 in the Methods chapter for a schematic of the site layout). The average oxygen consumption rates listed by test plot for the three site visits are presented in Table 5-14. Detailed results are listed in Tables 4-16 and 4-17 located in the Results chapter.

Table 5-14. Average oxygen consumption rates measured on the Norbec-Manitou test plots.

	Oct 1995	Jun 1996	Oct 1996
	Average Oxygen Consumption Rate (mol O_2 m^{-1} a^{-1})		
#6 (Control)	95	19	18.3
#1	13	28	1.0
#2	34	10	1.0
#3	31	6	4.3
#4	32	10	1.6
#5	39	16	0.2

The oxygen consumption rates measured on the test plots in October, 1995 were approximately a factor of three lower than the rates measured on the control plot at that time. The rates measured on the control plot during the June, 1996 visit were considerably lower than that measured in the previous October. Rates measured on the five covered test plots during June, 1996 also were notably lower than those measured in October, 1995. The oxygen consumption rate measured on the control test plot during the October, 1996 site visit was very similar to the rate measured in June. However, the oxygen consumption rates measured on the five covered test plots were substantially lower than those measured in June.

In general, there is a trend of lower oxygen consumption rates for the five covered test plots and for the exposed control plot over the three measurement rounds. The test plots were constructed in August, 1995, approximately two months prior to the first measurement round. There is concern that the severe disruption of the material in transporting it to the test plot location, and during the test plot construction led to non-steady-state conditions with respect to moisture, oxygen profiles, and possibly reaction kinetics. The implications of this may include that a significant amount of time may have been required for the re-establishment of steady state profiles within the control test plot and also within the five covered test plots.

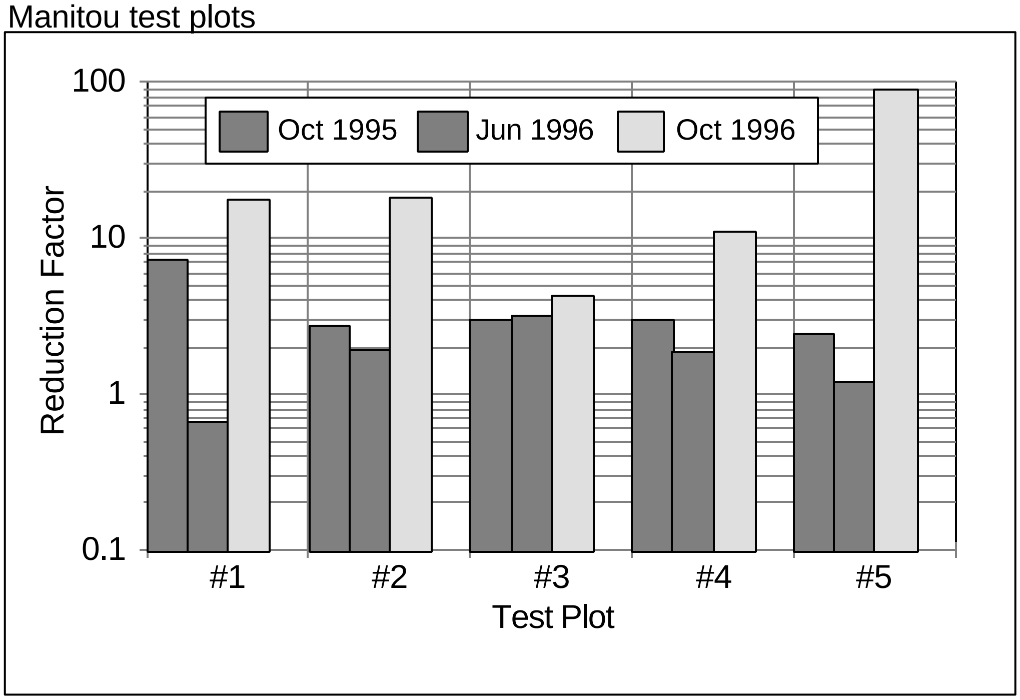
Table 5-15 lists the average reduction factors for the five test plots for each of the three measurement rounds. These values are calculated by dividing the average oxygen consumption rates measured on the control test plot by the average oxygen consumption rate for a test plot for each month. The average reduction factor for each test plot for all three measurement rounds is also reported. This value is intended to give an overall indication of the individual test plot efficiency. The average reduction factor seen for all five test plots is also listed to provide insight into the efficiency of all covers for individual measurement rounds.

Table 5-15. Average reduction factors for Norbec-Manitou test plots.

	Oct 1995	Jun 1996	Oct 1996	Average Reduction Factor
Test Plot	Reduction Factors			
#1	7.2	0.7	17.6	8.5
#2	2.8	1.9	18.3	7.7
#3	3.0	3.2	4.2	3.5
#4	3.0	1.8	11.1	5.3
#5	2.5	1.2	88.8	30.8
Average	3.7	1.8	28.0	11.1

The cover was much more effective at reducing oxygen transport to the underlying tailings during the October measurement round. Figure 5-7 is a plot of the average calculated reduction factors for the individual test plots based on a comparison of rates measured on the test plots and control plot for each month.

Figure 5-7. Average monthly individual test plot reduction factors for Norbec-Manitou test plots



Based on oxygen consumption rates measured for the June sampling round, the covers were minimally effective at reducing oxygen consumption rates. The reduction factors calculated form the oxygen consumption rates measured during the previous sampling round (October, 1995) were for the most part higher than those for June. In contrast the reduction factors resulting from the October, 1996 rates were notably higher than the other two sampling rounds. The overall performance of the covers during the three site visits can be examined in 'average' row of Table 5-15 which lists a single reduction factor for each sampling round. This value is the average of the reduction factors for all five test plots for each month compared to the oxygen consumption rate measured on the control test plot for the corresponding month.

The overall difference in cover performance between October, 1995 and June 1996 is small compared to that seen in October, 1996. From these data and the arguments developed above, it can be concluded that the performance of the cover systems improved over time and that comparison of the oxygen consumption rates measured on the test plots to those measured on the exposed control plot may be misleading due to increasing moisture content in this particular case. If the calculated reduction factors are averaged for the three measurement rounds for each of the five test plots as listed in Table 5-14 we can appreciate the overall effectiveness of the individual covers for the entire investigation. From such data, test plots covers #1 and #2 are of similar effectiveness and approximately a factor of two more effective than covers #3 and #4. Overall, cover #5 seemed to yield the greatest reduction factor but this value is very strongly influenced by the exceptionally low oxygen consumption rates measured on this test plot during the October, 1996 site visit. The reduction factors calculated for the other two measurement rounds were below average.

Based on the results and discussion forwarded for each of the six sites, several overall issues regarding oxidation rates in tailings impoundments and the effects of remedial efforts and various physical conditions can be addressed. These issues include some of the original site specific objectives such as age of the exposed tailings and the relationship of sulphide content and measured oxygen consumption rates. It is also possible to comment, in a relative sense and in some cases an absolute sense as well, on the effectiveness of a variety of cover scenarios employed at several sites. As few *in situ* oxidation rates have been reported, this collection offers an substantial resource to aid in the understanding of the rate of tailings oxidation in a general sense and provides insight into some of the controlling parameters.

5.7 Cross-Site Evaluation of Cover Efficiency

Oxygen consumption rates were measured on covers at three scales; at sites that were covered as a management strategy; at the sites where small test plots were constructed to evaluate cover options; and on gravel covers placed in the testing stations on impoundments of differing sulphide content. Table 5-16 lists the sites at which a cover (test plot or full scale) had been constructed and oxygen consumption rates measured as part of this investigation.

Table 5-16. Cover scenarios investigated.

Site	Cover Scenario(s)	Cover Type(s)	Scale
LTA	Covered site	Multi-layered	66ha
Cullaton Lake	Covered site	Single Layer	3.5ha
Kidd Creek	4 Test Plots	Single Layer / Two Layer	20m X 60m
Norbec-Manitou	5 Test Plots	Multi-layered	10m X 10m
Strathcona	3 cover types	Single Layer / Two Layer	$250cm^2$

Two sites, LTA and Cullaton Lake, where full-scale covers that had been installed as part of the site closure plan. The greatest difference between these two sites was that the LTA cover was a three-layered engineered cover and the cover at the Cullaton Lake site was simply a local till plowed on to the tailings impoundment. Table 5-17 lists the average oxygen consumption rate measured at the control stations and the calculated reduction factor (an average for all testing stations located on the covered portion of the site). The effectiveness of the cover is presented this way to highlight the efficiencies of the two different covers and the actual non-covered oxygen consumption rates at the two sites.

Table 5-17. Multi-layered vs. single layered cover for full-scale implementation.

LOCATION		Jun 96	Jul 96	Oct 96
Cullaton Lake				
OCR	**Control**		**105**	
RF	Site Average		10	
Barrick LTA				
OCR	**Control**	**389**		**389**
RF	Site Average	97		73

OCR – Oxygen consumption rate (mol O_2 m^{-2} a^{-1})
RF – Reduction Factor

The engineered cover yielded oxygen consumption rate reduction factors that were 7 to 9 times higher than those for the single layer cover. In other words, the multi-layered cover was approximately an order-of-magnitude more efficient at limiting the transport of oxygen to the underling tailings. In absolute terms however, the oxygen consumption rates measured through the cover at the Cullaton Lake and LTA sites were approximately equal but the oxygen consumption rates measured on the non-covered portions of the site were approximately four times higher for the LTA site.

Oxygen consumption rates measured on test plots from the Kidd Creek and Norbec-Manitou sites can be examined to compare the efficiency of multi-layered and single layered covers. Table 5-18 lists the average oxygen consumption rate measured at the associated control stations and the reduction factor of the various cover scenarios.

Table 5-18. Multi-layered vs. single layered cover for test plots.

LOCATION		Oct 95	Jun 96	Sep 96	Oct 96	May 97	Jun 97
Kidd Creek Test plots							
OCR	**Control**			**305**		**99**	**631**
RF	Clay			4		1	2
RF	Tailings & Slag			8		2	9
RF	Tailings			4		2	9
RF	Rock			8		5	8
Norbec-Manitou Test plots							
OCR	**Control**	**95**	**19**		**18**		
RF	#1	7	1		18		
RF	#2	3	2		18		
RF	#3	3	3		4		
RF	#4	3	2		11		
RF	#5	2	1		89		

OCR – Oxygen consumption rate (mol O_2 m^{-2} a^{-1})
RF – Reduction Factor

From the reduction factors listed in table 5-18 it is clear that the simple covers installed on the Kidd Creek test plots reduced the oxygen transport to the underlying tailings by less than one order-of-magnitude. The multi-level covers installed on the Norbec-Manitou test plots also yielded reduction factors less than a factor of ten for the October, 1995 and June, 1996 measurement rounds. Reduction factors calculated for the Norbec-Manitou test plots in October, 1996 were, for the most part significantly higher, up to a factor of 89. This Represents improved cover efficiency for the October, 1996 measurement round. Aubertin et al (1997), report a trend of increasing moisture content for the middle layer of the cover over the period of August through October, 1996. This increase in moisture content may be responsible for the observed efficiency of the covers in October, 1996.

The covers installed at the Norbec-Manitou site included a layer of low-sulphur tailings. This low-sulphur layer itself may be consuming oxygen at a low but measurable rate. Laboratory studies of the oxygen consumption rates for low-sulphur material (0.14%S to 1%S) were reported to range from 3 to 155 mol O_2 m^{-2} a^{-1}, (Bussiere et al., 1997) and field measurements in the range of 19-37 mol O_2 m^{-2} a^{-1} for 1%S pyrrhotite tailings are reported in this study. The oxygen consumption rates reported for the Norbec-Manitou test covers are consistently within this range. The low-sulphur content in the cover material may contribute to measured oxygen consumption rates over the short term but residual sulphide will be depleted through oxidation and the remaining material will continue to function as a potentially effective barrier.

The effect of the addition of a cover to minimize *in situ* sulphide oxidation was investigated at a scale smaller than the test plots. At the Strathcona tailings impoundments three gravel cover configurations were tested on tailings with sulphide contents of 1%S, 15%S and 30%S. In this testing arrangement, above ground portions of the Oxygen Consumption Method installation tubes were filled with candidate cover material. This apparatus is effectively a column scale test performed on *in situ* tailings and exposed to real would environmental conditions such as evaporation, and precipitation. Table 5-19 lists the average oxygen consumption rate measured at the control testing stations and the reduction factorfor the three cover scenarios.

Table 5-19. Background oxygen consumption rates and reduction factors for Strathcona test covers.

LOCATION		May 96	Sep 96	Oct 96
Strathcona 1%S				
OCR	**Control**	**29**		
RF	Gravel 'A'	1.9		
RF	Gravel 'B'	1.1		
RF	Gravel 'A' and 'B'	1.45		
Strathcona 15%S				
OCR	**Control**	**444**	**341**	
RF	Gravel 'A'	6.4	5.1	
RF	Gravel 'B'	4.6	3.5	
RF	Gravel 'A' and 'B'	12.3	4.3	
Strathcona 30%S				
OCR	**Control**	**5101**	**863**	**863***
RF	Gravel 'A'	15.7	2.9	*9.5*
RF	Gravel 'B'	11	3.4	*7.7*
RF	Gravel 'A' and 'B'	19.9	4.3	*24.7*

OCR – Oxygen consumption rate (mol O_2 m^{-2} a^{-1})
RF – Reduction Factor
* - *No control available. Sep 96 values assumed*

The effectiveness of the three cover scenarios is apparent from the above data. Reduction factors well over an order-of-magnitude were measured for the locations where the sulphur content was high and the associated oxygen consumption rates from the control stations were large.

Preliminary evaluation of potential simple covers by constructing the cover within the testing station tube is simple, low-cost and yields results that are consistent with measurements conducted on test plot and full- scale covers.

5.8 Tailings Moisture Content and Oxygen Consumption Rates

From data collected on two of the sites, it is possible to comment of the general effect that the position of the water table has on the oxygen consumption rates. Some of the transects of testing stations located on the Kidd Creek and the Dona Lake sites were oriented such that they approached ponded areas.

At Kidd Creek, transects #1 and #2 were oriented from the cone centre to perimeter and approached pond areas. The distance between the testing stations was approximately 85m. The average oxygen consumption rate for the ten testing locations located closest to the cone center for both transects were calculated.

These 10 testing stations were located on the steeper portion of the cone. The average oxygen consumption rate for the five testing station located closest to the pond areas was also calculated. Along transect #1, the five testing stations located closest to the pond were off-set from the main transect to avoid a constructed berm (Figure 3-6). To be consistent, the oxygen consumption rate for the five testing stations along transect #2 closest the ponded area was also averaged. At the Dona Lake site, transect 'B' was oriented to extend from Dyke 3 to towards the pond shore (Figure 3-9). Testing stations along transect 'B' The average were spaced at approximately 18m. Oxygen consumption rates for the five testing stations located closest to the pond and the five testing stations located furthest from the pond were calculated. Table 5-20 lists these values as well as the reduction factor that can be attributed to the decreased depth to the water table.

Table 5-20. Oxygen consumption rate trends with tailings moisture content.

	Average O_2 Consumption Rate mol O_2 m^{-2} a^{-1}		
LOCATION	Lower near-surface water content	High near-surface water content	Reduction Factor
Kidd Creek			
Transect #1	207	89	2.3
Transect #2	274	36	7.6
Dona Lake			
Transect 'B'	203	71	2.9

From these data we can conclude that the oxidation rates at locations where the depth of the vadose zone is reduced, the *in situ* oxidation rate will be diminished considerably (Elberling and Nicholson 1996). The reduction in the average oxygen consumption rate was approximately a factor of 2 to 8 for the two sites. These two sites differ in sulphide mineralogy, deposition method, and age of exposure. However, similar oxygen consumption rates were measured on areas of these sites where the unsaturated zone was shallow and the tailings had a high saturation and also for areas where the vadose zone was 1m thick or greater. Raising the water table (decreasing the extent of the vadose zone) to near surface levels may result in lower oxygen consumption rates for the tailings which ultimately translate into lower loadings of products, and the shorter period over which oxidation will occur, and potential decreased environmental impact. A similar effect might be expected in areas where ponding occurs. However, despite these benefits these data (and rates measured on the fresh, saturated Kidd Creek tailings) demonstrate that non-trivial oxidation rates do occur in tailings where the vadose zone may be nearly non-existent.

5.9 Applications of Oxygen Consumption Rate Measurements

The main objective of the Oxygen Consumption Method is to determine current oxygen consumption rates that that can be used to assess the *in situ* oxidation rate of an impoundment spatially, as a area survey, or temporally, to observe seasonally and long-term variations. These rates can also be translated into potential loadings (before considering secondary mineral reactions). These data can be used to evaluate potential maximum loadings in effluent draining from the tailings, surface water, seepage, and groundwater discharge. However, having the oxygen consumption rate, it is also possible to estimate other parameters based on stoichiometry. Such applications for the Oxygen Consumption Method data include first order estimates of concentrations in the pore water, and perhaps more importantly, sulphide and neutralization depletion rates.

5.9.1 Estimating Concentrations of Oxidation Products in Pore Water

Oxygen consumption measurements are an indirect indication of the rate of release of oxidation products such as Fe^{2+}, SO_4^{2-} and H^+ (see Equations 2-8 and 2-9 in chapter 2). These species are produced in the oxidation zone that is above the water table and extends downward from ground surface. The depth of this zone may vary from a few centimeters to a few meters depending on the physical and chemical properties of the tailings (Duborvsky *et al.*, 1985, and David and Nicholson 1995). Water that enters the tailings as infiltration is effectively “titrated” with oxidation products at a rate that can be estimated from the oxygen consumption measurements. The estimated flux of sulphate based on oxygen consumption can be used to calculate potential pore water concentrations that may be anticipated if infiltration rates are known. These can be used as first-order estimates to evaluate treatment requirements for seepage water originating as tailings pore water.

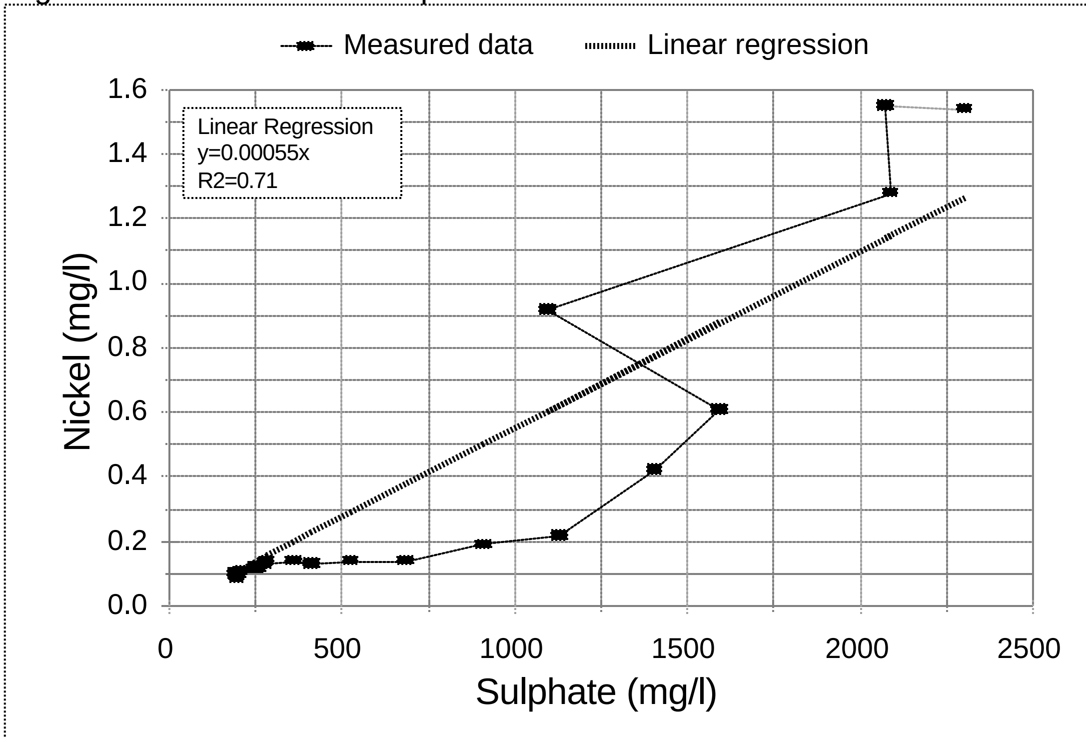
The “average concentration” of sulphate in tailings pore water is calculated in the following way. A typical oxygen consumption measurement is selected to represent a specified region of tailings. This value is converted to a sulphate flux (see Table 5-1) and divided by the annual infiltration rate. The resulting value is a potential average concentration only. It does not include any secondary geochemical processes that would be anticipated in many tailings materials, including precipitation of sulphate as gypsum ($CaSO_4 \cdot 2H_2O$), if dissolved calcium, or solid calcium carbonate (e.g. calcite) is present. The calculated concentration is therefore a potential maximum value. As an example, a tailings area with an average oxygen consumption rate of 200 mol O_2 m^{-2} a^{-1} and an infiltration rate of 250 mm a^{-1} would produce an “average” sulphate concentration in the pore water on the order of 40,000 mg L^{-1}. Although this value appears to be high, concentrations in the absence of calcite have been observed to be as high as 100,000 mg L^{-1} in shallow pore water in sulphide tailings (Blowes *et al.*, 1992). Lower sulphate concentrations in the pore water would be expected if some of the sulphate precipitates as gypsum ($CaSO_4 \cdot 2H_2O$). However, modelling studies (Nicholson et al., 1995) suggested the lower sulphate concentrations in the pore water would be balanced by the storage of the precipitated gypsum as a soluble mineral in the solid phase that can be released after sulphide mineral oxidation in that shallow zone ceases or the source of dissolved calcium becomes depleted.

5.9.2 Estimating Potential Metal Loading Rates

In some instances, oxygen consumption measurements may provide first-order estimates of metal loadings. Some metals such as zinc and nickel do not have important solubility controls (by metal hydroxide precipitation, for example) at pH levels below 7. As a result, even neutral waters can have elevated concentrations of these metals. It is common to observe moderate to strong linear correlations between sulphate and metal concentrations (nickel and zinc), in leachate samples from tailings and waste rock oxidation tests (i.e., column tests and Humidity Cell tests). The sulphate-metal correlation can be used to estimate metal concentrations or loadings if the corresponding sulphate values are known. Oxygen consumption measurements can be used to estimate the sulphate loading rates that can then be converted to approximate metals loading rates.

An example for a recent tailings investigation included field measurements of oxygen consumption rates and laboratory studies of tailings oxidation in column experiments. The laboratory data (Clulow, 1996) exhibited a reasonable linear correlation between sulphate and nickel concentrations in the column effluent (Figure 5-8). Only samples with sulphate concentrations less than 2500 mg/L were considered. These concentrations of sulphate are less likely to be affected by gypsum precipitation (or dissolution). The data suggest that sulphate and nickel production rates are related and this is likely, given that the most probable source of nickel is residual pentlandite [$(Fe, Ni)_9S_{10}$] in the tailings. A plot of sulphate versus nickel concentrations for a selected test is shown in Figure 5-8.

Figure 5-8. Correlation of sulphate and nickel in effluent water



The linear correlation coefficient (R^2) for these data is 0.71. The linear regression is given by: Ni=0.00055 (SO_4) if it is assumed that the intercept is zero. To exemplify how this can be applied Table 5-21 lists several possible oxygen consumption rates measured for a hypothetical pyrite tailings impoundment, the calculated maximum sulphate loading produced by pyrite oxidation and the possible nickel loading.

Table 5-21. Examples of calculated nickel loading rates.

O_2 Consumption Rate (mol O_2 m^{-2} a^{-1})	SO_4 Flux* (kg m^{-2} a^{-1})	Ni Flux	
		mg m^{-2} a^{-1}	kg ha^{-1} a^{-1}
10	0.5	281	3
100	5	2805	28
1000	51	28050	281

** – assumes complete oxidation of pyrite as described in equation 2-8*

From Table 5-21 we see that an oxygen consumption rate of 100 mol O_2 m^{-2} a^{-1} may potentially result in a maximum nickel loading of 28 kg ha^{-1} a^{-1}. These results are site-specific and should not be used for other impoundments. These calculations can then be used to provide a first-order assessment of downstream concentrations when the water balance components have been quantified for the watershed into which the tailings impoundment drains.

5.9.3 Estimating Sulphide Depletion Rates (Duration of AMD Generation)

Results from oxygen consumption rate measurements can be used to estimate the time over which oxidation could continue within an impoundment by calculating the time frame for sulphide mineral depletion above the water table. This value can be useful as a first-order approximation of the time that the impoundment could be generating AMD and as a guide in examining the effect of various remediation scenarios, such as raising the water table.

For a tailings with a sulphide content of 10% Pyrite and a bulk density of approximately 1800 kg m^{-3}, the mass of sulphide would be 180 kg FeS_2 m^{-3} or 1500 mol FeS_2 m^{-3}. The depletion rate for the sulphide can be calculated stoichiomentrically and converted to a depth of depletion over time. Table 5-22 lists several oxygen consumption rates and the corresponding sulphide depletion rates.

Table 5-22. Examples of calculated sulphide depletion rates.

O_2 Consumption Rate ($mol\ O_2\ m^{-2}\ a^{-1}$)	FeS_2 Depletion Rate ($mol\ FeS_2\ m^{-2}\ a^{-1}$)*	($cm\ a^{-1}$)
10	2.7	0.2
100	26.7	1.8
1000	267	18

** – assumes complete oxidation of pyrite as described in equation 2-8*

An oxygen consumption rate of 100 mol O_2 m^{-2} a^{-1} would translate to a sulphide depletion rate of approximately 2cm a^{-1}. If the depth to highly saturated conditions was 1.0m oxidation may be expected to continue at this site for at least 50 years. This is a minimum length of time because as the sulphide material located near the surface is consumed, oxygen must diffuse through this zone to reach the sulphide minerals located further from the surface and oxygen consumption rates should decrease over time as suggested by the observations at the Kidd Creek site and the results of modelling studies (Elberling, et al., 1994; Scharer et al., 1994).

5.9.4 Estimating Buffer Depletion Rates

Tailings may contain other minerals, such as calcite and dolomite, that will dissolve and buffer the acid generated through sulphide oxidation. This ability of the tailings to neutralize generated acidity is often referred to as neutralization potential or (NP). Neutralization potential is a quantified by adding excess acid to a tailings sample dissolve the neutralizing solids and then back titrating to a specified pH with a base (NaOH). Different protocols have been used including boiling samples and titration to different pH end points. The pH after addition of acid is generally in the range of 1 to 3.5. The neutralization available in this range may not be representative of neutralization available at neutral pH. Many samples show good correlation between carbonate content and measured NP. More recently carbonate content (excluding siderite) has been used to assess usable NP (Lawerence, 1997). Acid potential (AP) is the $CaCO_3$ equivalent amount of acid produced from the oxidation of the sulphide content assuming the sulphide is pyrite and oxidizes according to equation 2-8. Historically, acid generation potential has been assessed by comparing AP and NP. If NP was greater than AP it was assumed that there was sufficient neutralization potential to buffer any acid produced by sulphide oxidation. If NP was less than AP it was implied that the tailings pore water would become acidic at some time. The assessment of NP and AP does not consider the rate of sulphide oxidation and can not address the issue of when the tailings may be depleted of neutralization potential and when the onset of acidic pore water conditions may occur.

Oxidation occurs from the surface downward and the tailings surface is usually the first to become acidic if there is insufficient NP to consume the acid produced over the long-term (eg. NP<AP). This shallow, acidic pore water can be of poor quality and can impact runoff from the tailings. The presence of initially neutral pH water in the shallow tailings pore water does not mean, however, that oxidation is not occurring. Indeed, measurements made during this study indicated that oxidation rates in neutral tailings can be similar to those measured in tailings that have already become acidic. Knowledge of the time until the onset of acidic conditions can be useful for planning tailings management strategies.

The equivalent $CaCO_3$ that is reported for the oxygen consumption rate can be used as a measure of the buffer depletion rate. This rate can than be used to assess the potential depletion time of calcite or dolomite in the near surface zone of the tailings.

A tailings with a NP value of 50 (kg $CaCO_3$ t^{-1}) and a bulk density of 1800 kg m^{-1} will have a $CaCO_3$ content of 90 kg $CaCO_3$ m^{-3}. Table 5-23 lists several oxygen consumption rates, and the NP depletion rate expressed as a mass of $CaCO_3$ per square meter per year and as vertical depletion in the tailings profile.

Table 5-23. Examples of calculated NP depletion rates.

O_2 Consumption Rate (mol O_2 m^{-2} a^{-1})	Equiv. $CaCO_3$ Consumption (Kg $CaCO_3$ m^{-2} a^{-1})		NP Depletion Rate (cm a^{-1})	
	Min[1]	Max[2]	Min[1]	Max[2]
10	0.3	0.5	0.3	0.6
100	2.8	5.4	3	6
1000	28	54	32	60

1 – no oxidation of Fe^{2+}
2 – including oxidation of Fe^{2+}

The range reported for equivalent $CaCO_3$ consumption reflects the oxidation of pyrite as described in equation 2-4 where the oxidation product Fe^{2+} is not oxidized and equation 2-8 in which Fe^{2+} is oxidized. As discussed in Chapter 2, the actual rate will be between these two values. If the top 0.25m is considered to be the zone of interest for buffer depletion and possible source of oxidation products to surface water, then the total amount of buffer in this zone will be 22.5 kg $CaCO_3$ per square metre. For an oxygen consumption rate of 100 mol O_2 m^{-2} a^{-1} the NP depletion rate would range from 2.8 to 5.4 kg $CaCO_3$ m^{-2} a^{-1} for oxidation of pyrite. At these rates, the buffer minerals in the upper 0.25-m of tailings could potentially be depleted in 4 to 8 years.

Although the buffer depletion rates are not precise because of uncertainties in the amount of H^+ produced in the oxidation, these values can provide a range of times for the possible onset of low pH conditions in the near surface of the tailings.

The oxygen consumption measurements do provide a means of estimating the time required for buffer depletion and the probable onset of acidic pore water conditions. These time estimations can have important implications because intrinsic oxidation rates can increase dramatically when the pH falls below 4.5 due to catalysis by bacteria such as *Thiobacillus ferrooxidans*. The primary role of the bacteria in the generation of acid mine drainage is thought to be the catalysis of aqueous ferrous iron oxidation to ferric iron. In an inter-laboratory study, Olson (1991) found that *T. ferrooxidans* enhanced the oxidation rate of pyrite tailings by a factor of 10 to 100 times under laboratory conditions. The enhancement of the acid generation rate due to iron-oxidizing bacteria was estimated to be between a factor of 5 and 20 times, based on field data (Morin *et al.*, 1990). If oxidation rates increase in the near-surface zone due to bacterial catalysis, buffer depletion rates throughout the tailings will also increase and the problem compounds itself. Such conditions may be avoided if the time until acidic near-surface conditions is understood and appropriate action to prevent such conditions is undertaken in a timely manner.

5.10 Sources of Error, Uncertainty and Natural Variation

The rate of oxygen consumption was calculated from the measured decrease in oxygen partial pressure (expressed as $V \cdot s^{-1}$), in the closed headspace above the tailings or cover material during an 1 hour test, typically. Potential sources of error can be categorized as being associated with, instrumentation, the operator, environmental factors, or the treatment of the data.

5.10.1 Errors Induced by Instrumentation

The data-loggers have finite limits to which voltage can be recorded. For extremely low rates this issue may become important. The Hydra data acquisition system has a resolution of 10μV in the manner used. The Lakewood system had a resolution of 30μV, as used. The minimum decrease in voltage measured for the oxygen consumption rate test was in the range of 1-2 milli-volt. For tests where low oxygen consumption rates were expected, the Hydra data-logger was used because of its greater resolution. The resolution of the voltage measurement was typically 1-3% of the measured decrease in voltage. This potential error may be considered small.

The electrochemical nature of the sensor's measurement dictates that the sensor will itself consume a small quantity of oxygen during the oxygen consumption rate test. Williams (1993) quantified the rate at which the sensor consumes oxygen at approximately $8.0X10^{-8}$ mol O_2 hr^{-1}. The mass of oxygen in the 0.02m headspace of a test would be 0.0203 mol O_2. During a one hour test approximately $4X10^{-5}$% of the oxygen in the headspace would be consumed by the sensor. Clearly, for short duration tests with a relatively large volume of air in the headspace, such as those conducted in this research, the error introduced by oxygen consumption by the sensor is negligible. For longer tests, lasting several days, such as those conducted by Anderson (1996) this potential error my become more important.

5.10.2 Potential Operational Errors

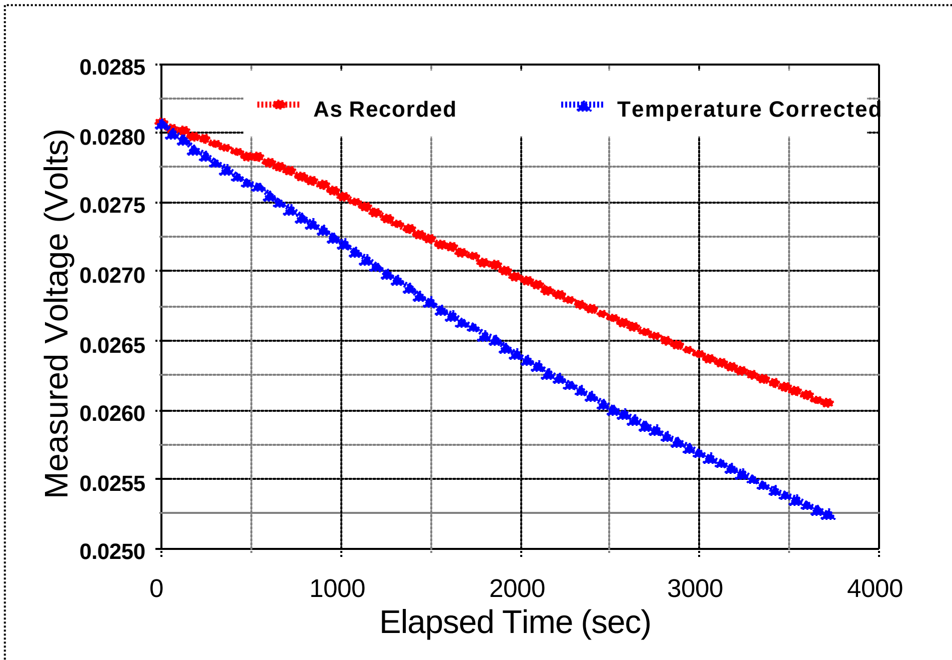
Care was taken to insure that a gas-tight seal was established between the removable cap and the installed aluminum tubing. This included cleaning the installed tubes and o-ring assembly prior to the test and application of vacuum grease around the seal.

The headspace was measured by placing a straight edge across the top of the aluminum tube and the depth to the surface of the tailings or cover measured at several points using a ruler with divisions in millimeters. The average of the measurements was calculated and used for the value of $^A/_V$ in the determination of oxygen consumption rate. Typically 15–25 individual measurements were taken. The error associated with an individual reading would be $\pm$ 0.5 mm (one-half of the smallest division of the scale). The headspace for oxygen consumption rate tests were typically 1-2cm. The maximum error associated with headspace measurement was, therefor in the range of 5%.

5.10.3 Environmentally Induced Errors

Field measurements are often subject to harsher environmental conditions than measurements conducted in the laboratory. For the oxygen consumption rate test conducted for this research, the greatest potential source of error is likely associated with fluctuation in the ambient air temperature during the test. The magnitude of this error is proportional to the change in temperature. For a $1^{o}C$ change in temperature an induced error of approximately 0.5mV will occur. An decrease in temperature during the test will cause a higher voltage reading and result in a shallower slope of voltage versus time and lead to the calculation of a false low oxygen consumption rate. A temperature correction factor was derived (Appendix A) to correct potential errors induced by temperature fluctuations. Figure 5-9 is a plot of recorded voltage versus time data from an oxygen consumption rate test and the same data after the temperature correction factor was applied.

Figure 5-9 Example oxygen consumption rate test data showing temperature corrected data.



During this test, the temperature decreased by approximately 2^{o}C. Attempts were made to insulate the cap assembly from temperature changes but temperature fluctuations on the order of 1-2^{o}C were recorded during some tests. If the data were not corrected for temperature effects an error of approximately 3 mol O_2 m^{-2} a^{-1} per degree C^{o} could potentially occur. For sites where the oxygen consumption rate is small (ie less than 10 mol O_2 m^{-2} a^{-1}), this would represent a major source of error.

5.10.4 Errors Associated with Post Measurement Data Treatment

The collected voltage versus time data is corrected for error induced by temperature fluctuations. The natural logarithm of the normalized corrected voltage values was calculated and a first order linear regression was performed.

The R^2 value of individual tests varied greatly but were usually 0.80 or higher. Poorer R^2 values were calculated for data collected early in the study, prior to increased efforts to insulate the test from fluctuations in the ambient temperature during the test and on tests where extremely low oxygen consumption rates were being measured. The R^2 value is a measure of the goodness of fit of the data to the linear regression. Improved control over temperature fluctuations resulted in smoother data and larger R^2 values. The error associated with this issue was not quantified but, on average, this error is likely to be small and better fit of the data to the regression does translate to greater confidence in the accuracy of the calculated oxygen consumption rate.

5.10.5 Reproducibility of the Measurement

Repeated testing at one location to assess the reproducibility of the measurements for identical conditions was not conducted in the field. The test disrupts the oxygen versus depth profile within the tube. The time required for re-establishment of steady-state would be, at minimum, equal to the length of the test. Changes in ground temperature and moisture profiles in the tailings preclude true replicate testing in the field. However, laboratory studies have reported good reproducibility for the Oxygen Consumption Method (Elberling, et al., 1994 and Häussermann, Pers. Comm., 1997).

Häussermann (1997) conducted research investigating the effect of the degree of water saturation on oxygen consumption rates in a laboratory column study. In this study the water table was set and the oxygen consumption rate was measured twice daily over a two week period. Once steady-state was established the repeated measurements may be considered replicates. Table 5-24 lists the mean, minimum, and maximum oxygen consumption rate as well as the number of measurements, the standard deviation for each of three experimental runs on one of the columns.

Table 5-24. Reproducibility of the Oxygen Consumption Method in a controlled laboratory study. Data from Häussermann (1997)

	Number of	Oxygen Consumption Rate mol (O_2 m^{-2} a-1)				
%sat	Measurements	mean	min	max	std. Dev.	% of mean
59	14	563	529	638	29	5
83	24	637	519	795	87	14
92	21	101	78	134	15	14

The standard deviation for the repeated measurements was in the range of 5-15% for experiments at moderate to high degrees of saturation. This degree of relative error is not large compared to the 100-800 mol O_2 m^{-2} a^{-1} range of oxygen consumption rates measured in the laboratory study.

In the field, tests on multiple stations located within a 10m radius of one another yielded relative errors approximately twice those of the laboratory study (Table 5-25). The number of measurements in the data set was considerable smaller. The relative error was 20-30% for the two measurement rounds.

Table 5-25. Reproducibility of the Oxygen Consumption Method over a small area in the field. (Data from Kidd Creek site)

	Number of	Oxygen Consumption Rate mol (O_2 m^{-2} a^{-1})				
Date	Measurements	mean	min	max	std. dev.	% of mean
May, 96	4	69	57	86	7	19
Jun, 96	4	98	63	124	14	30

5.10.6 Variability and Scale of Measurement

Results from one site can be used to assess the variability in the measurement at different aerial scales. Table 5-26 lists the mean, minimum, and maximum oxygen consumption rates as well as the number of measurements, the standard deviation for sets of data measured in June 1996 at the Kidd Creek site. Statistical information is listed for stations located as close as 10m up to the site size scale for an area of approximately 600ha.

Table 5-26. Variability in oxygen consumption rates at different scales. (Data from Kidd Creek site – June 1997)

	Number of	Oxygen Consumption Rates mol (O_2 m^{-2} a^{-1})				
Scale	Measurements	mean	min	max	std. dev.	% of mean
10m	4	98	63	124	29	30
100m	4	261	151	551	194	74
1000m	8	227	121	325	62	27
600ha	16	224	3	631	168	75

A large range of rates can be encountered over a relatively small scale as shown in the standard deviation calculated for the measurements on the 100m scale. Statistical treatment of these data sets using a two sample F-test to examine the variance between scales was also calculated. A statistical summary is listed in Appendix B. The F-test results show that there are statistically significant differences (at the 5% level or better) between almost all scales of measurement (Table 5-26). This analysis suggests that the variance differs significantly among the data sets and is not due solely to random variations. There was no significant difference between the measurements on the 100m versus the 600ha scale.

More simply stated this means that the variation expected over the site (1000m or more) may differ significantly from that within a relatively small area (10m).

The statistical analysis was conducted for the Kidd Creek site because a large database was available with repeated measurements at individual stations. However, it has been noted that the Kidd Creek site represents a relatively homogenous tailings impoundment and appears to exhibit a smaller range of rates than has been observed at other tailings facilities. Even with the relatively homogenous conditions, however, significance in variations were observed at different scales of measurement.

Reproducibility is important for any measurement. Values of standard deviations on the order of 15% may seem high compared to those for chemical analysis, for example, but in the context of rates that varied over four orders-of-magnitude in this study (0.1-5000 mol O_2 m^{-2} a^{-1}), these variations are small. Variations in rates is not surprising considering the natural variation of many properties, such as moisture content in the field. David and Nicholson (1995) observed changes in the moisture content in the top one meter of a tailings that resulted in greater than two orders-of-magnitude change in calculated diffusion coefficients. Such large variations in the diffusive characteristics of the tailings over such a small area would have significant effects on the measurable oxygen consumption rate in the field.

6. Summary of Conclusions

Oxygen consumption rates were measured over a range of five orders-of-magnitude among the six field sites investigated for this investigation. Significant variation in oxygen consumption rates was observed on exposed tailings. The variability was attributed to natural variations in the tailings moisture content across the site and on fine-scale layering at the local scale.

A strong trend of increasing oxygen consumption rate with increasing sulphide content was observed. This trend was attributed to an increase in potential oxidation sites with increasing sulphide content and also to the diminished diffusion control associated with shallower zones of oxidation in higher sulphide content tailings.

A trend of lower oxygen consumption rates was associated with development of a highly cemented layers (hardpan) on the high sulphur content tailings at one location. The formation of the hardpan layer resulted in a 6 fold decrease in oxygen consumption rates at one location. Reductions of this magnitude are not expected over the site as a whole due to the development of hardpan expansion cracks (pop-ups) that would result in preferential diffusion pathways.

A trend of decreasing oxygen consumption rate with age of tailings exposure was suggested by measurements on tailings exposed 3-4, 5-6, and approximately 10 years. This trend was attributed to the depletion of the sulphide inventory in the near-surface of the tailings over time. The zone of oxidation migrates deeper and material depleted of sulphides acts as a diffusion barrier. Lower diffusion coefficients are also expected with increasing depth due to Increased moisture contents. This also acts to lower the oxygen consumption rate. Measurements of oxygen consumption rates on freshly deposited, unconsolidated material at the same site demonstrated that despite the saturated conditions oxidation was occurring at non-trivial rates.

A trend of lower oxygen consumption rates with increasing tailings moisture content was observed. Oxygen consumption rates measured near to ponded water bodies or in other areas where the tailings were highly saturated were lower than at locations where the vadose zone was developed to a greater extent. This trend was also attributed to the strong influence that water content has on the effective diffusion coefficient in the tailings. At higher water contents the value of the effective gas diffusion coefficient (D_e) is much lower and oxidation rates are limited. Despite the extremely limited depth that the zone of oxidation would occur within tailings of high moisture contents, non-trivial oxidation rates were measured within meters of ponded water and on highly saturated tailings. One of the implications of this behaviour is that raising the water table may not result in significant lowering of oxidation rates immediately.

A trend of lower oxygen consumption rates with the cooler, wetter climatic conditions associated with spring and autumn was observed. Oxygen consumption rates were as much as a factor of four lower in early May compared to rates measured in June and in September. The observed lower rates were likely caused by lower kinetic rates associated with lower temperature and decreased diffusion in the tailings caused by increased moisture. Despite temperatures as low as 4^{o}C oxidation occurred at measurable and environmentally significant rates. Many workers have considered oxidation rates to be insignificant during winter months, these rates indicate that further research on cold temperature oxidation rates are required before cold weather contributions to the yearly oxidation products can be so easily dismissed.

Oxygen consumption rate measurements were conducted on sites were full-scale covers had been implemented and on several test plots of covers of a variety of design configurations. It was observed that the addition of a cover resulted in a reduction in the oxygen consumption rate. This reduction factor ranged from 2 to 100 times compared to uncovered locations on the same tailings materials. Simpler, single-layer covers provided a reduction of at best an order-of-magnitude while multi-layered covers yielded a range of reduction factors, reflecting degrees of design success, that were as high as two orders-of-magnitude. Some of the engineered covers suffered from drying out and this adversely affected the diffusion barrier efficiency. More care must be taken in design of multi-layer covers to maintain the desired high saturation levels in the diffusion barrier (fines) layer.

A first order assessment of potential cover material was conducted by placing the material in the above ground portion in the aluminum tubes used in the Oxygen Consumption Method. At this scale the tests were essentially *in situ* column tests exposed to site environmental conditions. This configuration allowed for rapid testing of various thickness of different cover material on several tailings impoundments of differing sulphide content. These simple covers were effective at reducing oxygen consumption rates by as much as a factor of 20 for the very high sulphide material.

Calculations using the results from the oxygen consumption rate measurements can provide approximations on the potential flux of oxidation products to the pore water and maximum potential loadings to receiving water bodies. These values can be used to assess potential impacts on receiving waters.

Rates of sulphide depletion and tailings neutralization potential depletion can also be calculated based on the oxygen consumption rate. These calculations are insightful to understand the potential time-span over which the site may generate AMD and how long before acidic near-surface pore water conditions occur in tailings with a Neutralization Potential values that are lower than Acid Potential values.

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Appendix A

DERIVATION OF
TEMPERATURE CORRECTION FACTOR

Derivation of Temperature Correction Coefficient

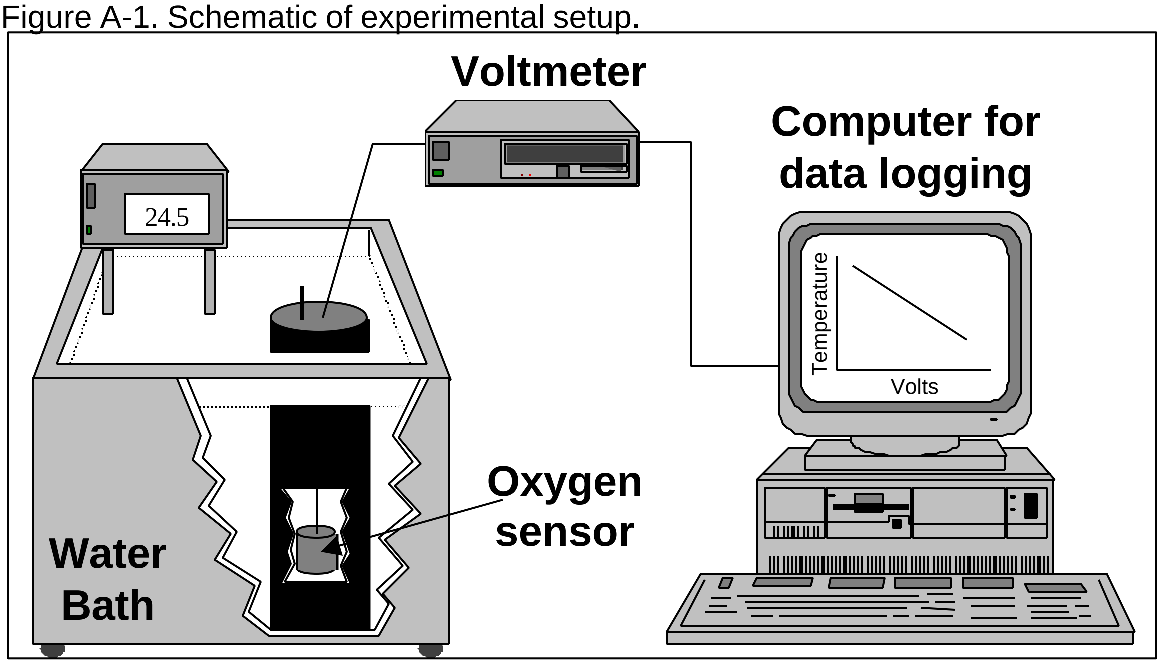
The sensitivity of the oxygen sensor to relative changes in the ambient temperature was noted early in the development of the Oxygen Consumption Method (Williams, 1993). Initial efforts to minimize errors in the oxygen consumption rate measurements due to temperature fluctuations focused on providing protection to the cap assembly from direct sunlight and insulation to aid in maintaining a constant temperature. These efforts did provide significant relief from induced errors where the oxygen consumption rate was moderate to high (most exposed tailings).

When the Oxygen Consumption Method was applied to the evaluation of oxygen consumption rates as measured through covers the issue of errors due to thermal fluctuation became an important issue. Improvements were made to the insulation method within the cap and also in the material used to cover the cap assembly while it was on the tube and the test was running. In addition to these modifications experiments were conducted in the laboratory to derive a temperature correction factor.

Experimental method

The sensor was placed in a 250 ml stainless steel container that was sealed and placed in a temperature controlled water bath (Figure A-1). The temperature of the water bath was then altered at a slow rate and the temperature and output voltage from the sensor was recorded.

Figure A-1. Schematic of experimental setup.

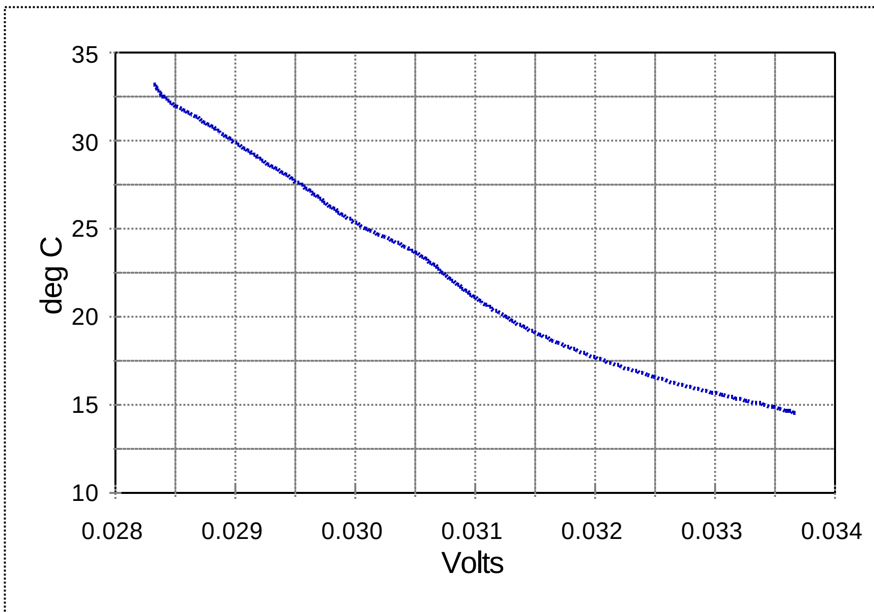


The reading generated by the sensor is also sensitive to pressure fluctuations. The sensor measures concentration of oxygen in the gas phase. It follows that an increase in the partial pressure of oxygen would result in an increase in the value in volts registered by the sensor. To prevent changes in pressure within the stainless steel testing chamber a small diameter section of tubing was attached with one end open to the atmosphere, the other end open to the interior of the test chamber. To minimize convective transport between the interior of the test chamber and the room, the tube was filled with fiber glass batting. With the outlined steps it is assumed that the water bath was able to create and maintain temperatures within the test chamber with a of precision of +/- 0.05 ^{o}C.

Results

The sensor's output in volts was inversely proportional to the change in temperature. An increase in temperature resulted in a decrease in the output voltage from the sensor and conversely a decrease in temperature resulted in an increase in the output voltage. Figure A-2 provides a plot of temperature in ^{o}C versus output voltage from the sensor.

Figure A-2. Example plot of sensor output versus temperature



Three experiments were conducted using this setup. The temperature range for each experiment along with the resulting Δ Volt / ΔT is listed in Table A-1.

Table A-1. Results from temperature effects experiments.

Temperature Range	Δ Volt / ΔT
14-27	-3.163E-04
34-22	-3.042E-04
8-14	-3.864E-04
Average	**-3.356E-04**

The Δ Volt / ΔT for each experiment was determined using a first order linear regression. The R^2 value for the regressions ranged from 0.974 to 0.995. From the linearity of the Δ Volt / ΔT data it was concluded that the relationship between sensor output was inversely proportional to the change in temperature. The average temperature correction coefficient for the three experiments was -3.356E-04.

Williams (1993) measured the sensor output for two sensors at 4, 18, and 33^{o}C. One sensor was relatively new, the second sensor had been in operation for several months. Williams concluded that the sensor output was linear with respect to temperature changes. Corrections factors calculated from Williams (1993) data were -3.50E-04 and -1.87E-04. These values are similar to those calculated by the author. The sensor that yielded a slope of -1.87E-04 was one that had been in operation for many months and was nearing the end of its useful life span.

From this investigation it was concluded that:

- The sensor is notably effected by temperature
- The relationship between temperature change and output voltage is linear and inversely proportional
- The correction factor used in this study is the average values as calculated from the three water bath experiments.

The formula for correcting imprecision in the collected voltage data resulting from changes in ambient temperature during the oxygen consumption rate test is;

$$(\text{Volts})_{\text{corrected}} = (\text{Volts})_{\text{measured}} - (\Delta T * -3.356E\text{-}04) \qquad \text{(A-1)}$$

Appendix B

STATISTICAL TREATMENT OF SELECTED DATA

Statistics on rate variation with season.
Kidd Creek Transect #1 A, B, E, F, I, J, P, and Q test stations

Sept96 vs May97 (95%)
t-Test: Paired Two-Sample for Means

	Variable 1	*Variable 2*
Mean	187.500	36.75
Variance	9650.857	970.5
Observations	8.000	8
Pearson Correlation	0.864	
Pooled Variance	5310.679	
Hypothesized Mean Difference	0.000	
df	7.000	
t	5.839	
P(T<=t) one-tail	0.000	
t Critical one-tail	1.895	
P(T<=t) two-tail	0.001	
t Critical two-tail	2.365	

June97 vs May97 (95%)
t-Test: Paired Two-Sample for Means

	Variable 1	*Variable 2*
Mean	226.875	36.75
Variance	3808.982	970.5
Observations	8.000	8
Pearson Correlation	-0.578	
Pooled Variance	2389.741	
Hypothesized Mean Difference	0.000	
df	7.000	
t	6.426	
P(T<=t) one-tail	0.000	
t Critical one-tail	1.895	
P(T<=t) two-tail	0.000	
t Critical two-tail	2.365	

Sept96 vs June97 (95%)
t-Test: Paired Two-Sample for Means

	Variable 1	*Variable 2*
Mean	187.5	226.875
Variance	9650.85714	3808.98214
Observations	8	8
Pearson Correlation	-0.4808913	
Pooled Variance	6729.91964	
Hypothesized Mean Difference	0	
df	7	
t	-0.8018383	
P(T<=t) one-tail	0.22450299	
t Critical one-tail	1.8945786	
P(T<=t) two-tail	0.44900597	
t Critical two-tail	2.36462425	

Statistical testing of rates on 3-4year exposed vs 5-6year exposed
t-Test: Two-Sample Assuming Unequal Variances at 95% level

	Variable 1	*Variable 2*
Mean	273.4214	182.0138
Variance	171231.897	17127.4952
Observations	24	28
Pearson Correlation	NA	
Pooled Variance	88015.52	
df	27	
t	1.03856392	
P(T<=t) one-tail	0.15410972	
t Critical one-tail	1.70328844	
P(T<=t) two-tail	0.3082	
t Critical two-tail	2.0518	

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	224.201924	81.1494782
Variance	88406.9154	3917.51718
Observations	52	4
Pearson Correlation	NA	
Pooled Variance	83713.0599	
df	19	
t	2.76355054	
P(T<=t) one-tail	0.00618302	
t Critical one-tail	1.72913281	
P(T<=t) two-tail	0.01236603	
t Critical two-tail	2.09302405	

Statistical treatment of the question of variance and scale using F-Test Two-Sample for Variances

sept

Transect vs full site

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	206.21	187.50
Variance	12626.18	9650.86
Observations	14.00	8.00
df	13.00	7.00
F	1.31	
P(F<=f) one-tail	0.38	
F Critical one-tail	3.55	

10m vs Transect

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	102.40	187.50
Variance	3167.65	9650.86
Observations	3.00	8.00
df	2.00	7.00
F	3.05	
P(F<=f) one-tail	0.11	
F Critical one-tail	3.26	

100m vs Transect

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	346.00	187.50
Variance	37538.00	9650.86
Observati	2.00	8.00
df	1.00	7.00
F	3.89	
P(F<=f) o	0.09	
F Critical	5.59	

May

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	44.19	36.75
Variance	1132.83	970.50
Observations	16.00	8.00
df	15.00	7.00
F	1.17	
P(F<=f) one-tail	0.44	
F Critical one-tail	3.51	

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	68.50	36.75
Variance	172.33	970.50
Observations	4.00	8.00
df	3.00	7.00
F	5.63	
P(F<=f) one-tail	0.03	
F Critical one-tail	3.07	

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	83.50	36.75
Variance	1104.50	970.50
Observati	2.00	8.00
df	1.00	7.00
F	1.14	
P(F<=f) o	0.32	
F Critical	5.59	

June

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	223.88	226.88
Variance	28327.45	3808.98
Observations	16.00	8.00
df	15.00	7.00
F	7.44	
P(F<=f) one-tail	0.01	
F Critical one-tail	3.51	

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	97.75	226.88
Variance	836.92	3808.98
Observations	4.00	8.00
df	3.00	7.00
F	4.55	
P(F<=f) one-tail	0.05	
F Critical one-tail	3.07	

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	260.50	226.88
Variance	37593.00	3808.98
Observati	4.00	8.00
df	3.00	7.00
F	9.87	
P(F<=f) o	0.01	
F Critical	4.35	

sept

100m vs 10m

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	346	102.396525
Variance	37538	3167.6537
Observations	2	3
df	1	2
F	11.850411568	
P(F<=f) one-tail	0.0750135358	
F Critical one-tail	18.512820508	

100m vs Site

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	346	206.214286
Variance	37538	12626.1813
Observations	2	14
df	1	13
F	2.97302874	
P(F<=f) one-tail	0.10392593	
F Critical one-tail	4.66719273	

10m vs site

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	102.396525	206.214286
Variance	3167.6537	12626.1813
Observati	3	14
df	2	13
F	3.98597275	
P(F<=f) o	0.03938525	
F Critical	2.76316736	

May

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	83.5	68.5
Variance	1104.5	172.333333
Observations	2	4
df	1	3
F	6.4090909091	
P(F<=f) one-tail	0.0853030824	
F Critical one-tail	10.127964484	

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	83.5	44.1875
Variance	1104.5	1132.82917
Observations	2	16
df	1	15
F	1.02564886	
P(F<=f) one-tail	0.32625387	
F Critical one-tail	3.07318555	

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	68.5	44.1875
Variance	172.333333	1132.82917
Observati	4	16
df	3	15
F	6.57347679	
P(F<=f) o	0.00419404	
F Critical	2.48978774	

June

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	260.5	97.75
Variance	37593	836.916667
Observations	4	4
df	3	3
F	44.918450662	
P(F<=f) one-tail	0.0054201352	
F Critical one-tail	9.2766281532	

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	260.5	223.875
Variance	37593	28327.45
Observations	4	16
df	3	15
F	1.32708733	
P(F<=f) one-tail	0.30040654	
F Critical one-tail	3.2873821	

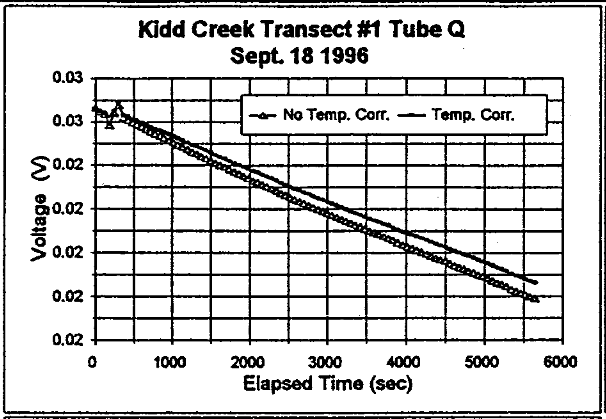
F-Test Two-Sample for Variances

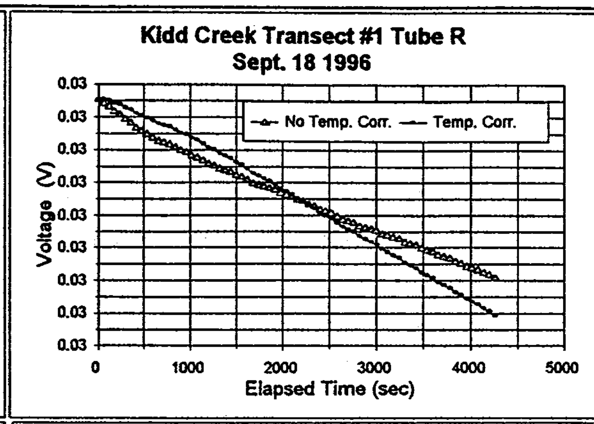
	Variable 1	*Variable 2*
Mean	97.75	223.875
Variance	836.916667	28327.45
Observati	4	16
df	3	15
F	33.8473962	
P(F<=f) o	3.6893E-07	
F Critical	2.48978774	

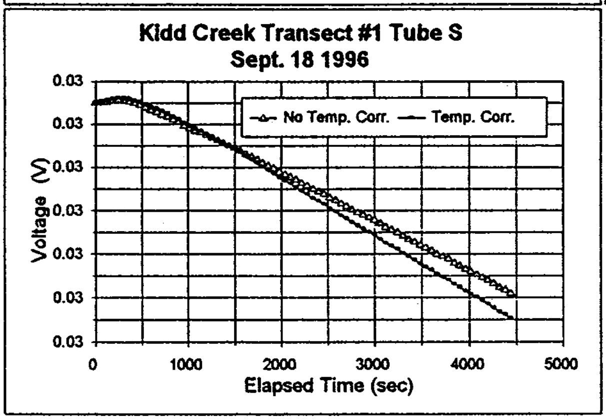
Appendix C

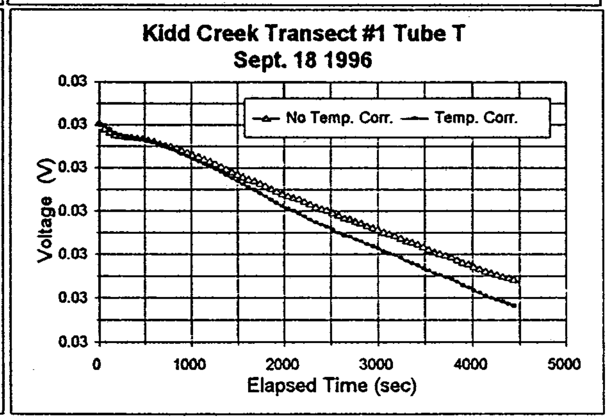
DATA COLLECTED FOR OXYGEN CONSUMPTION RATE TESTS

Kidd Creek. Transect #1 September 1996

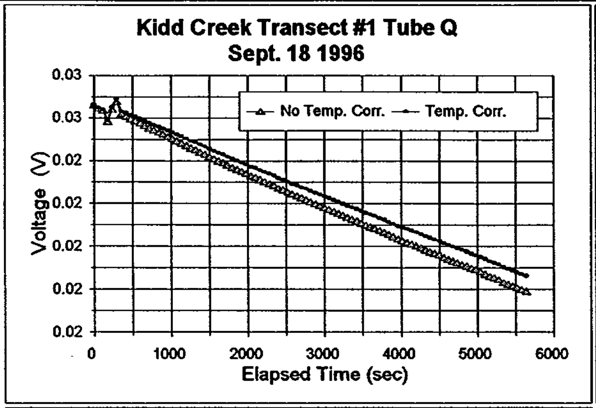


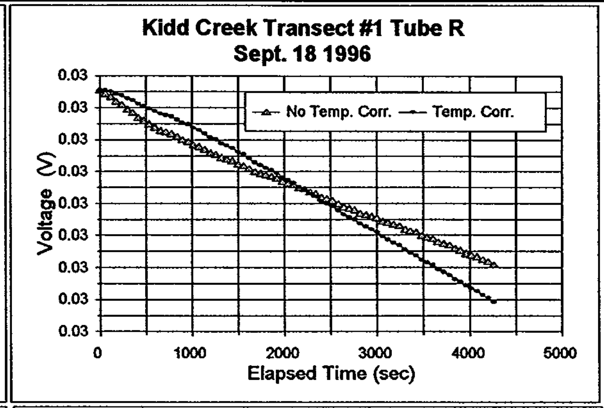


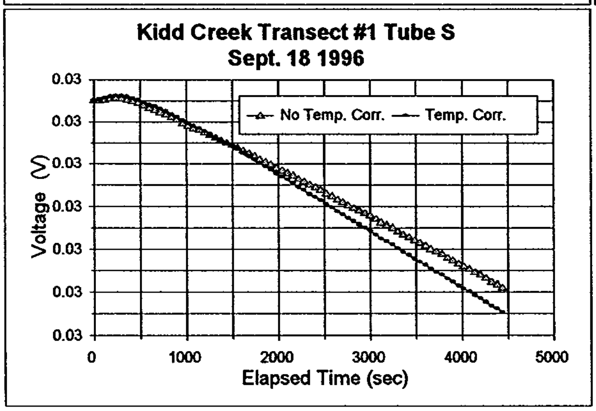


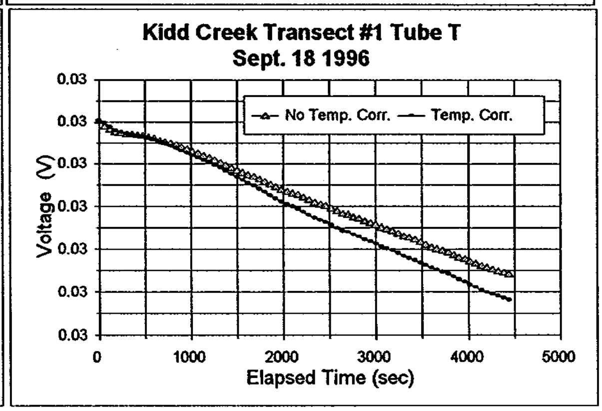


Kidd Creek. Transect #1 September 1996

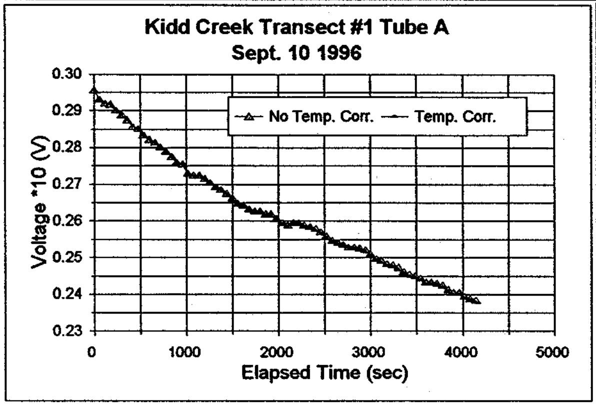


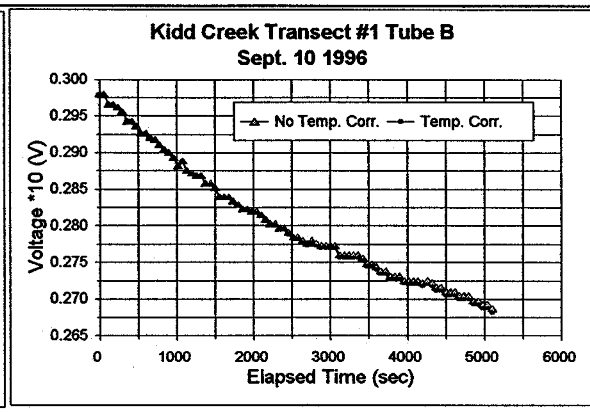


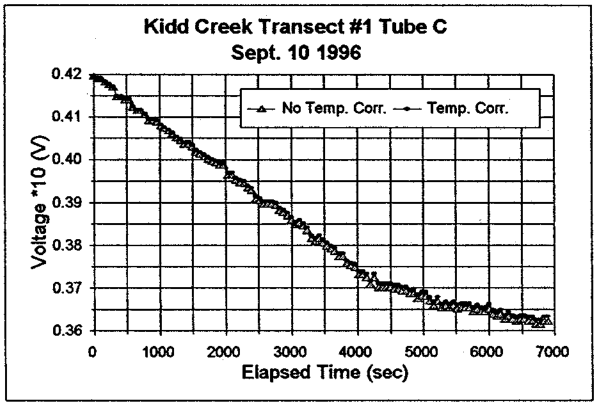


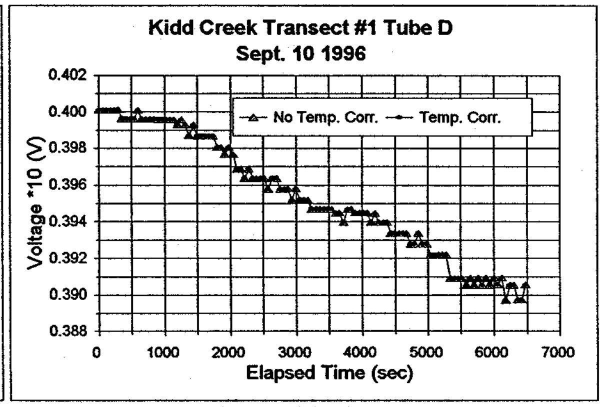


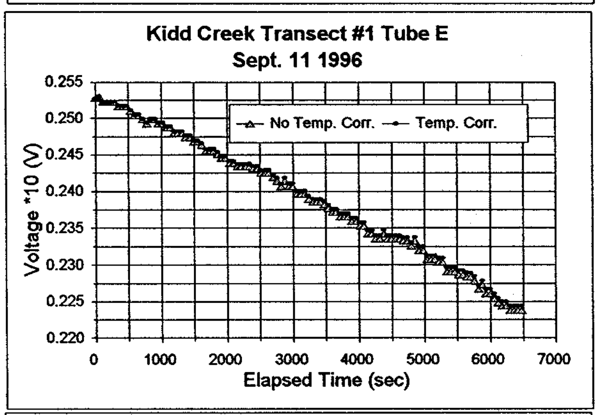
Kidd Creek. Transect #1 September 1996

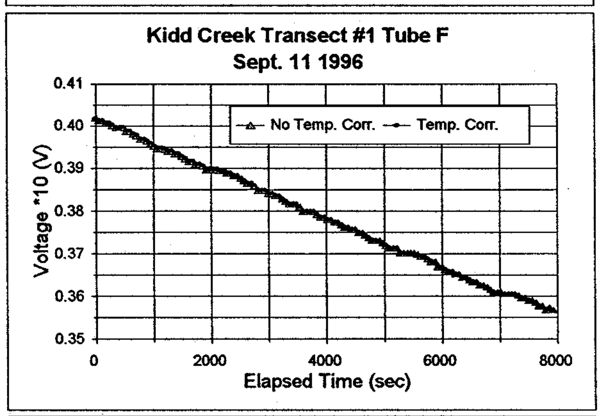


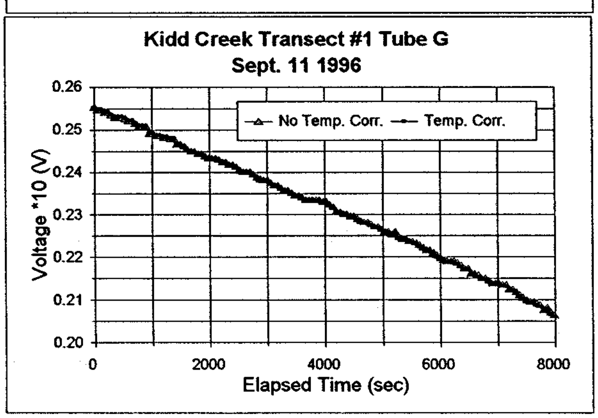


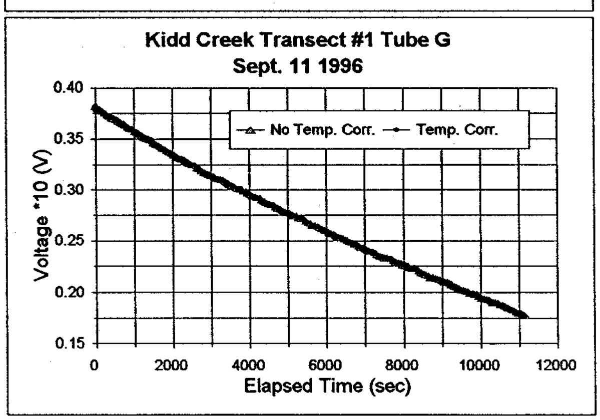




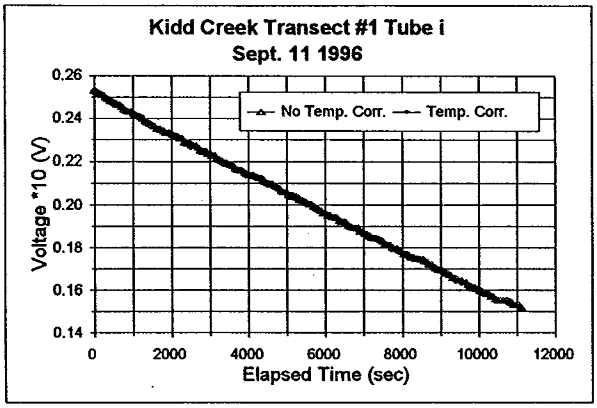


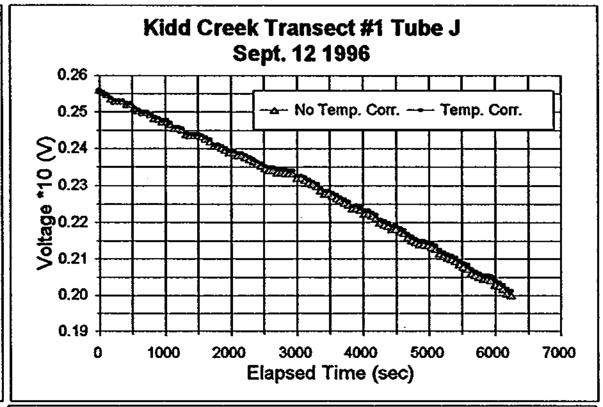


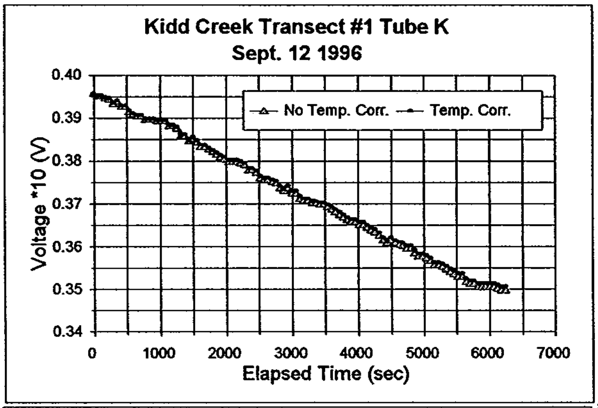


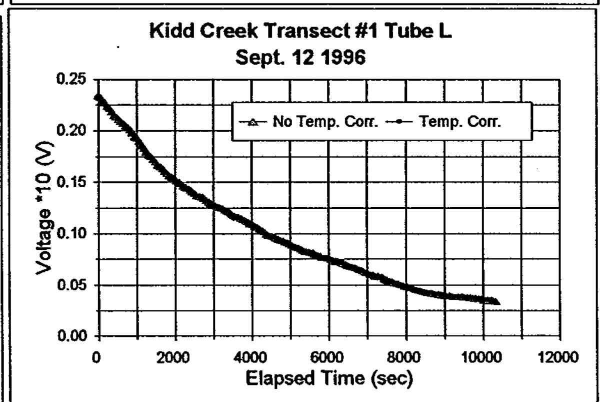


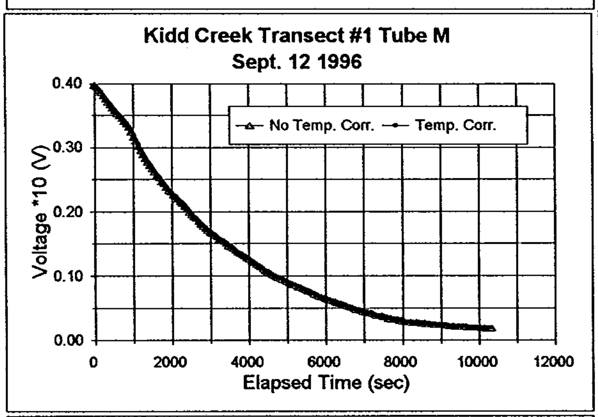
Kidd Creek. Transect #1 September 1996

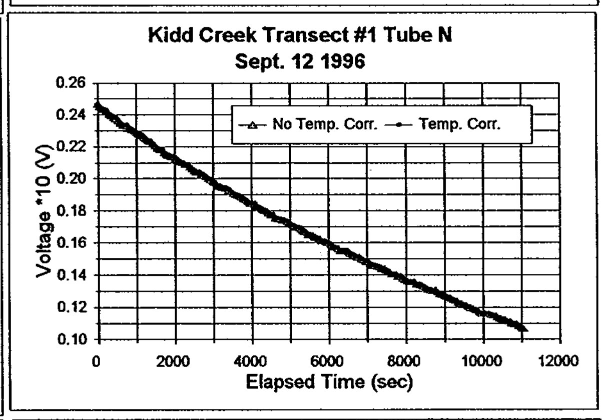


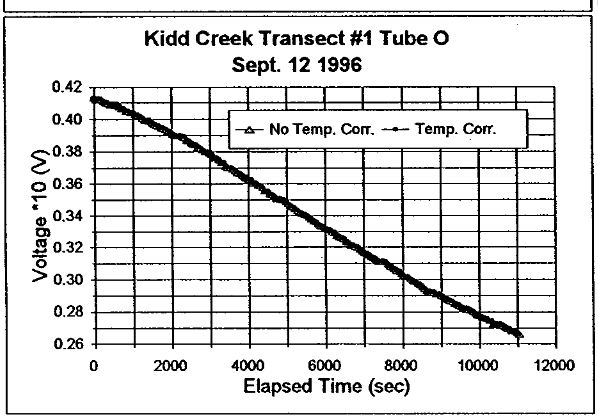


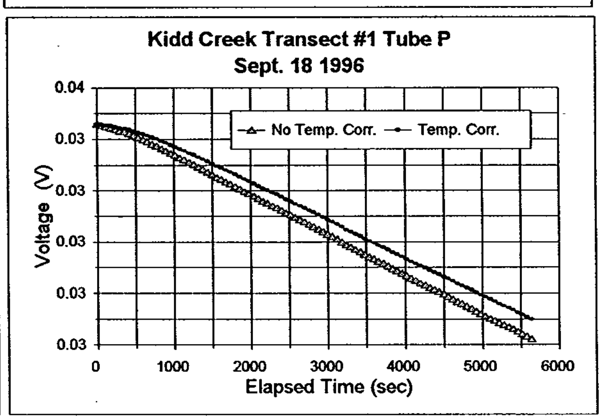












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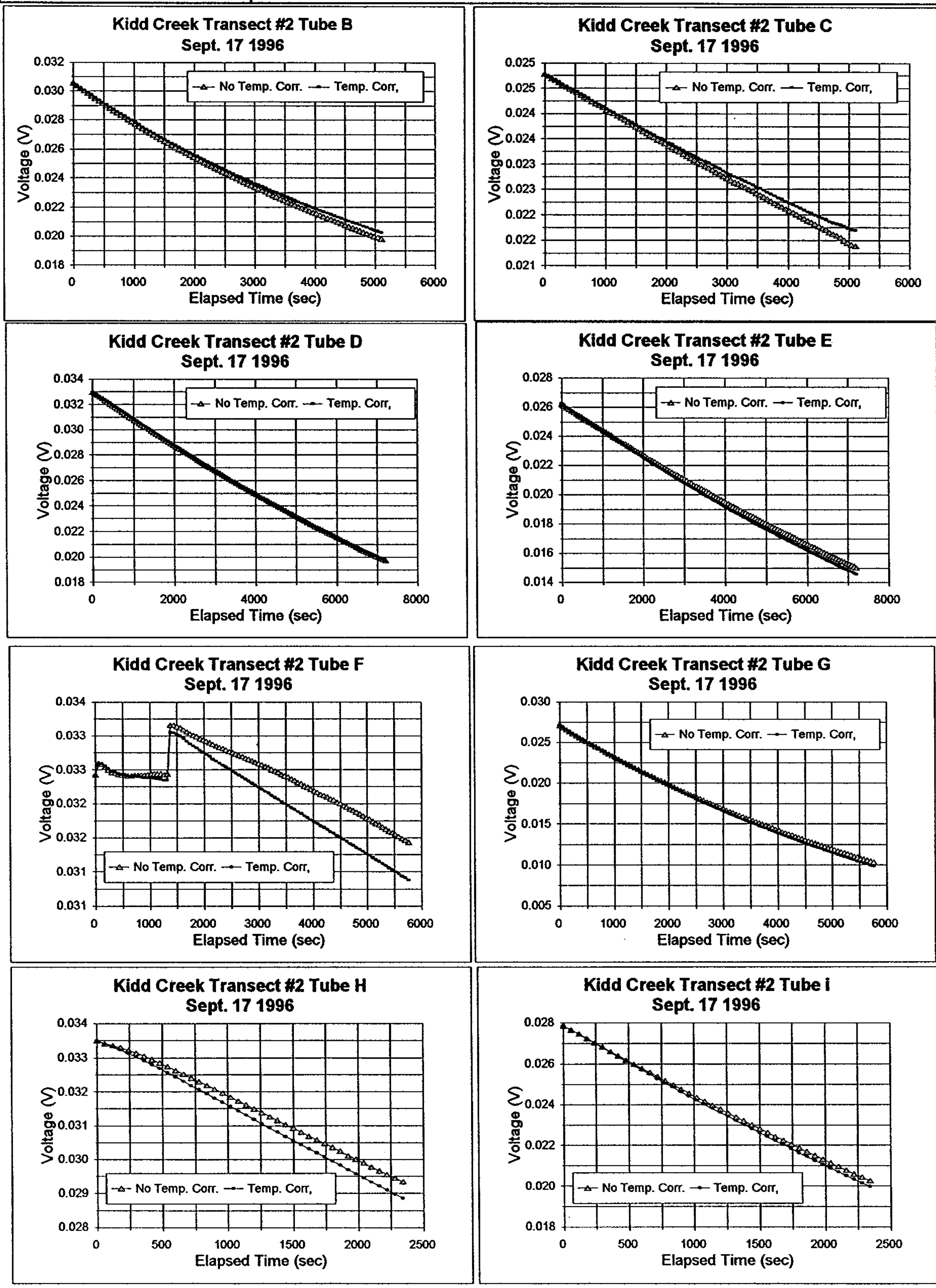
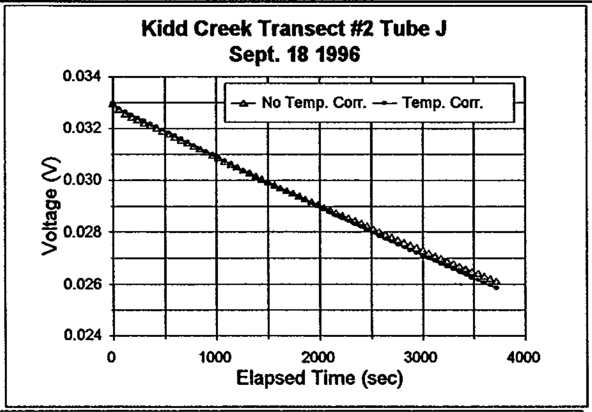
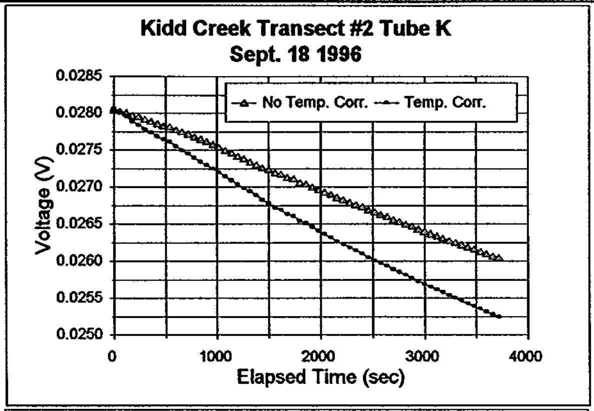
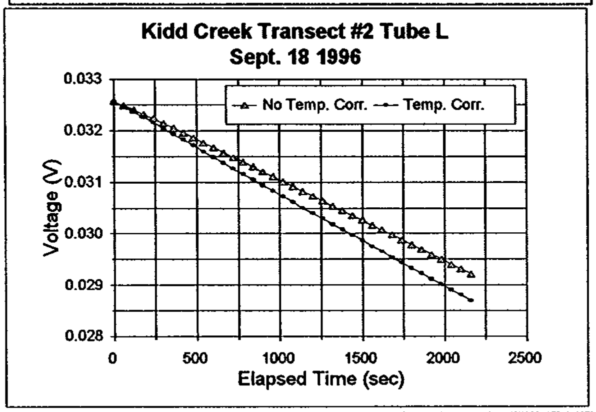
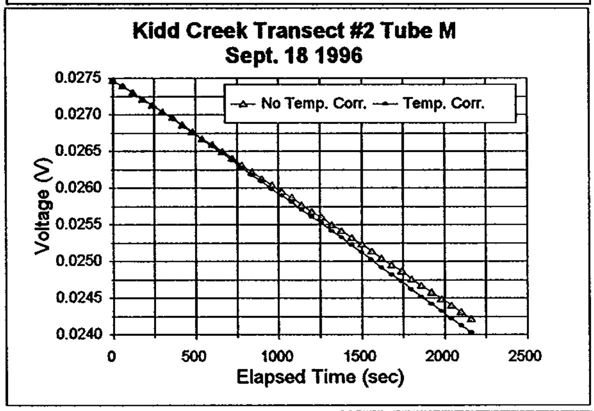


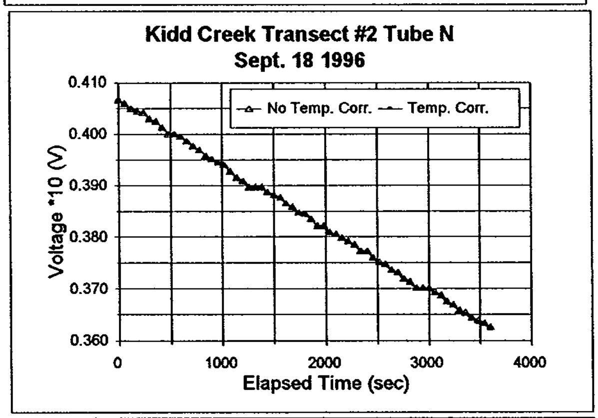
Kidd Creek. Transect #2 September 1996

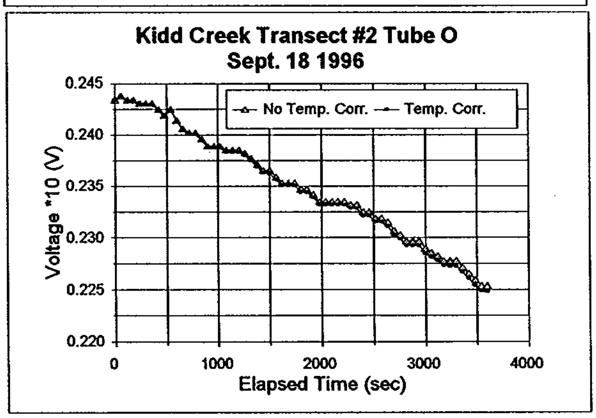


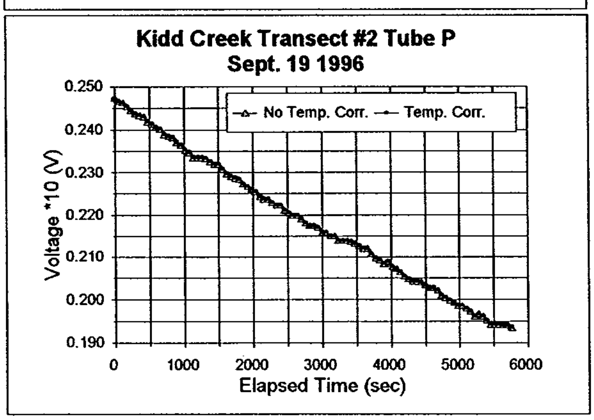


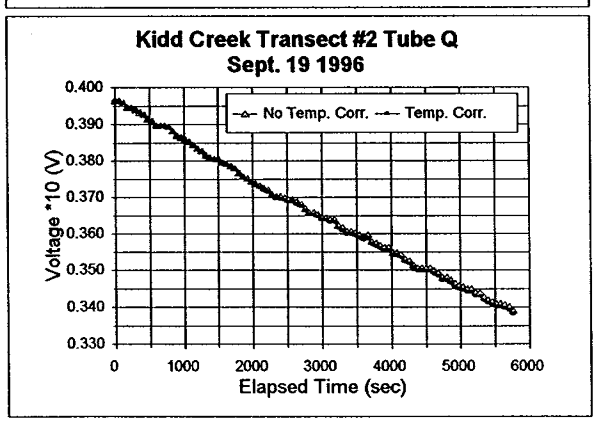




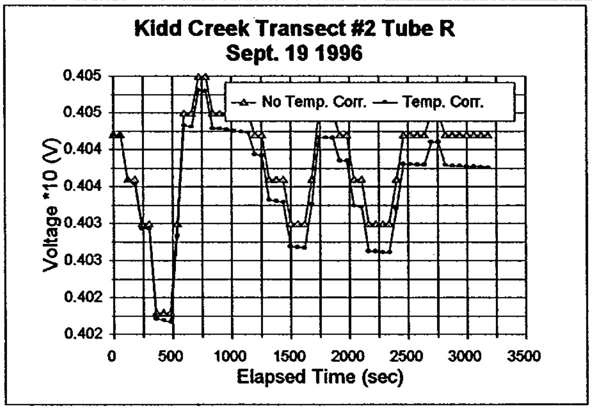


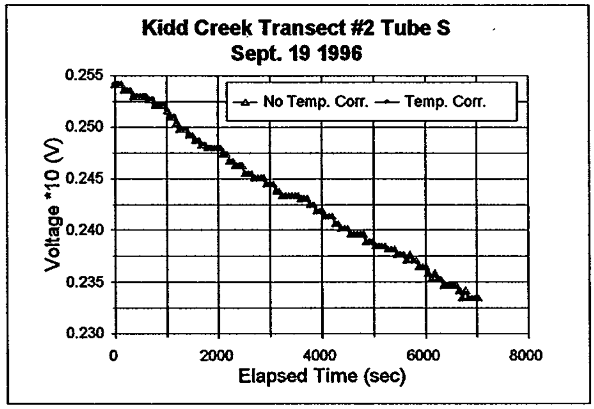


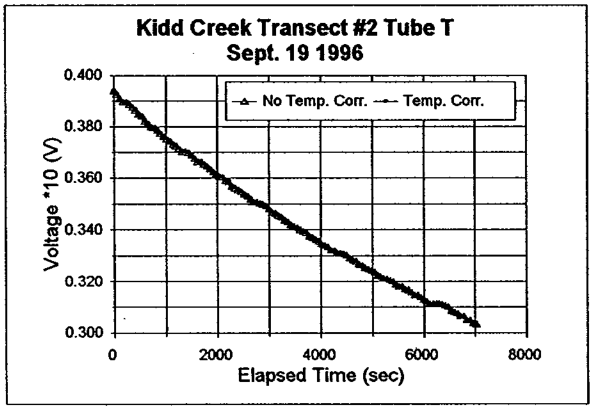


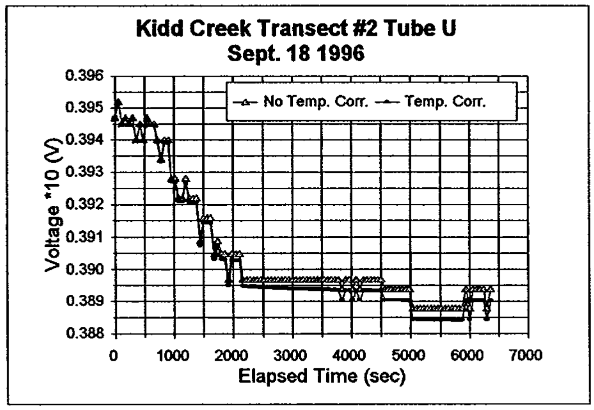


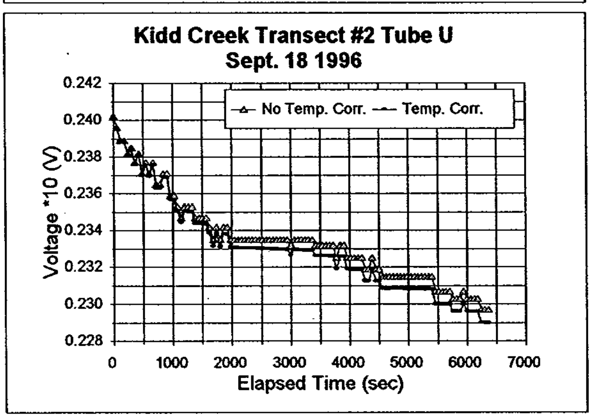
Kidd Creek. Transect #2 September 1996





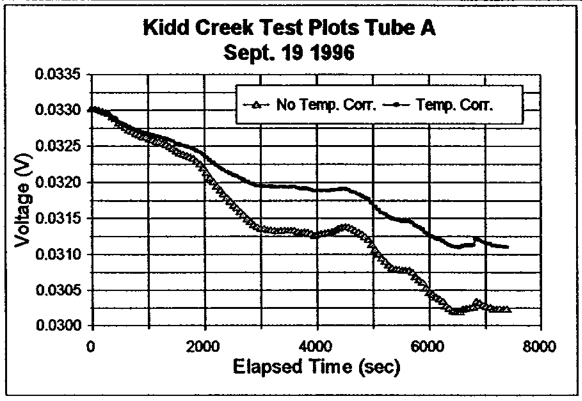


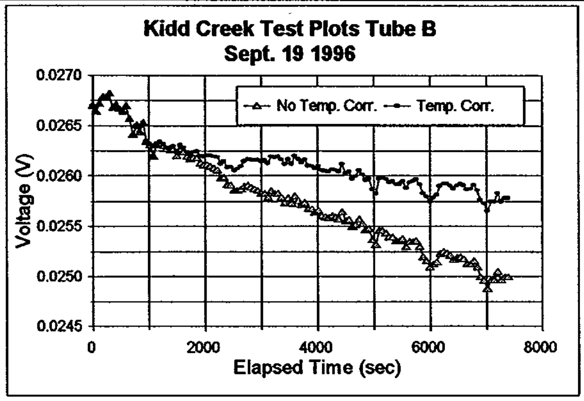




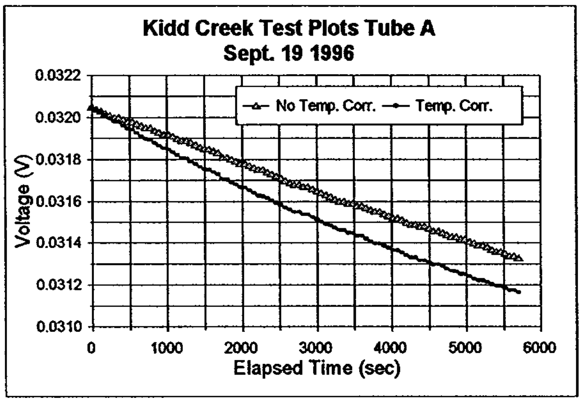
Kidd Creek Testplots Sept 1996

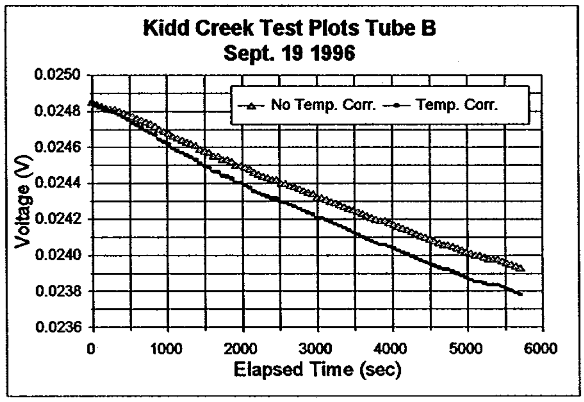
Kidd Creek. Test Plots. Clay-Till Plot September 1996



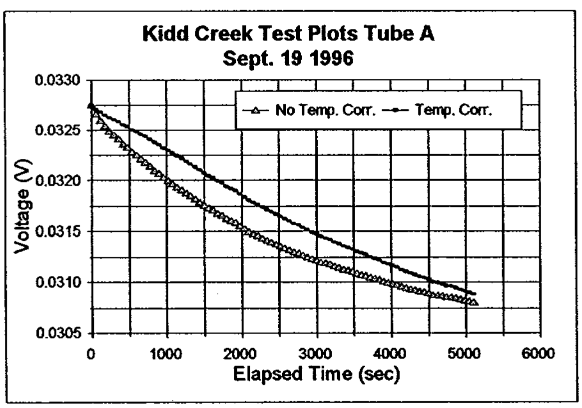


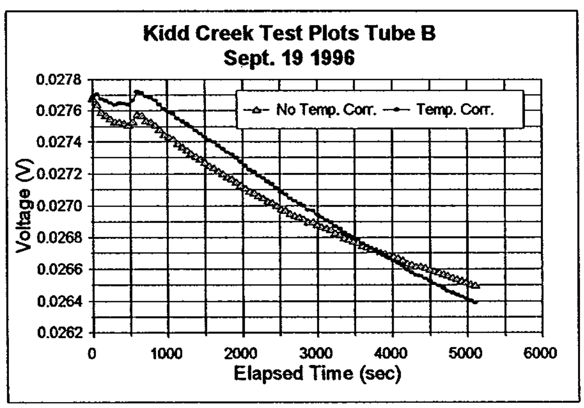
Kidd Creek. Test Plots. Low-S Tailings over crushed slag Plot. September 1996



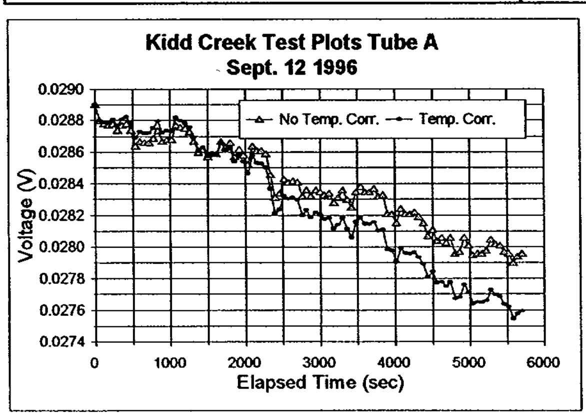


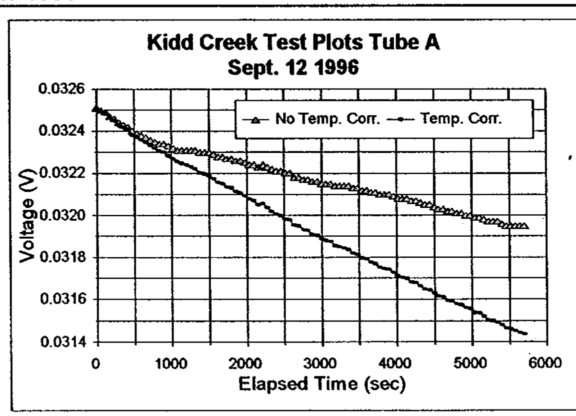
Kidd Creek. Test Plots. Low-S Tailings September 1996



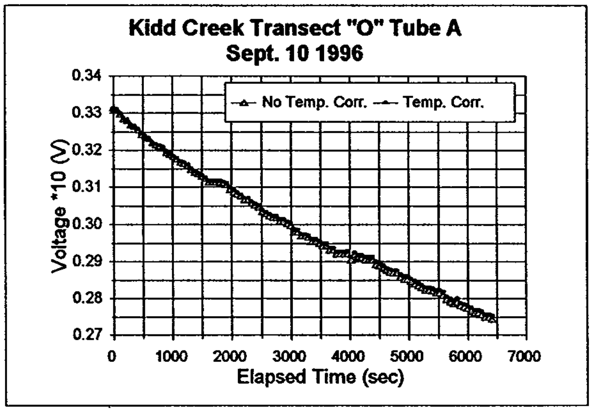


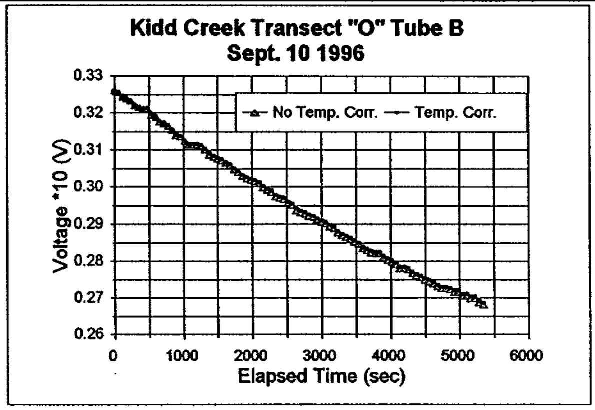
Kidd Creek. Crushed Waste Rock Test Plot. September 1996

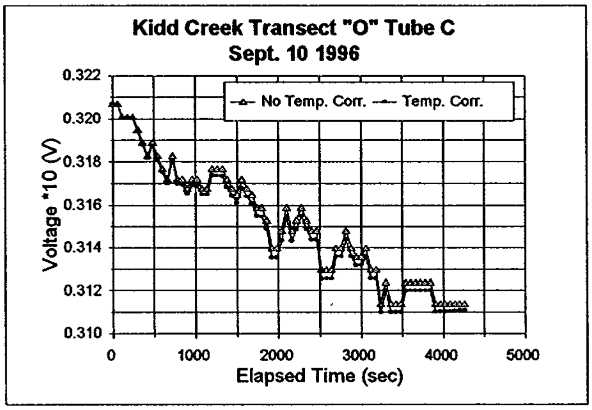


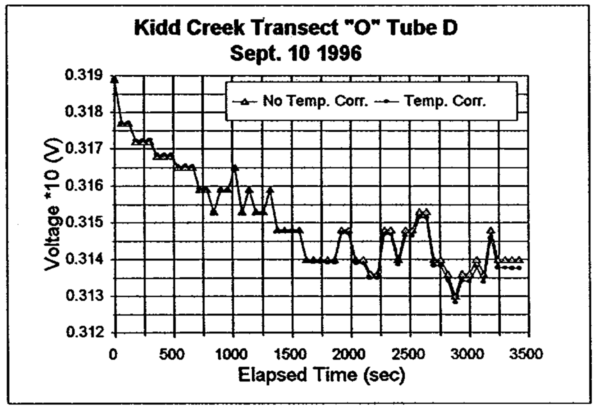


Kidd Creek. Transect "O" 10 year old tailings. September 1996

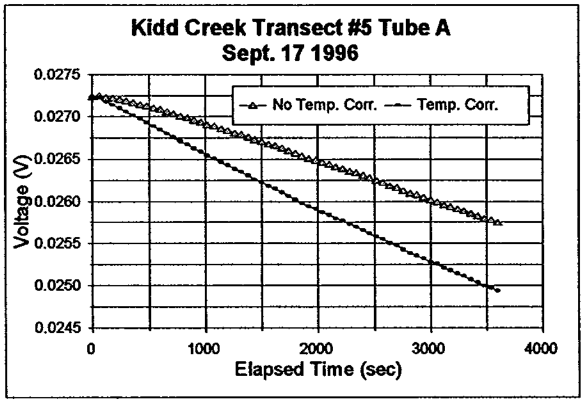


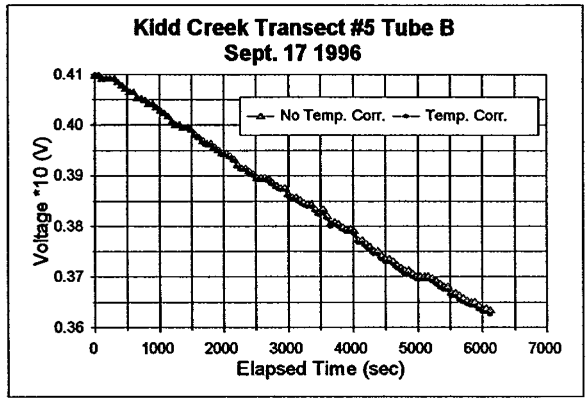


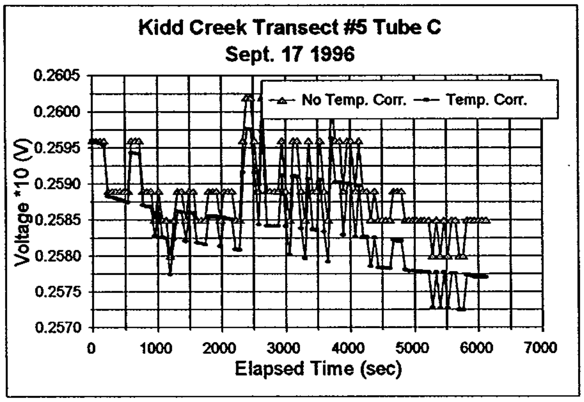


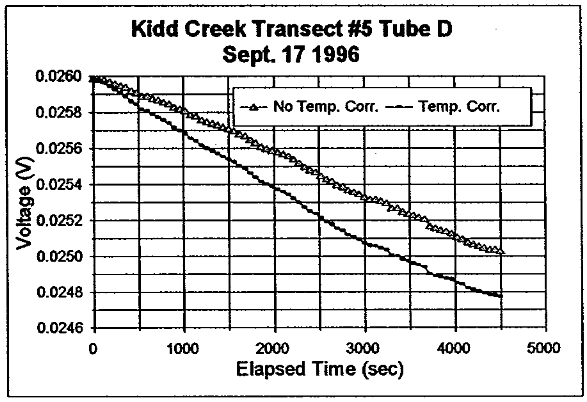


Kidd Creek. Transect #5 September 1996

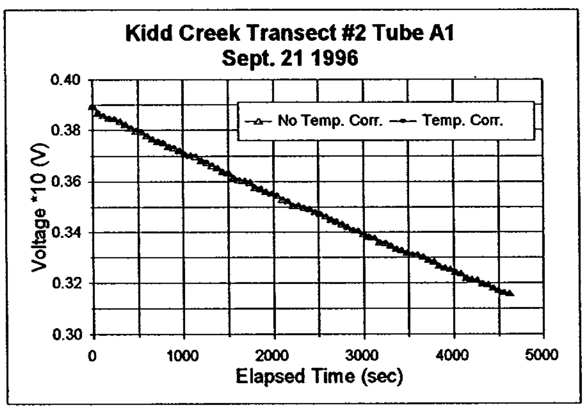


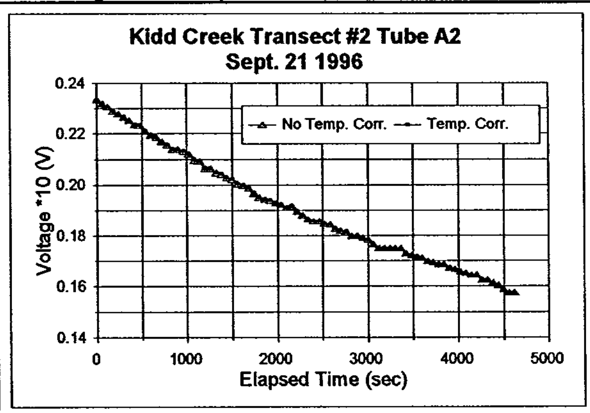




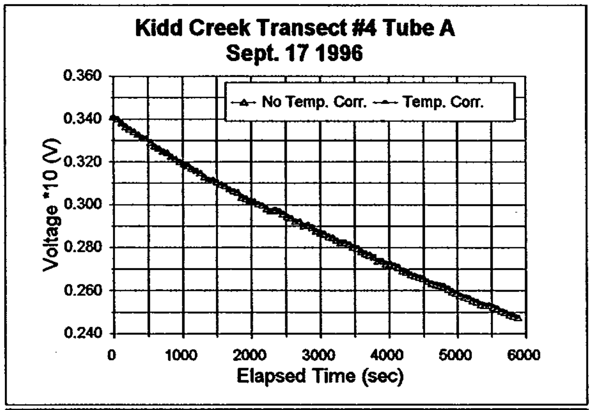


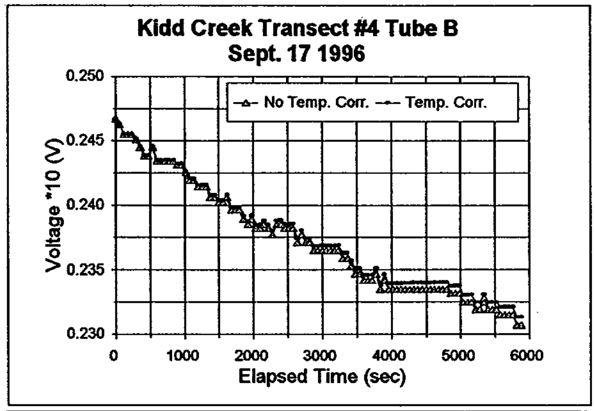
Kidd Creek. Transect #2 Control stations for Test Plot investigations. September 1996

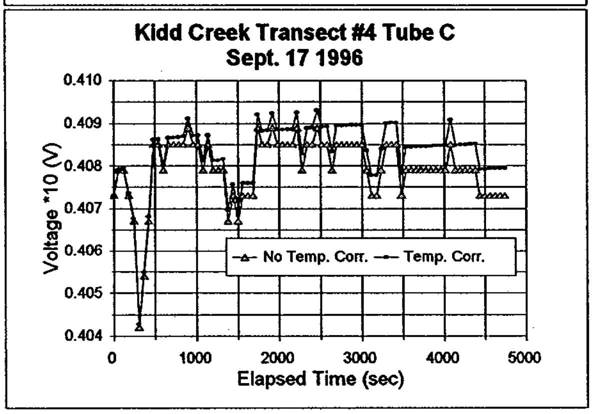


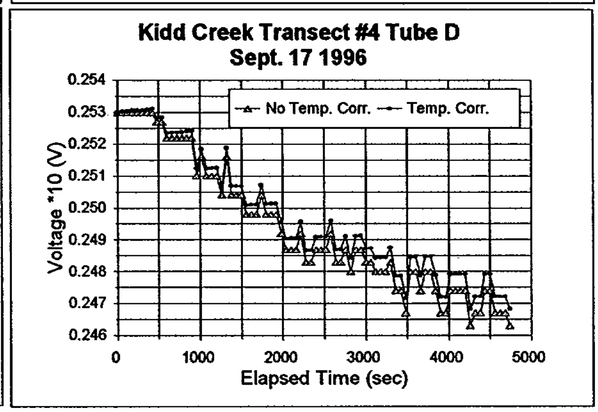


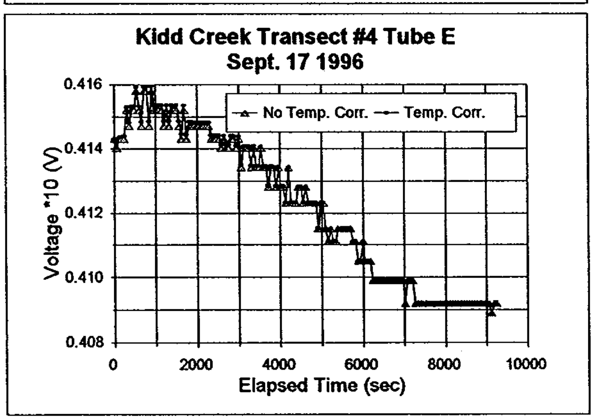
Kidd Creek. Transect #4 September 1996

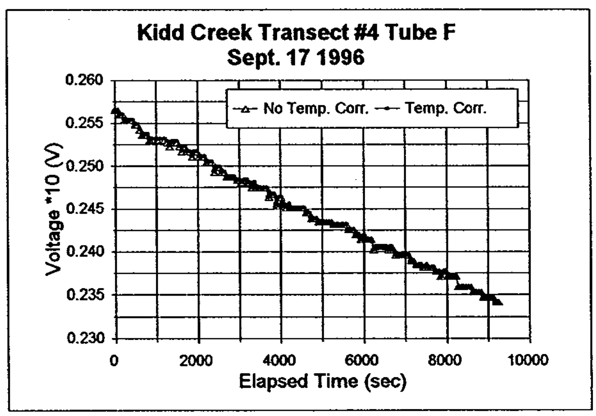


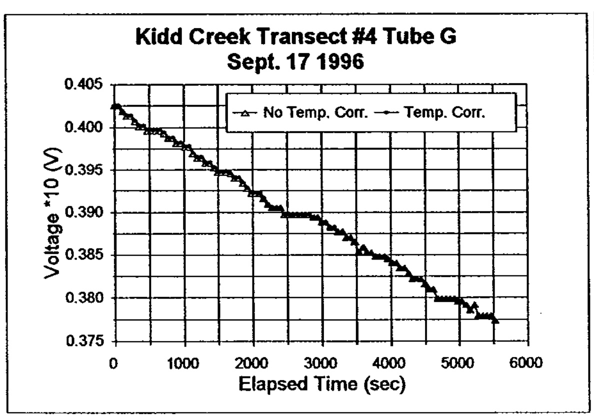


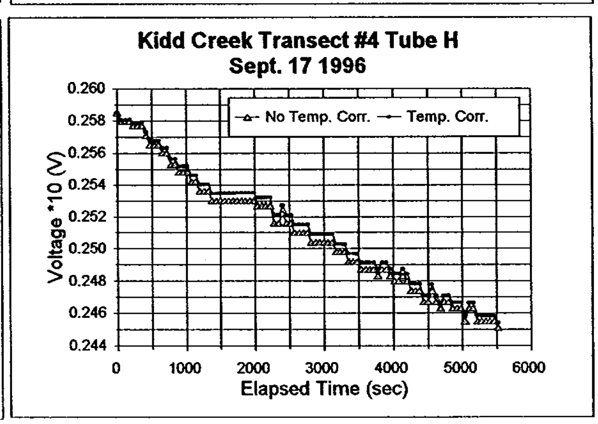




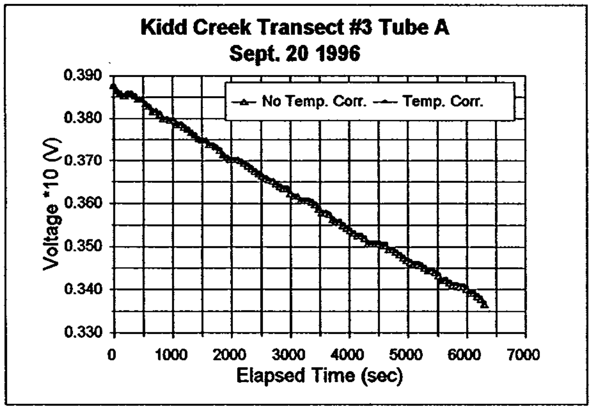


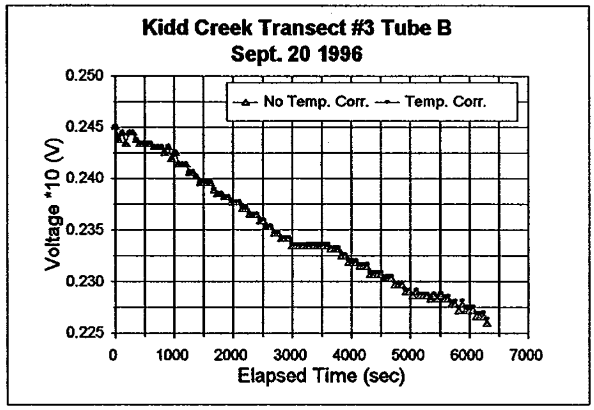


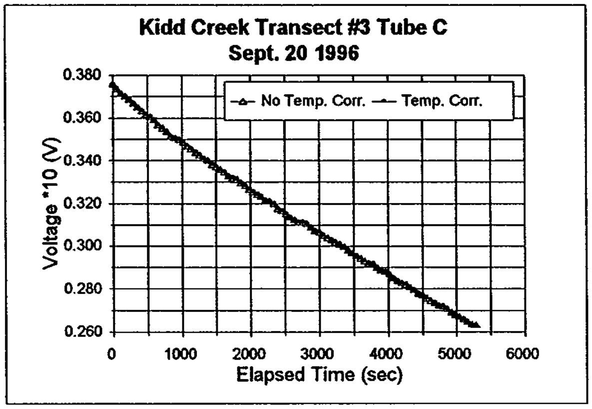


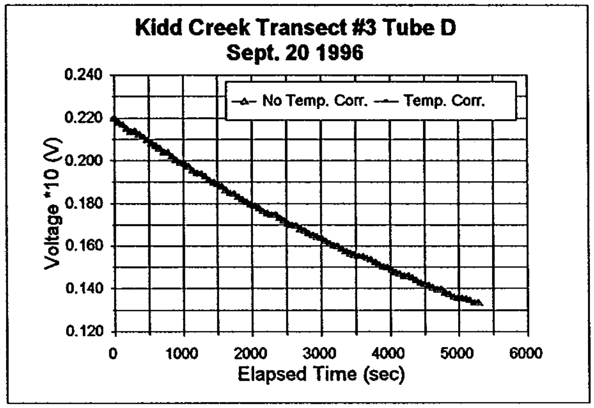


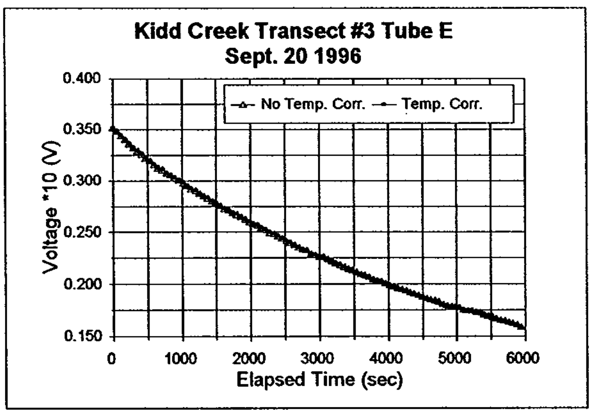
Kidd Creek. Transect #3 September 1996



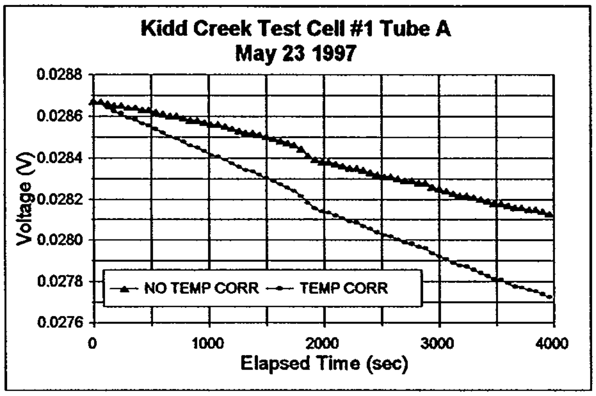


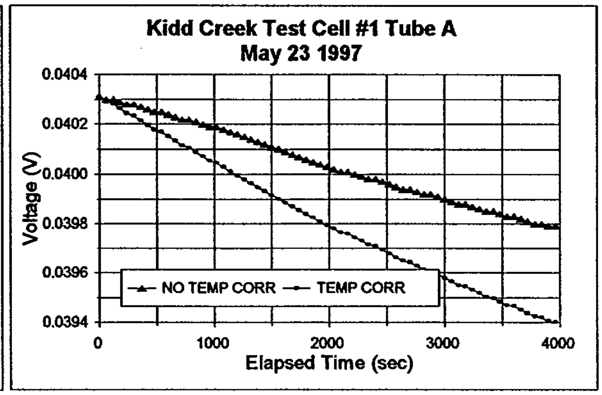




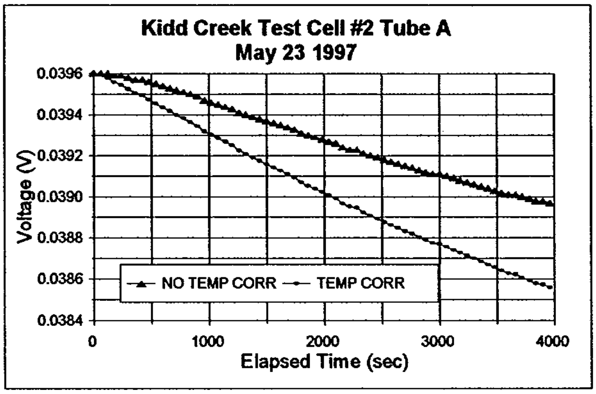


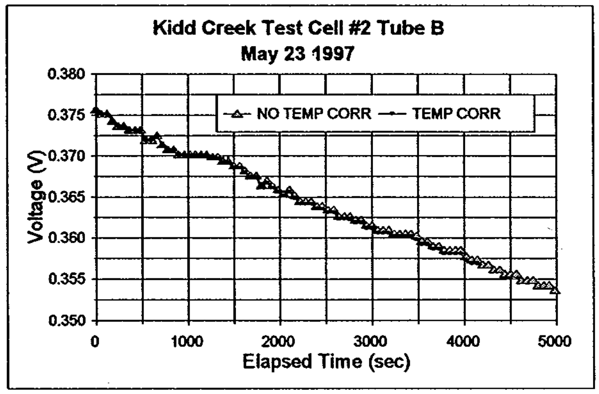
Kidd Creek. Tests Cell #1 Clay-till. May 1997



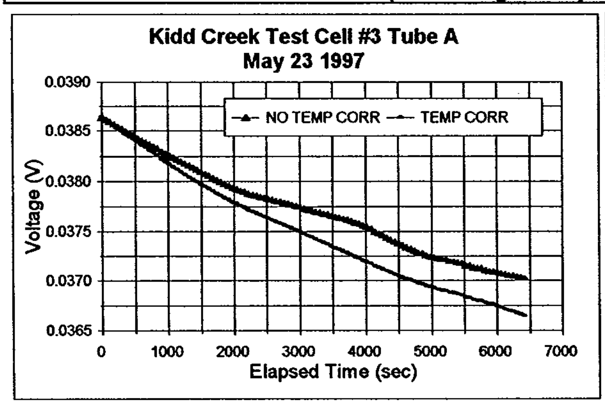


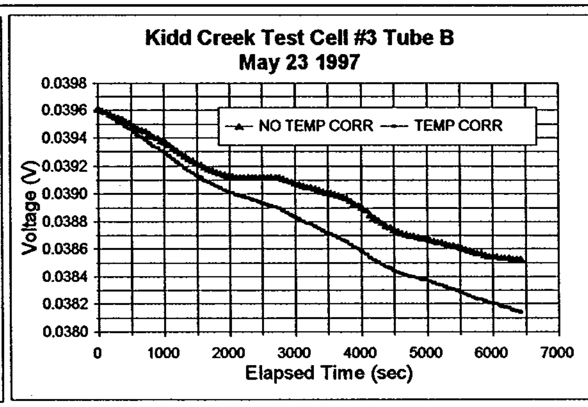
Kidd Creek. Tests Cell #2 Low-sulphur Taings / Slag. May 1997



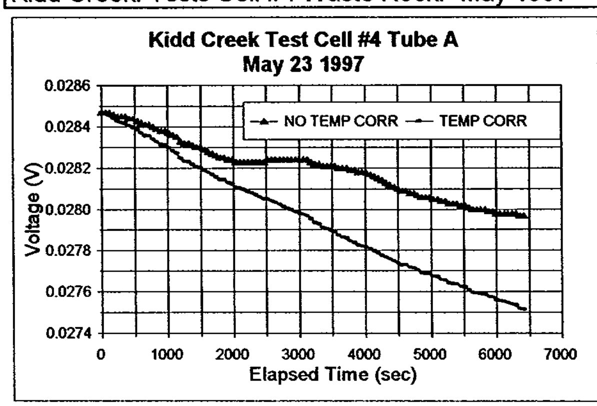


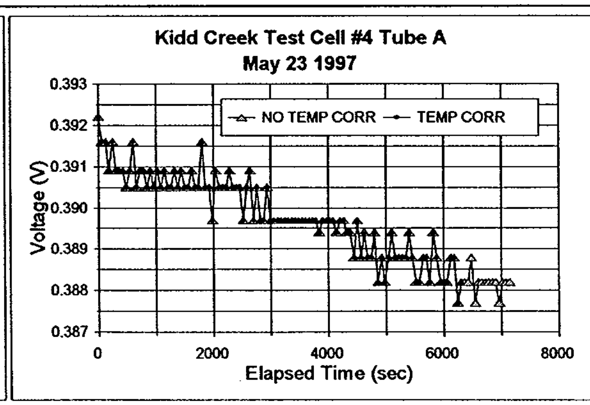
Kidd Creek. Tests Cell #3 Low-sulphur Taings. May 1997



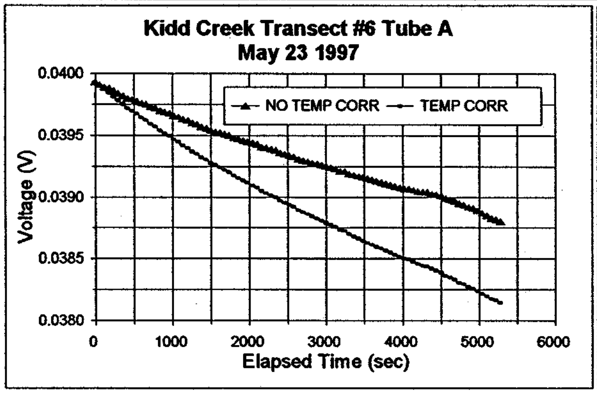


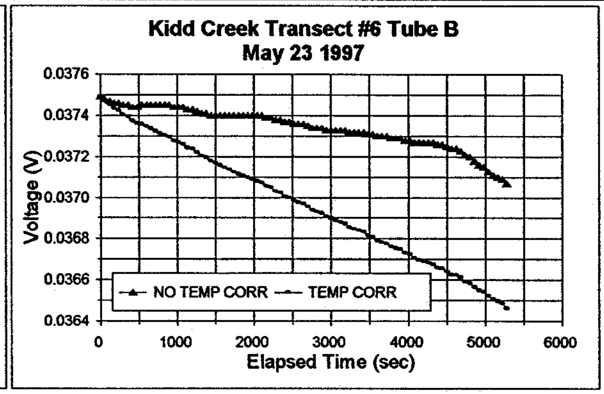
Kidd Creek. Tests Cell #4 Waste Rock. May 1997

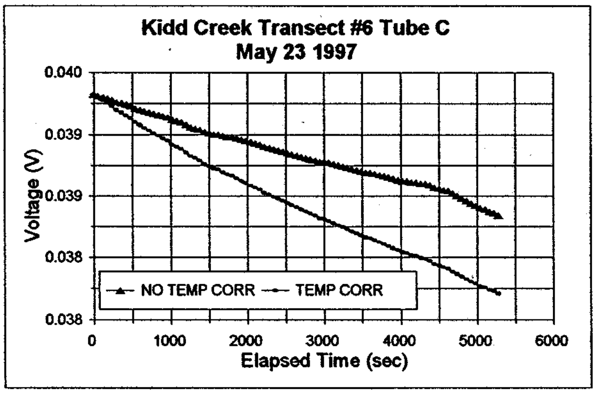


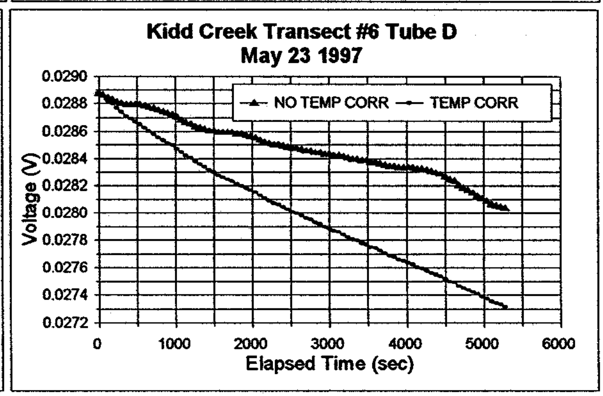


Kidd Creek. Transect #6 (Fresh Tailings) May 1997

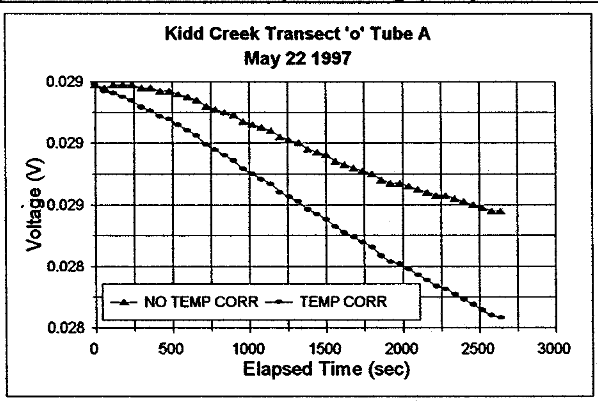


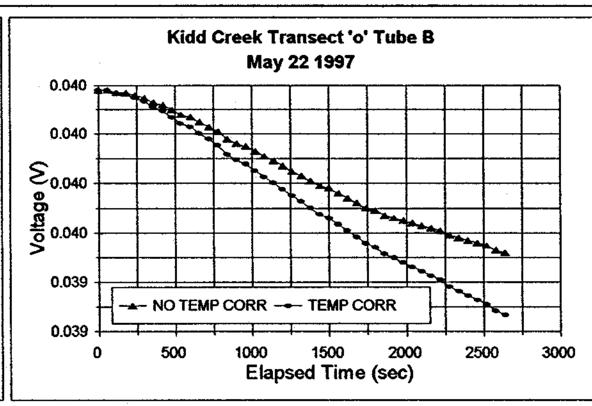


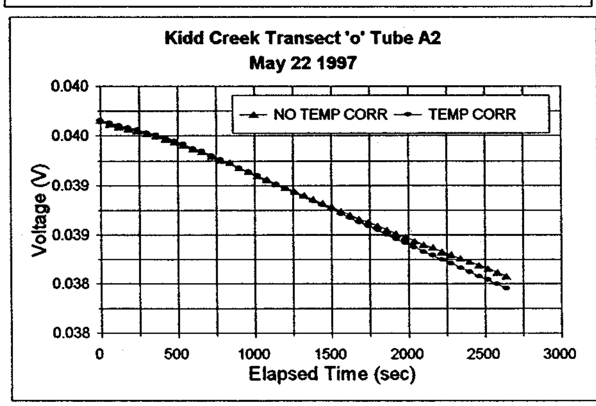




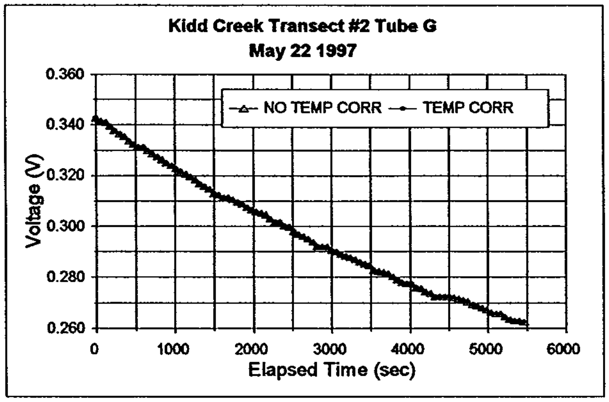
Kidd Creek. Transect 'o' (Old Tailings) May 1997

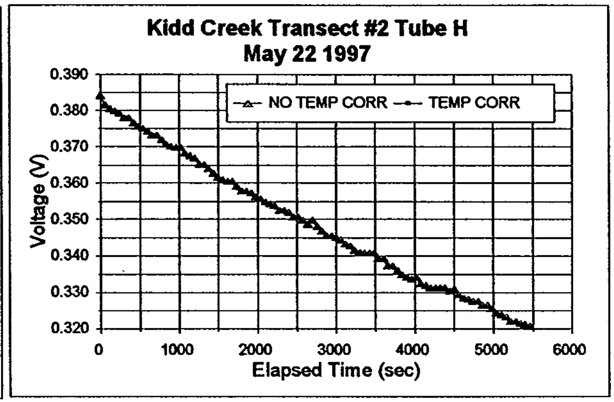


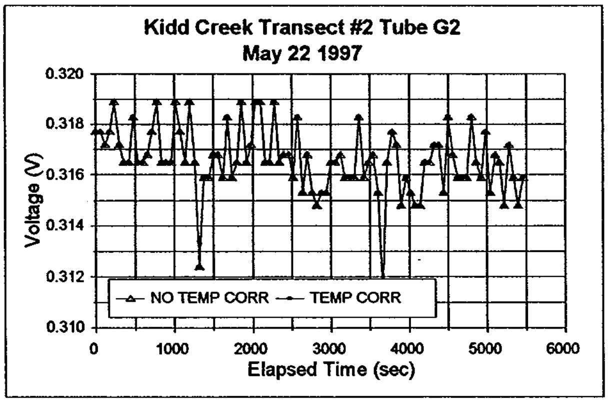


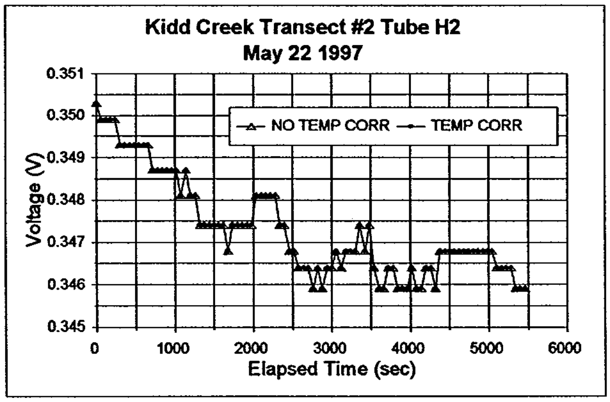


Kidd Creek. Transect #2 May 1997



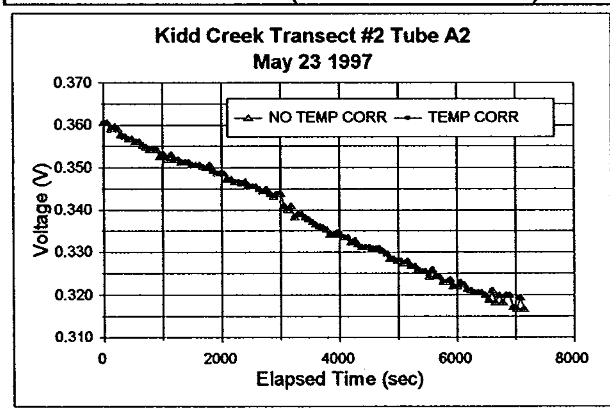


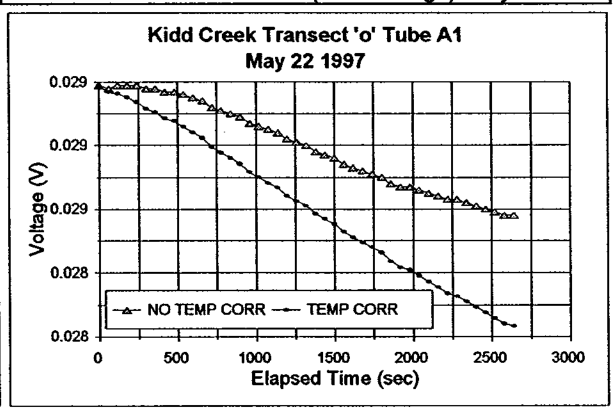




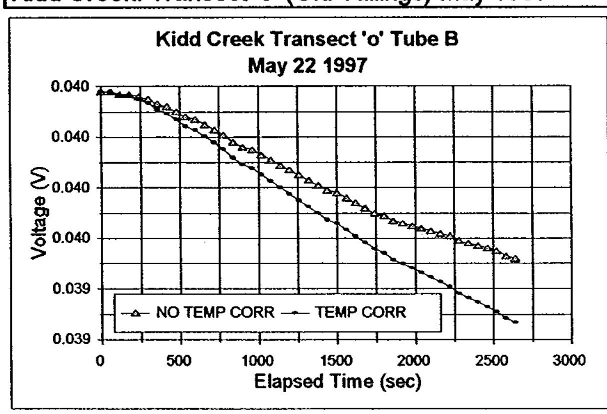
Kidd Creek. Transect #2 (Control for Test Cells)

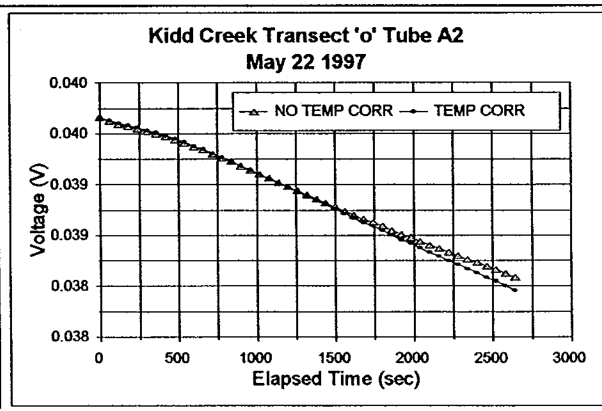
Kidd Creek. Transect 'o' (Old Tailings) May 1997



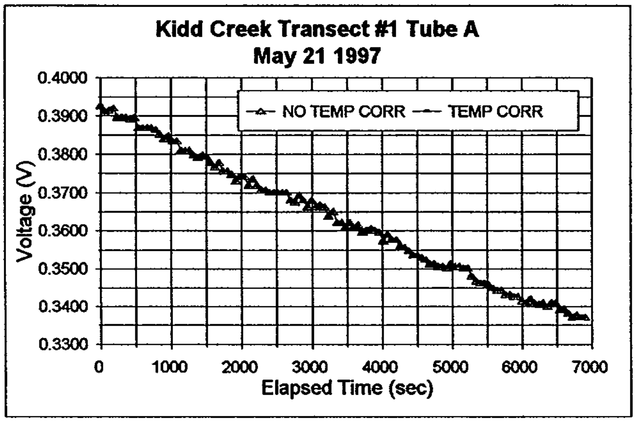


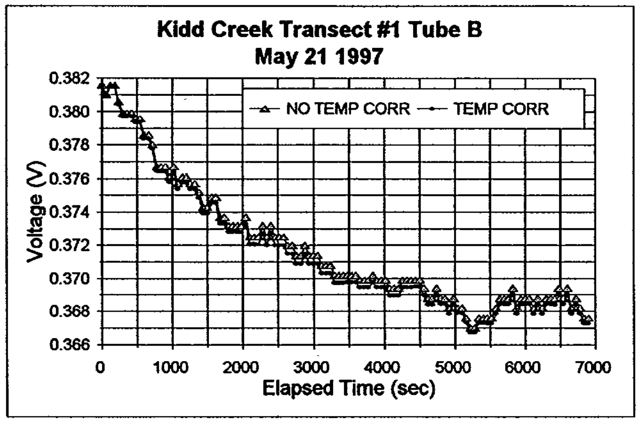
Kidd Creek. Transect 'o' (Old Tailings) May 1997

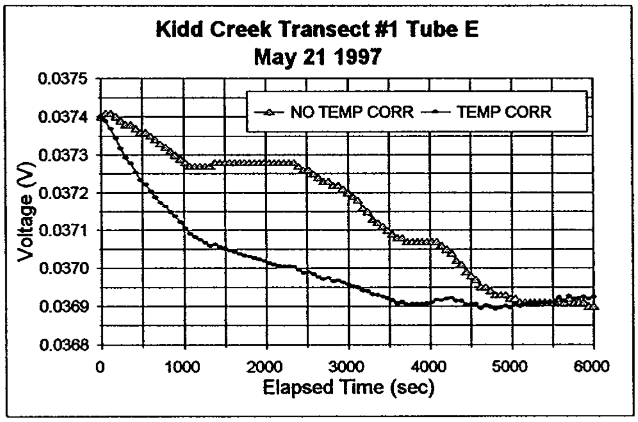


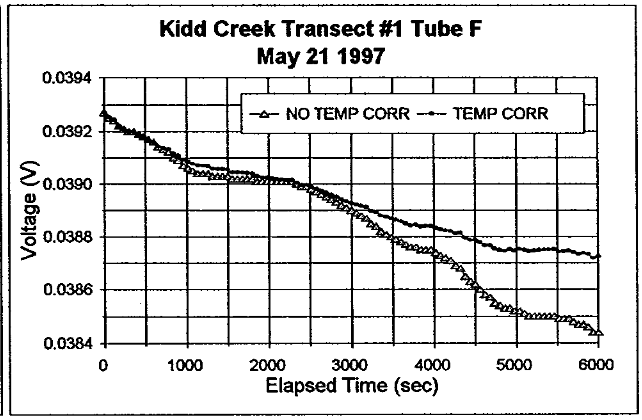


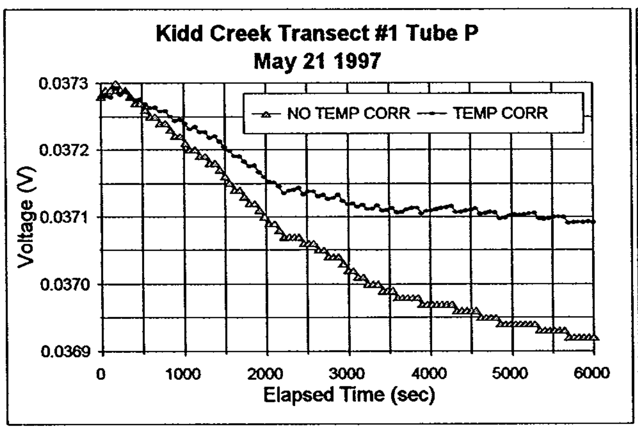
Kidd Creek. Transect #1 May 1997

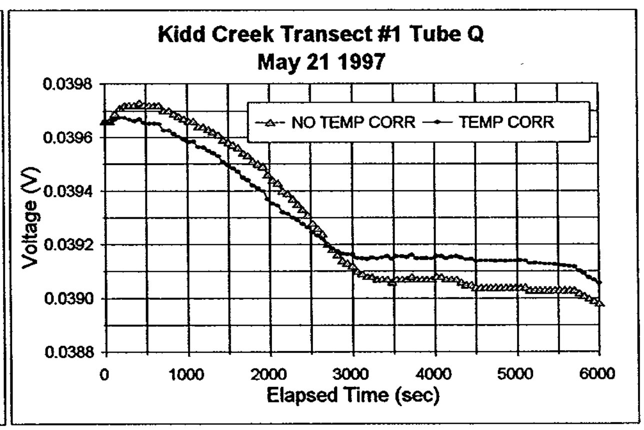




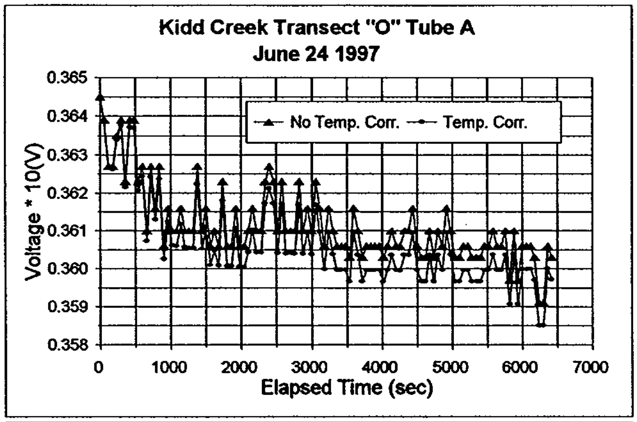


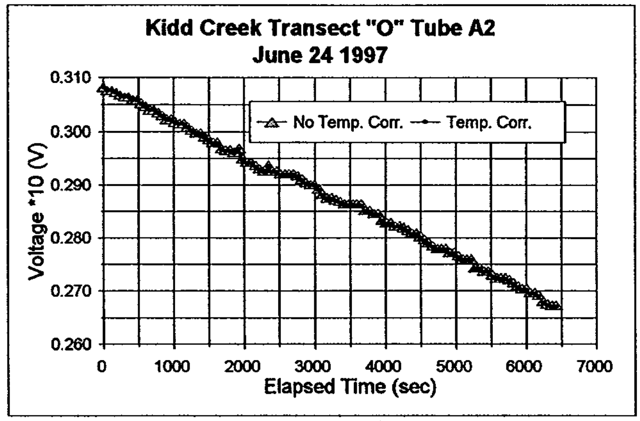


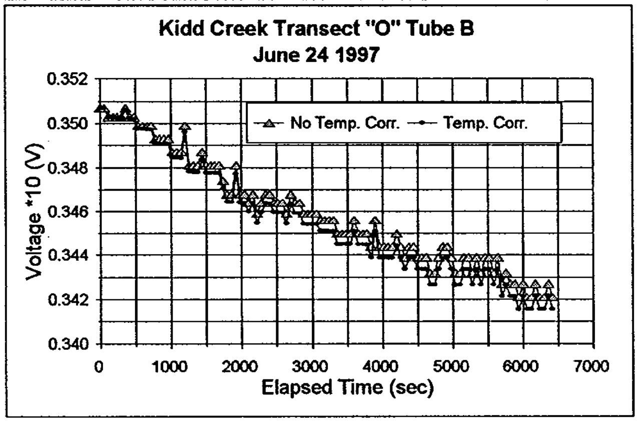


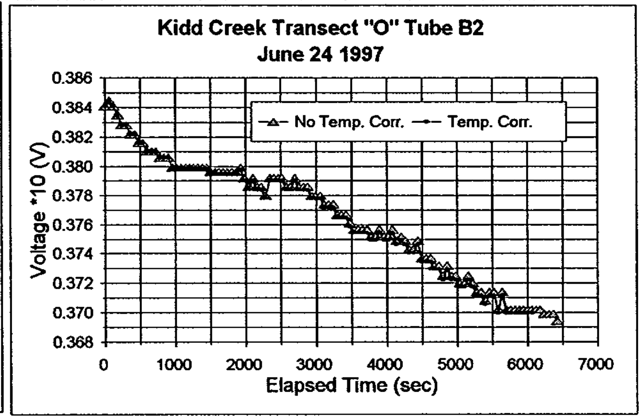


Kidd Creek. Transect "O" (10 year old tailings) June 1997

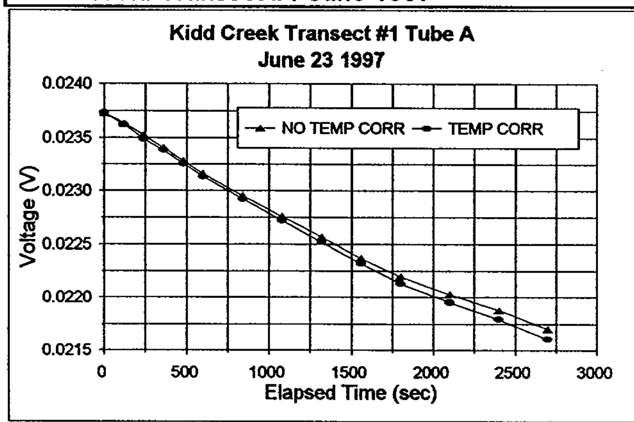


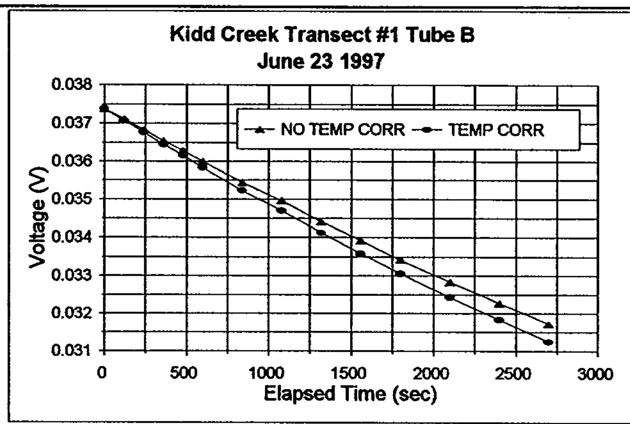


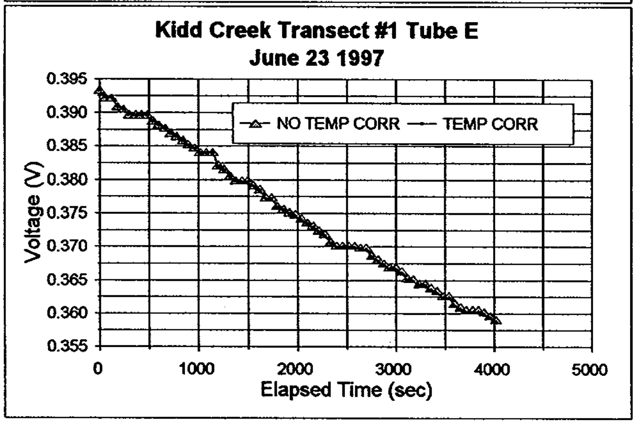


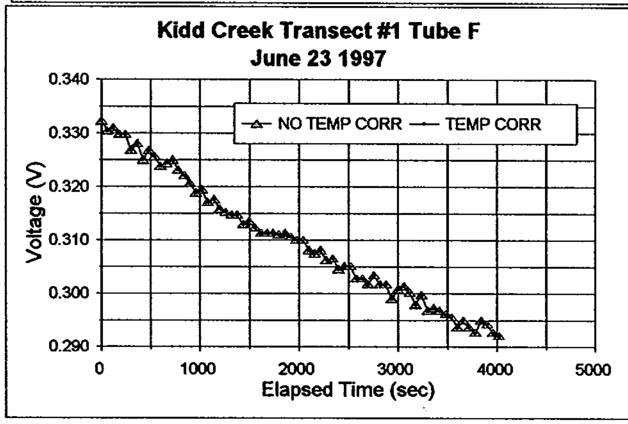


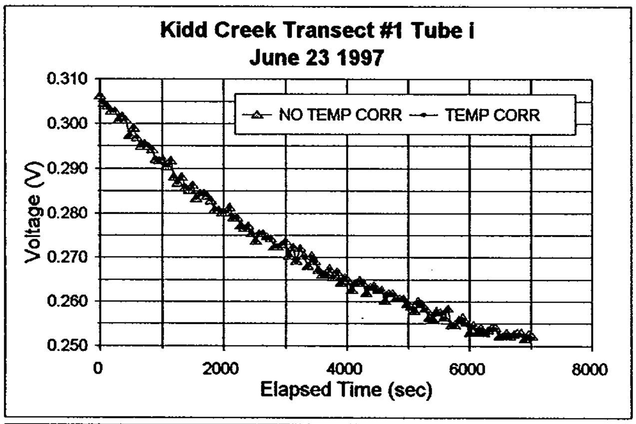
Kidd Creek. Transect #1 June 1997

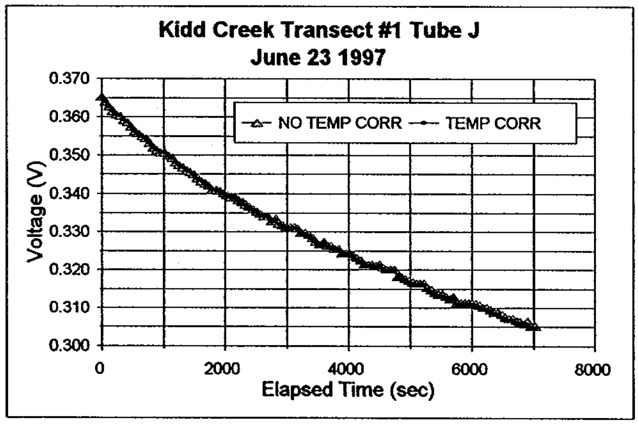


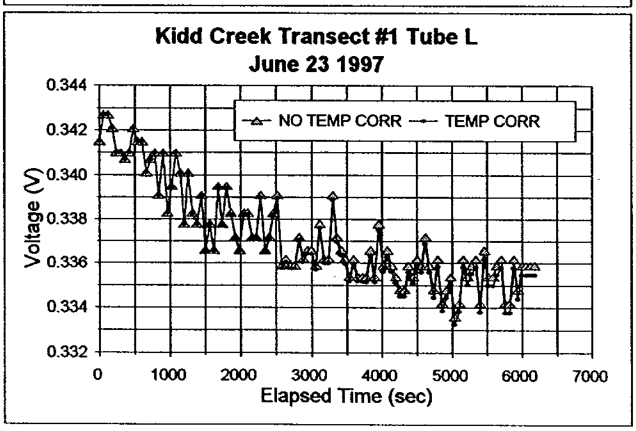


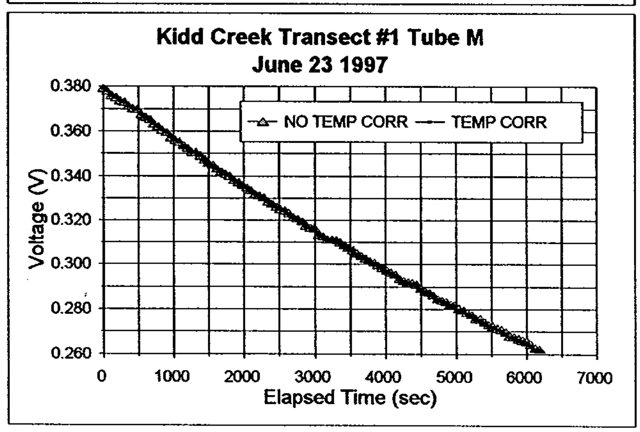




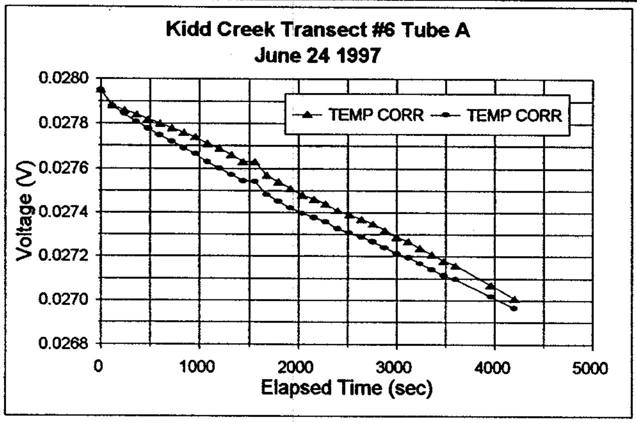


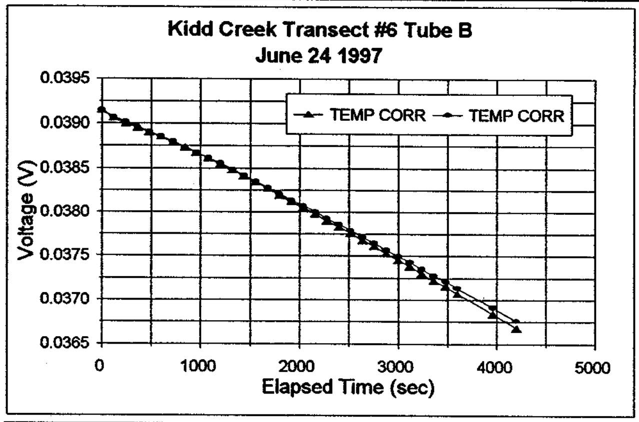


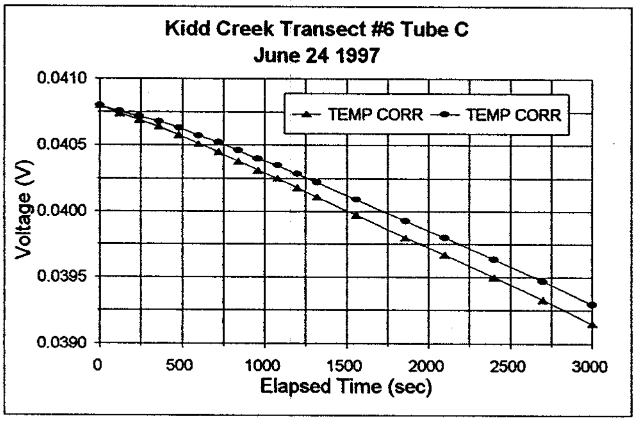


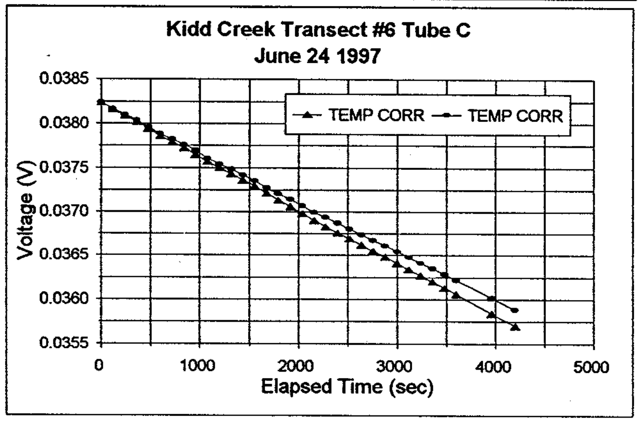


Kidd Creek. Transect #6 (Fresh Tailings) June 1997

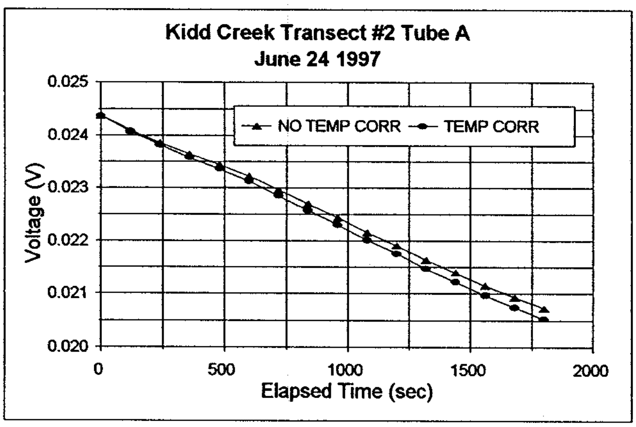




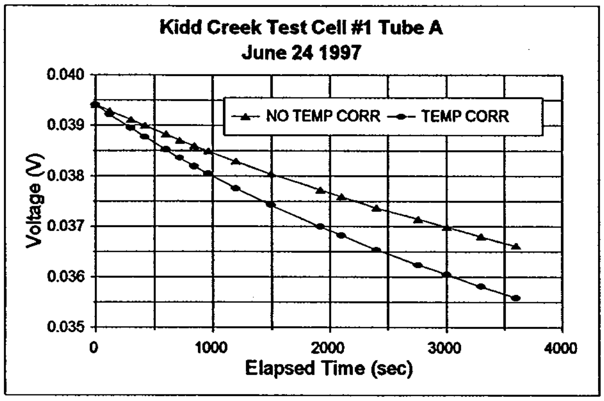


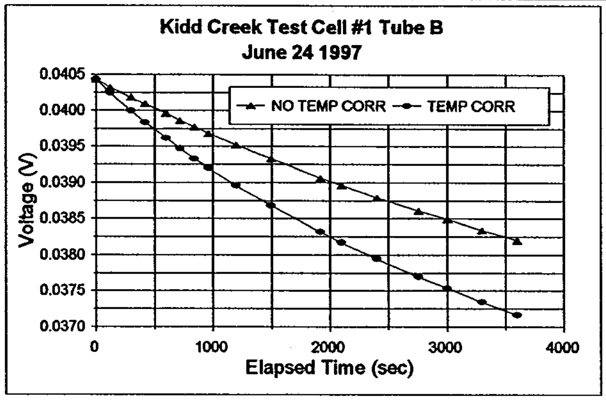


Kidd Creek. Transect #2 (Control for Test Cells) June 1997

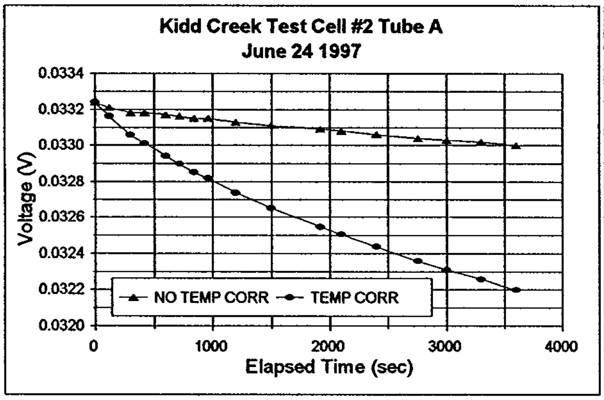


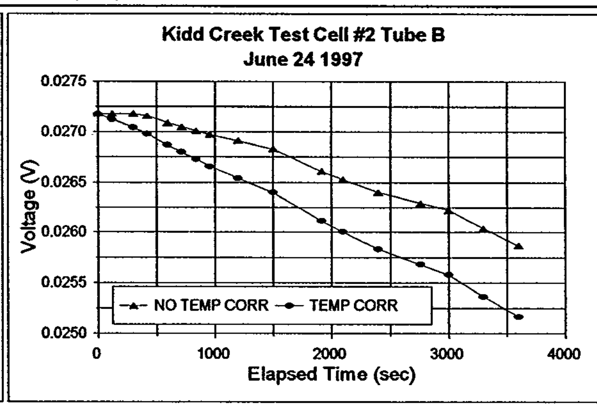
Kidd Creek. Tests Cell #1 Clay-till. June 1997



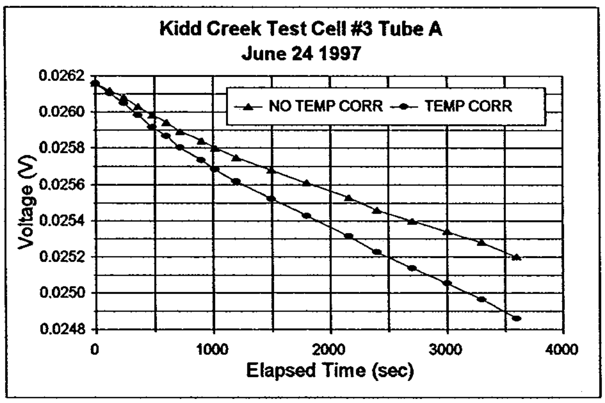


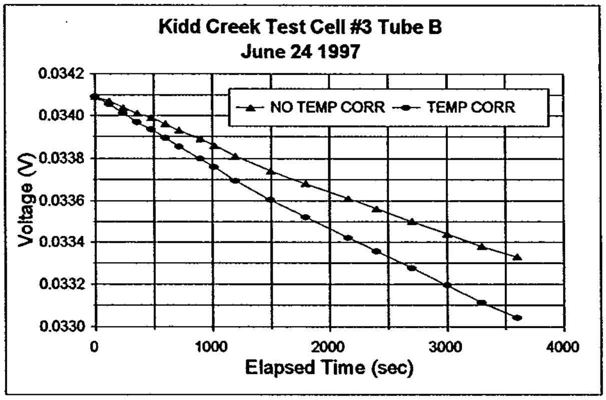
Kidd Creek. Tests Cell #2 Low-sulphur Taings / Slag. June 1997



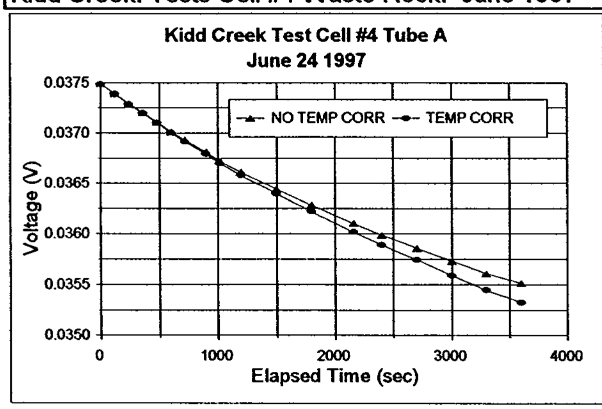


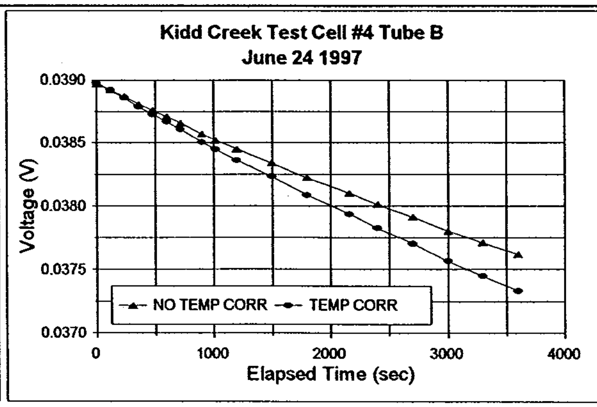
Kidd Creek. Tests Cell #3 Low-sulphur Taings. June 1997



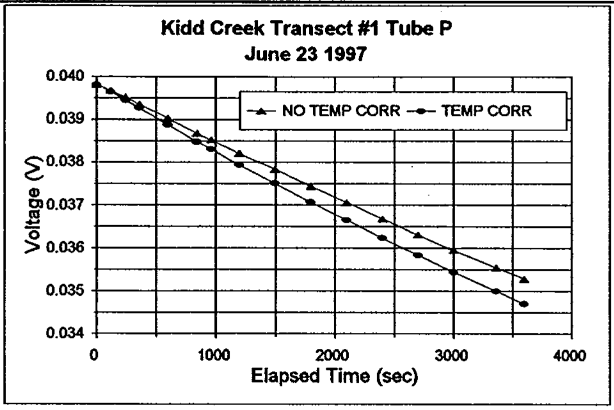


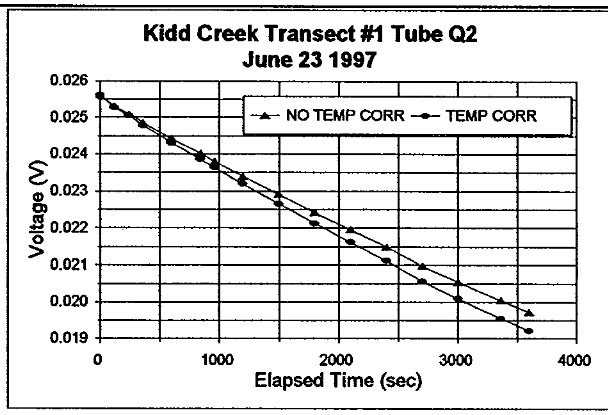
Kidd Creek. Tests Cell #4 Waste Rock. June 1997

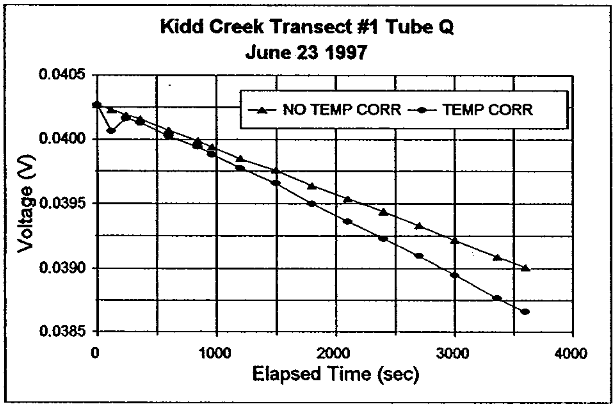




Kidd Creek. Transect #1 June 1997







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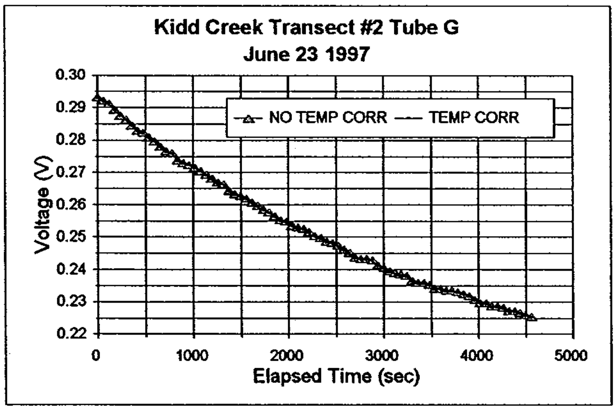
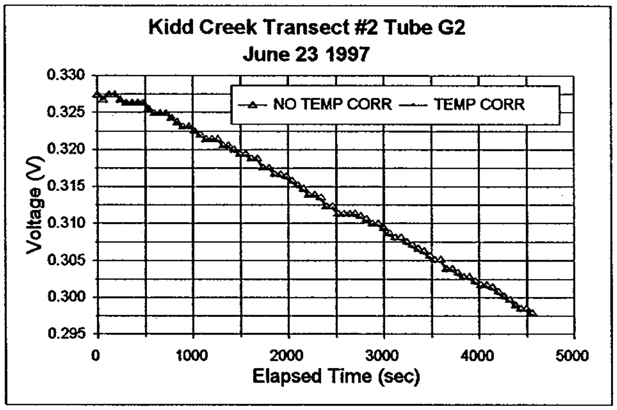
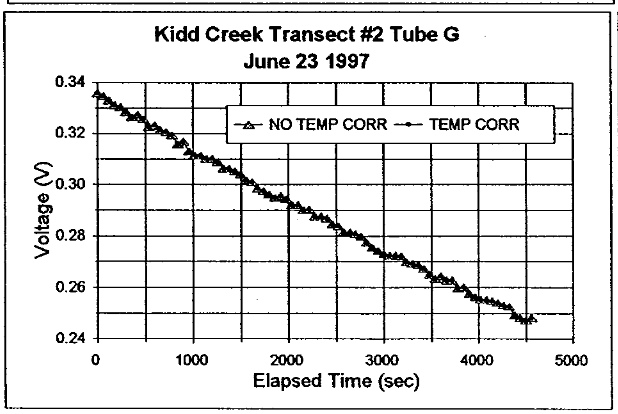
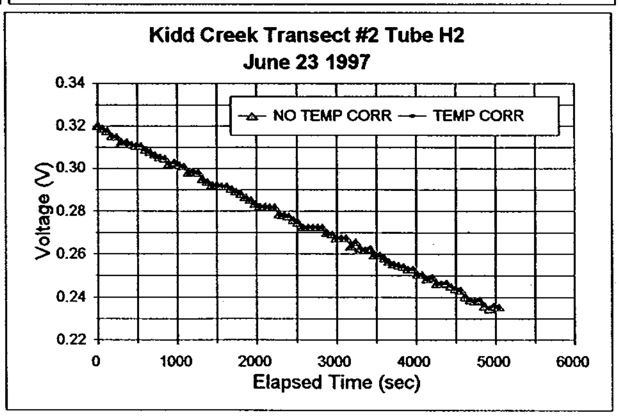
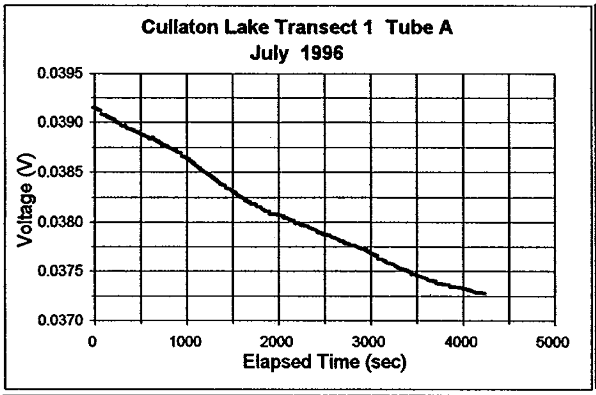


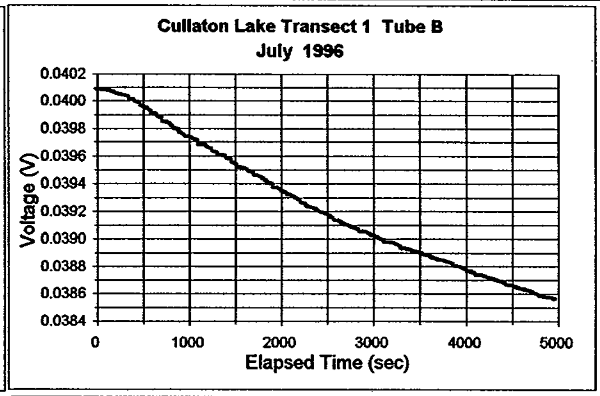


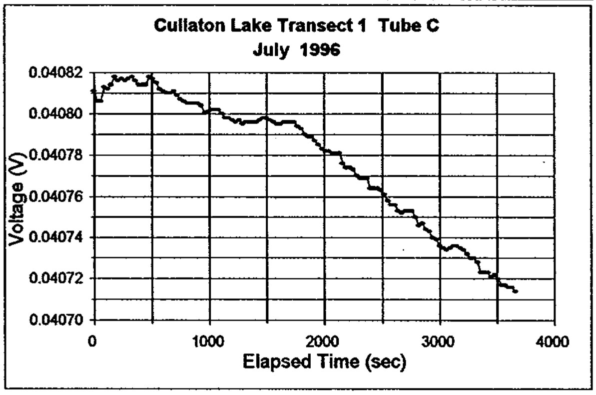


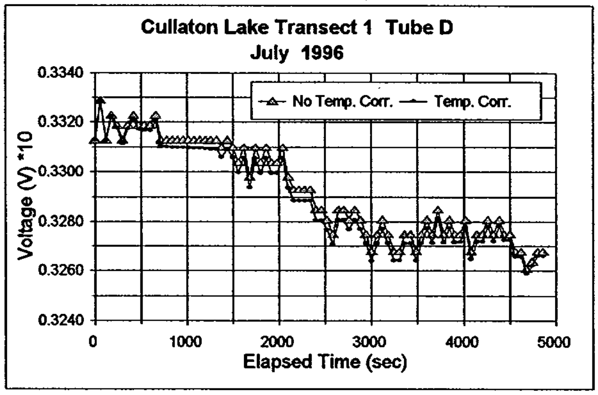


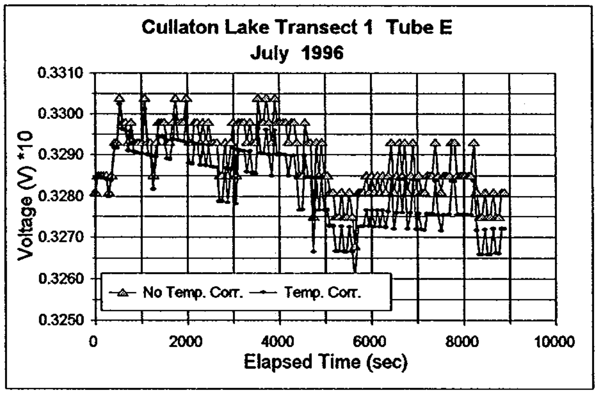
Cullaton Lake. Transect 1 August 1996

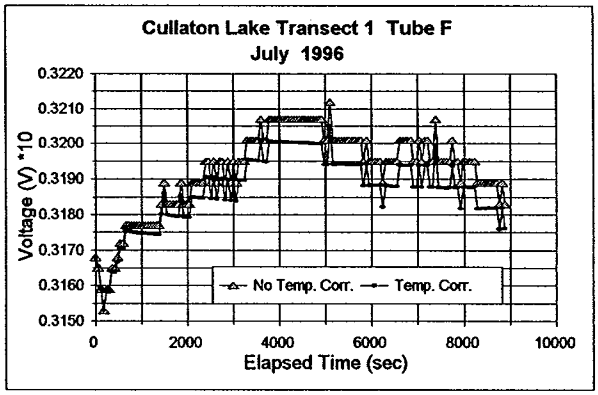




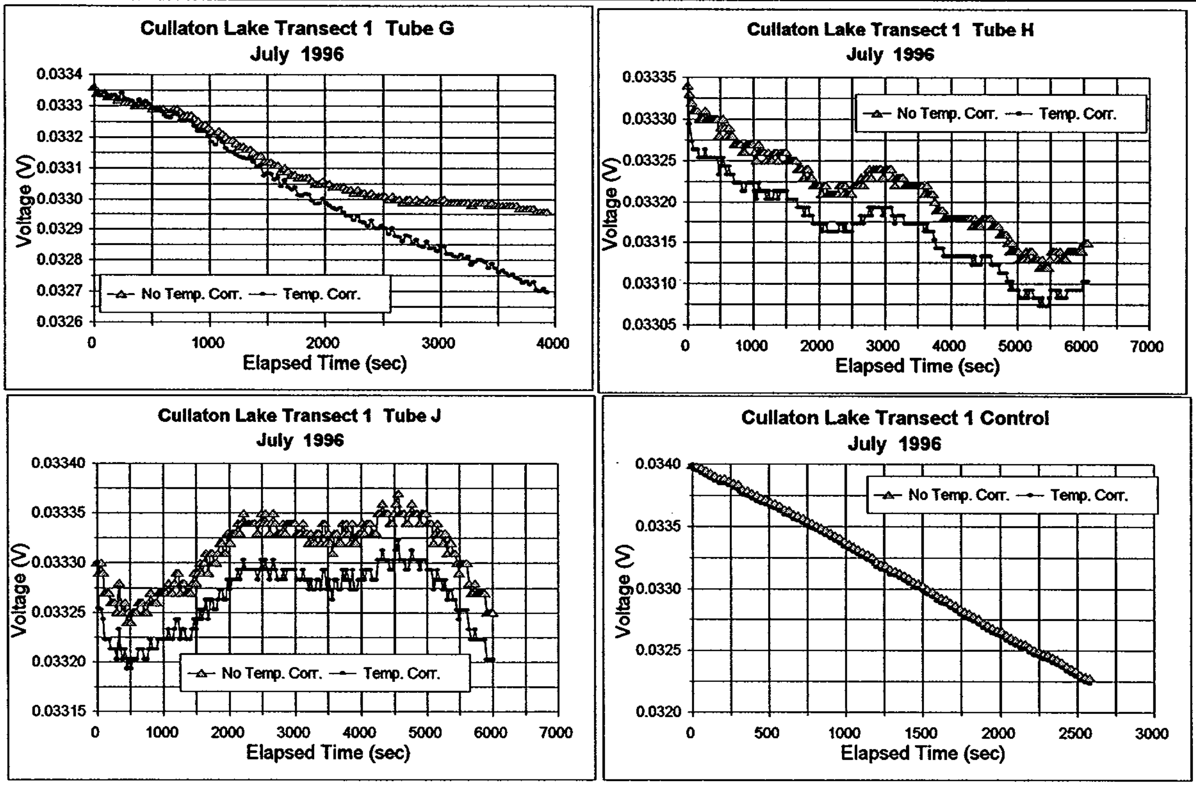




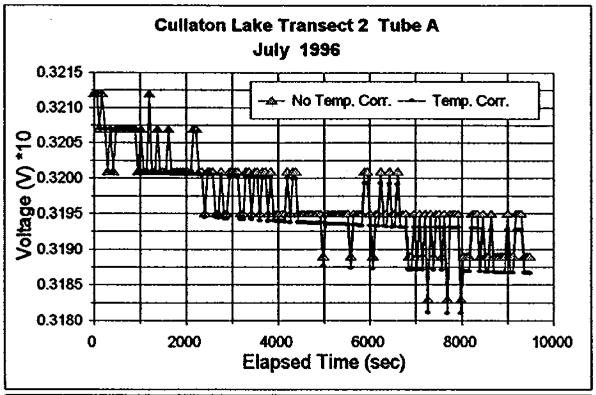


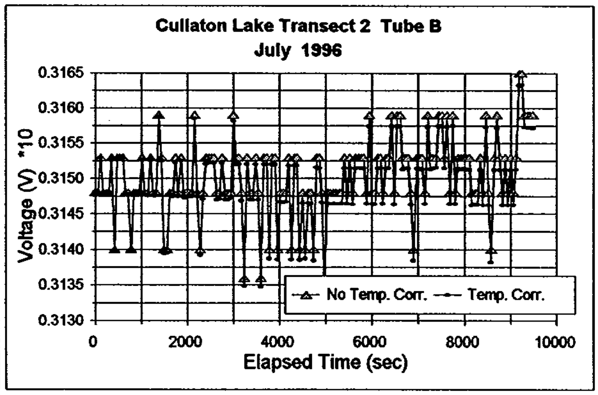


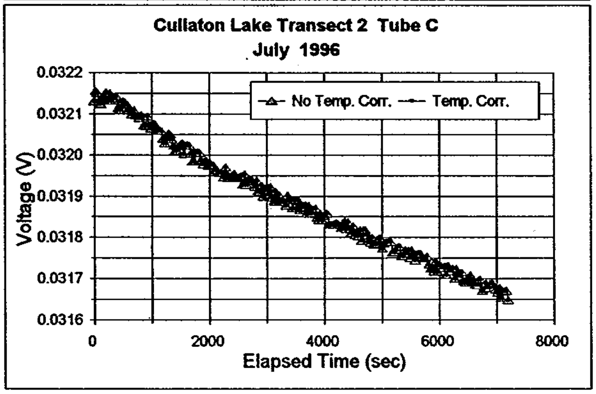
Cullaton Lake. Transect 1 August 1996



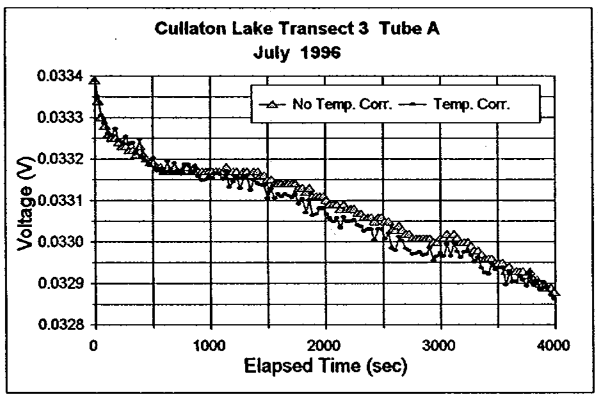
Cullaton Lake. Transect 2 August 1996

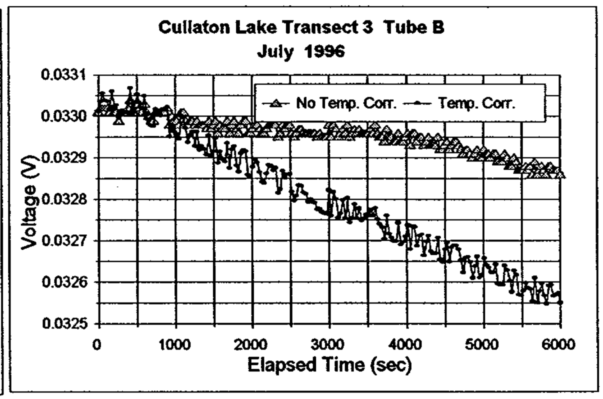


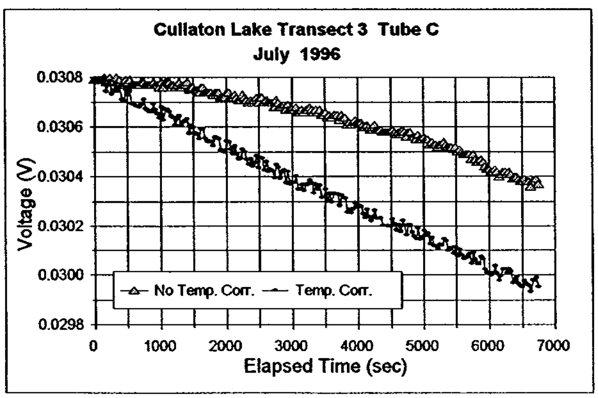




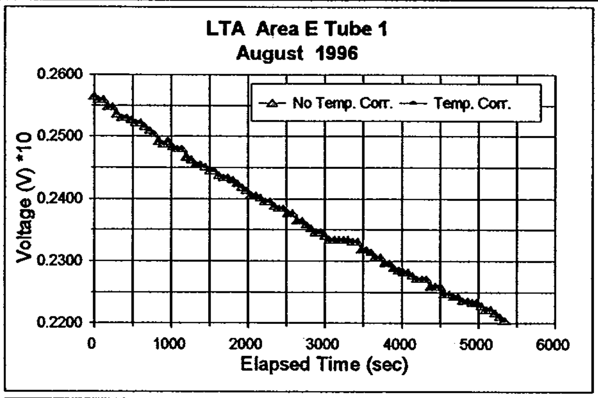
Cullaton Lake. Transect 3 August 1996

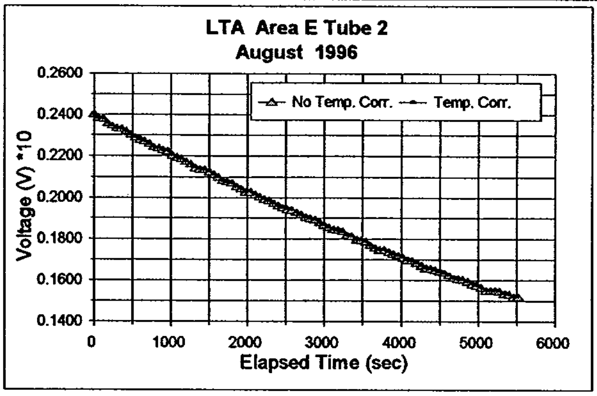


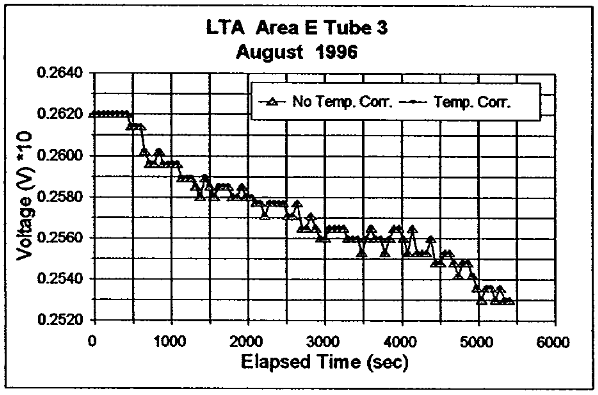




DONA LAKE. Area E August 1996







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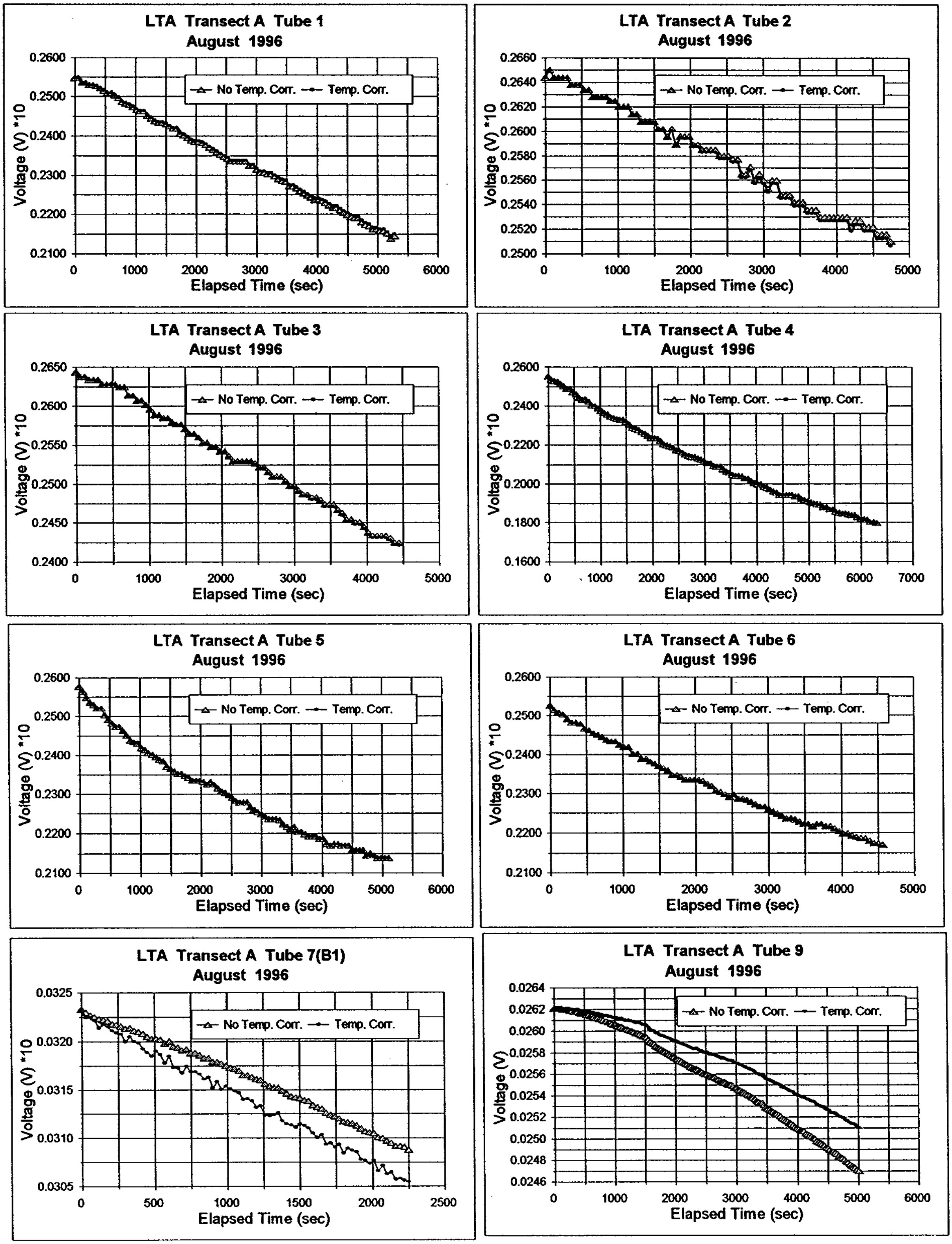

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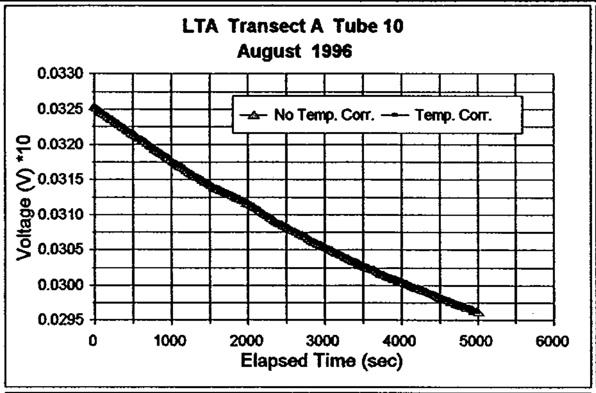

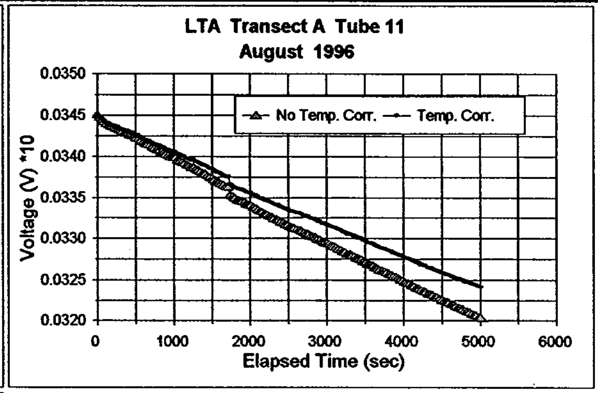

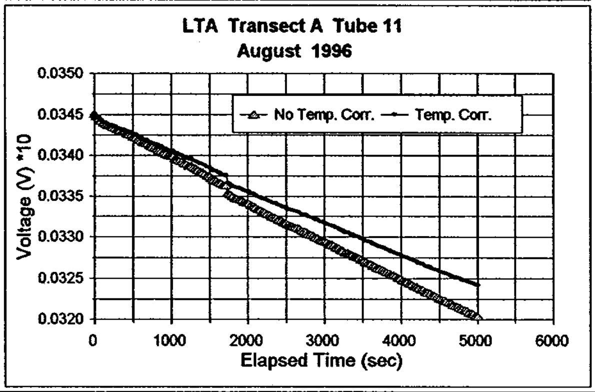

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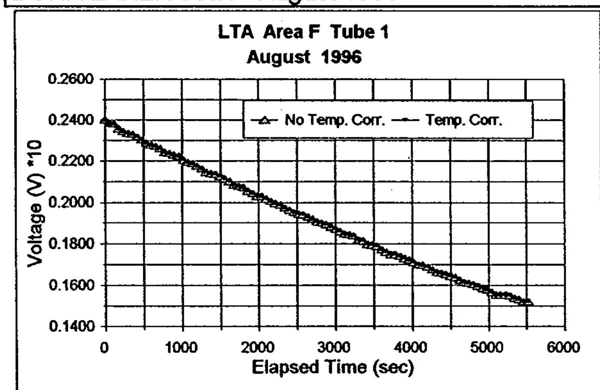

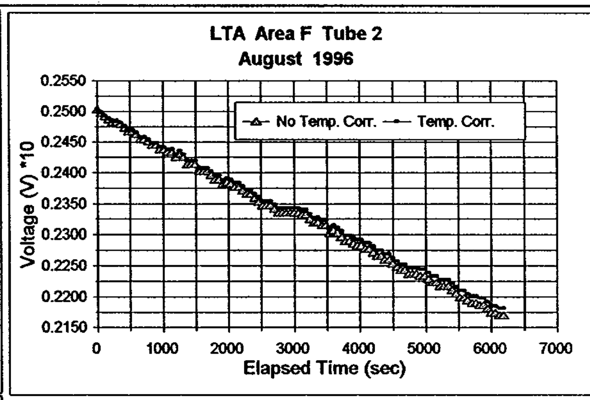

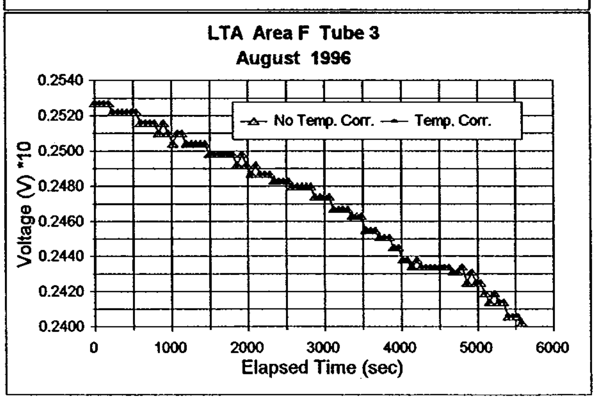

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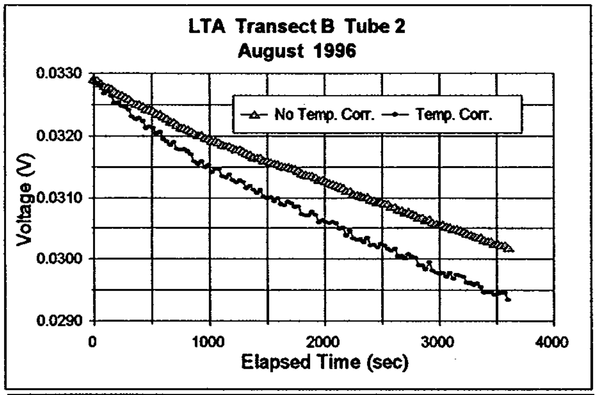

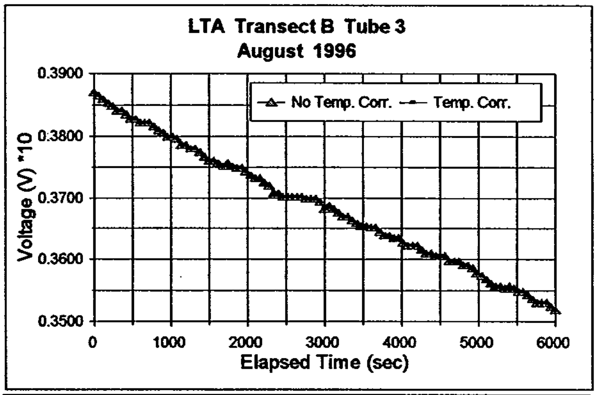

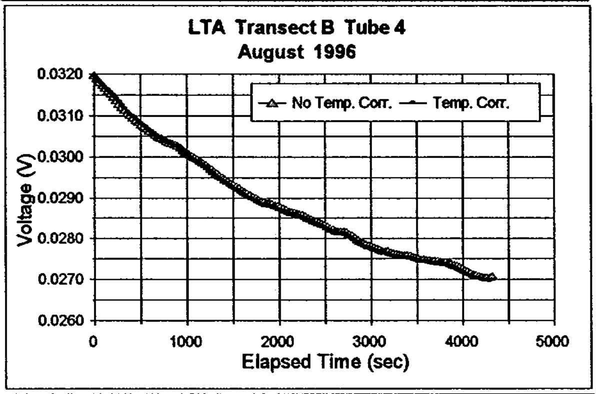

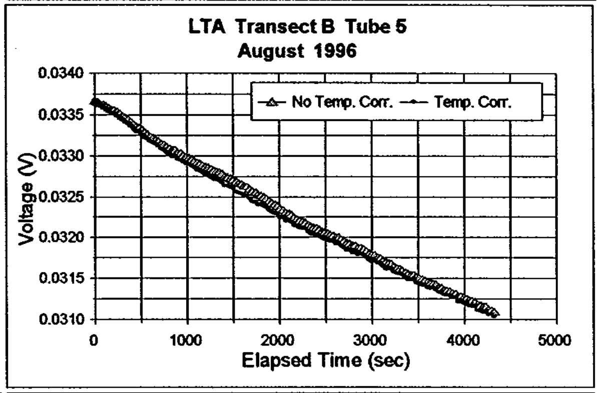

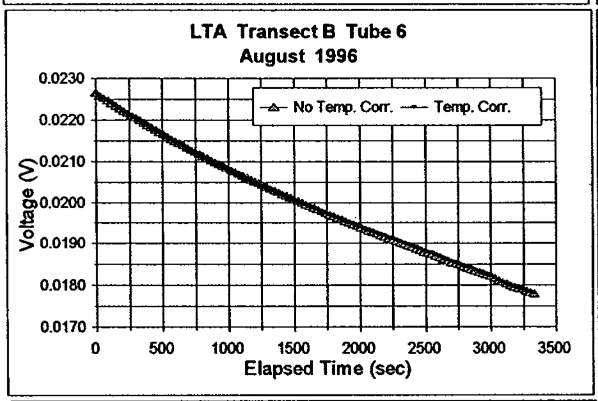

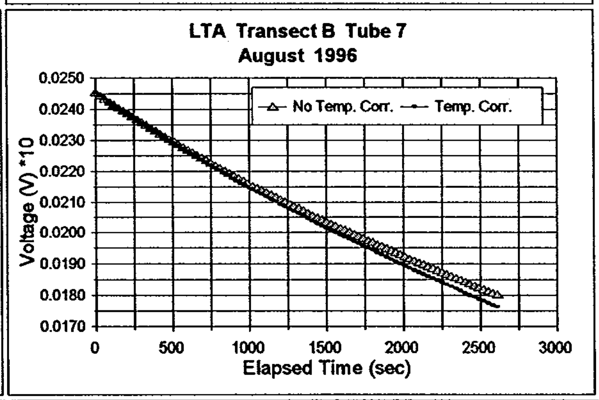

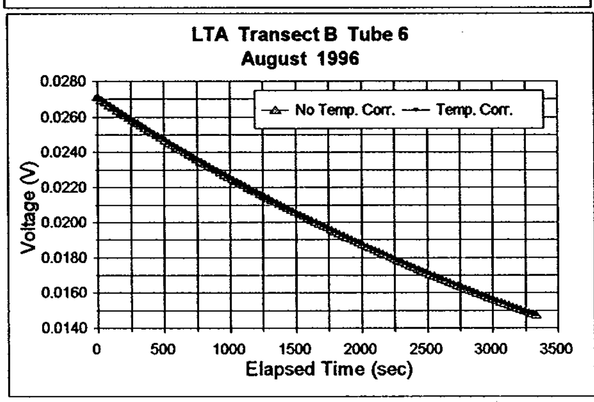

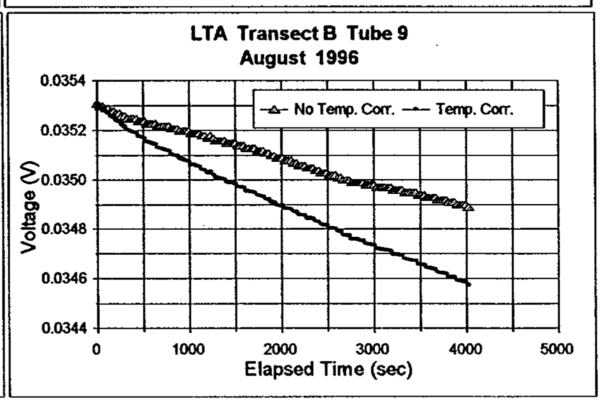

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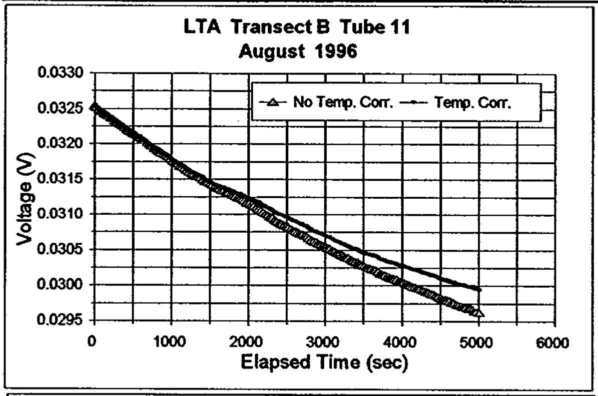

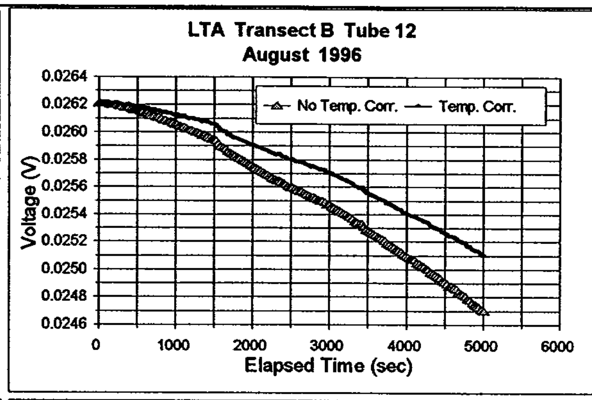

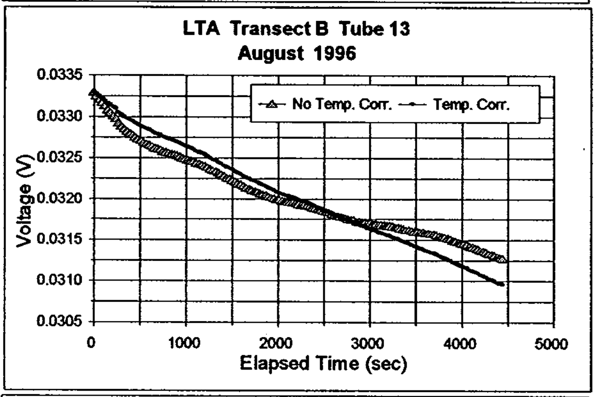

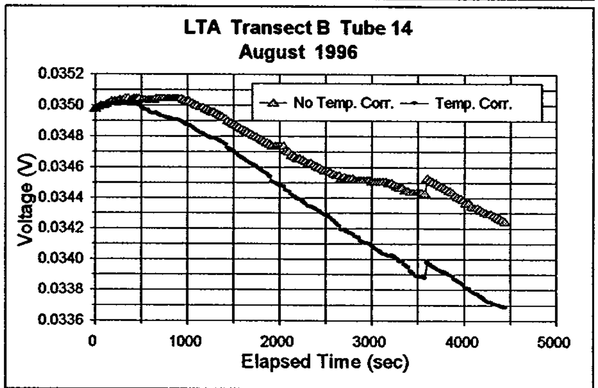

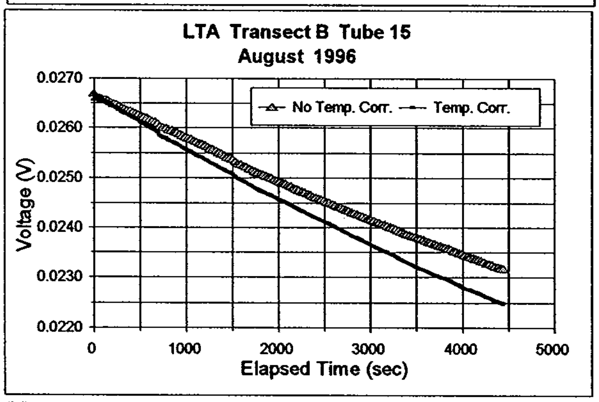

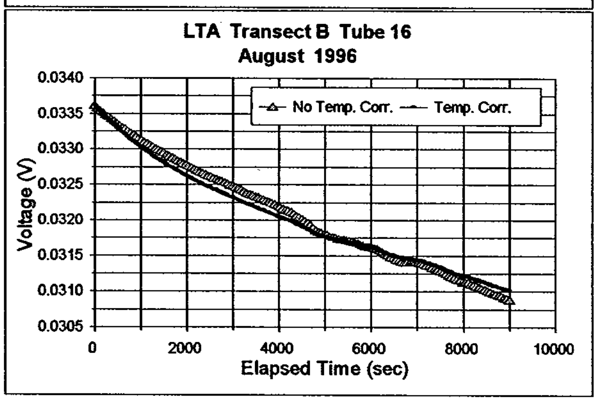

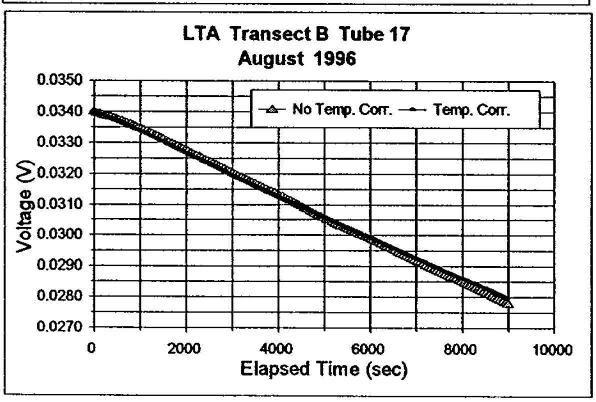

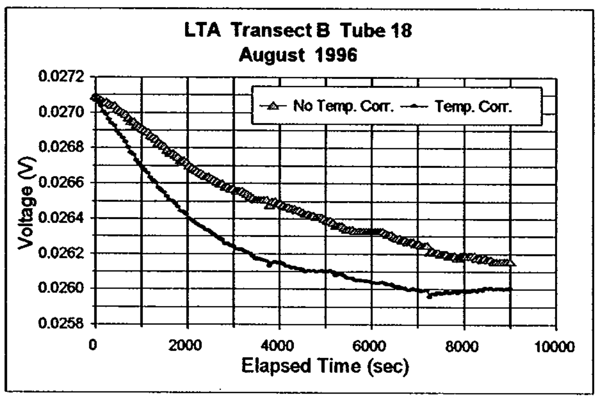

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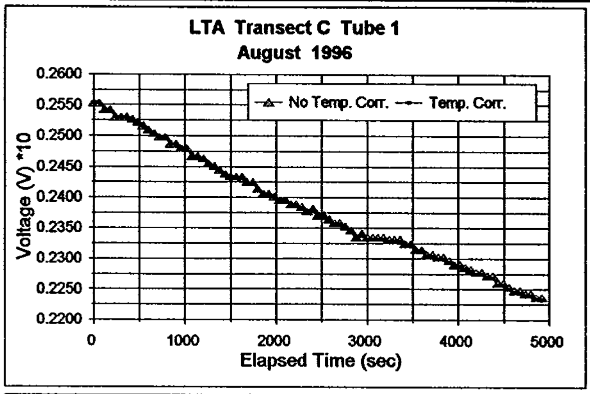

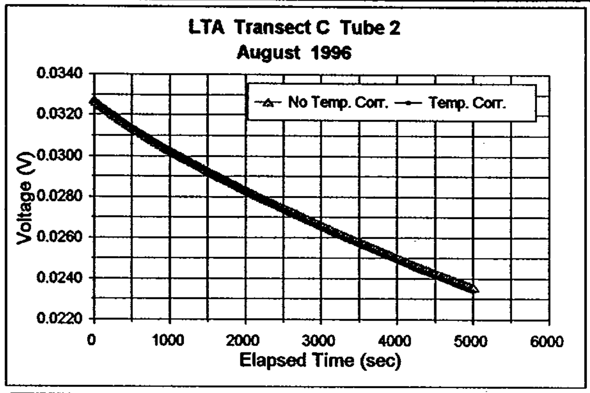

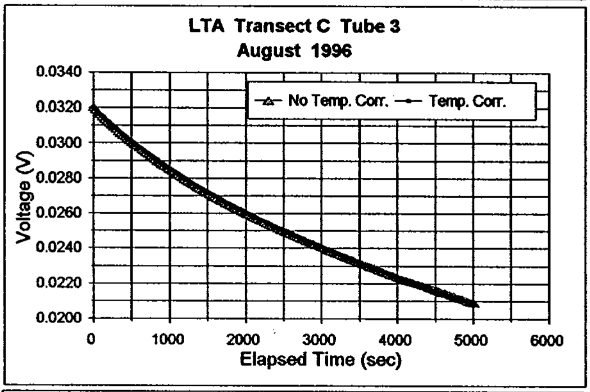

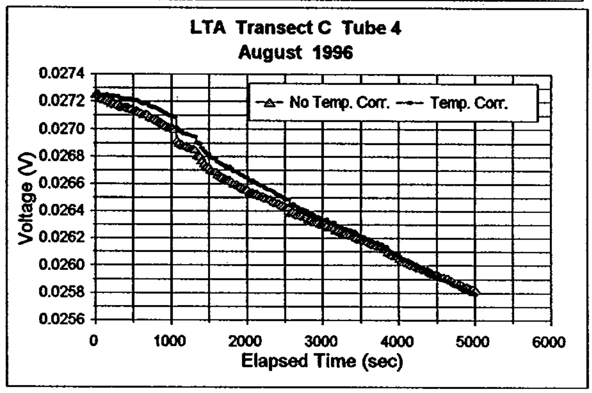

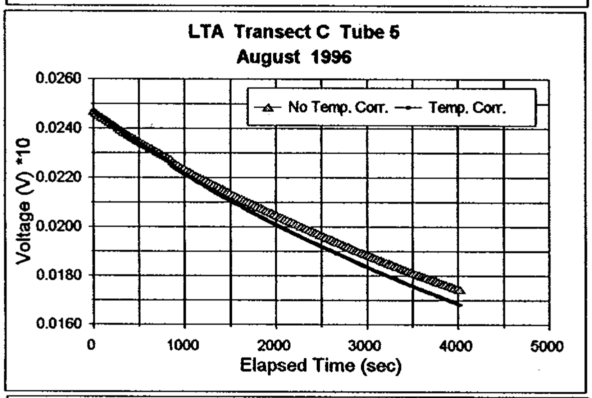

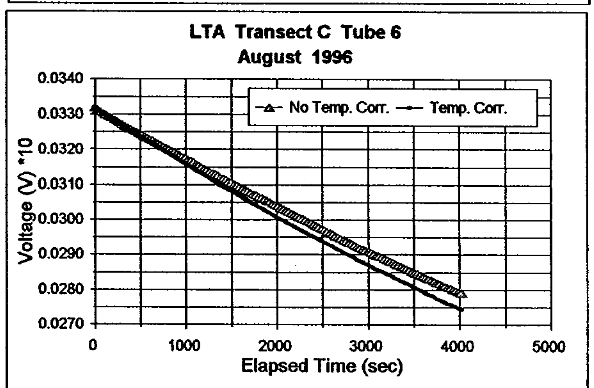

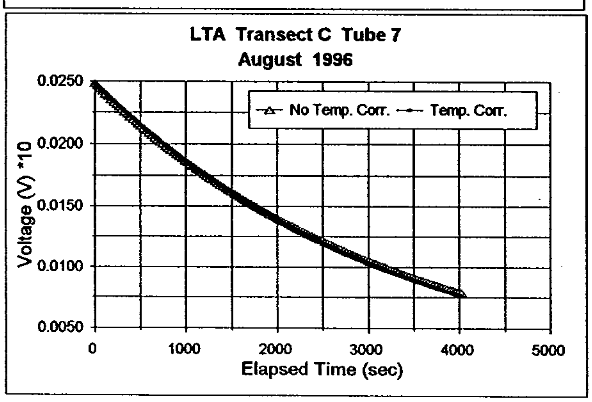

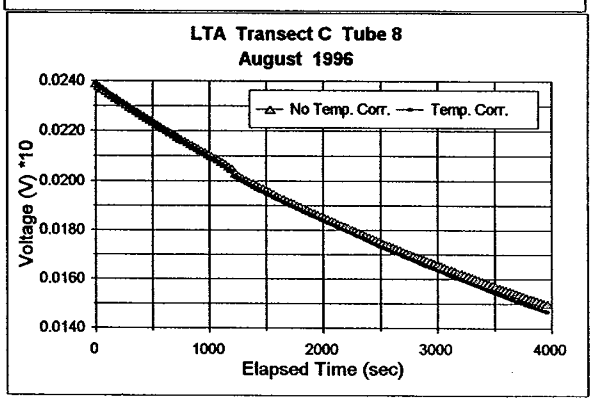

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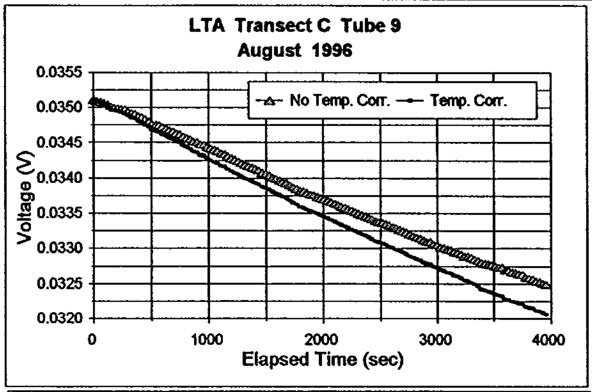
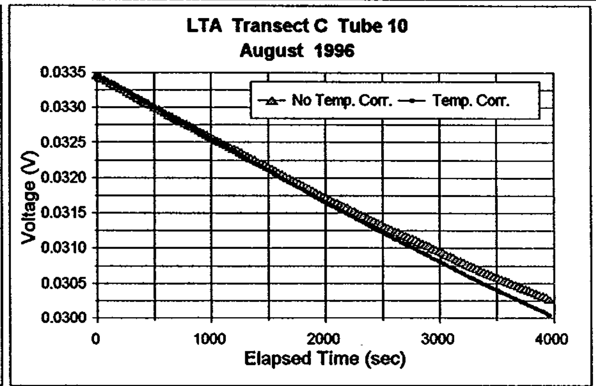
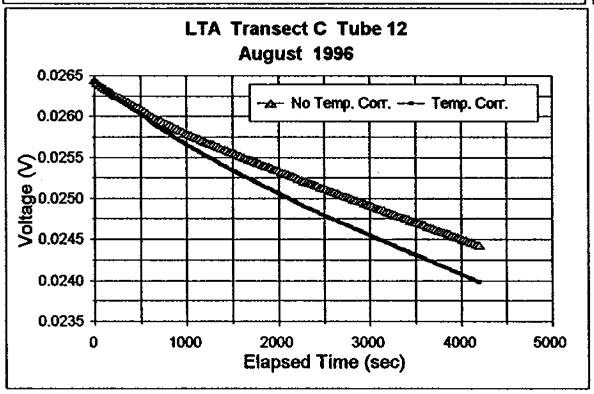
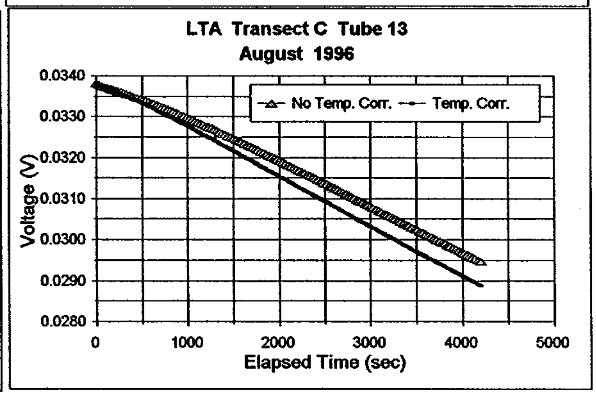
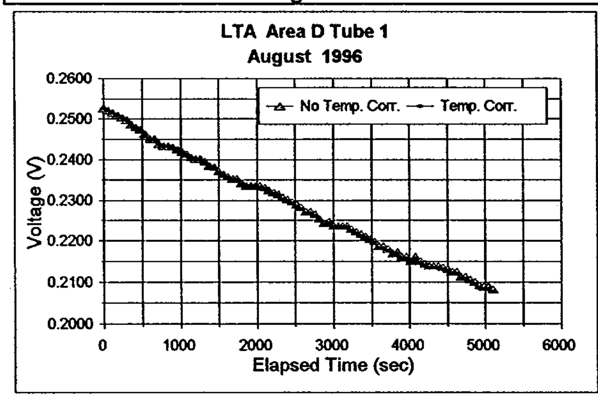


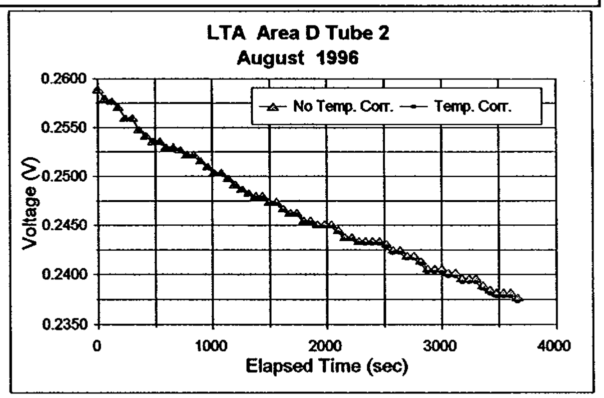






DONA LAKE. Area D August 1996





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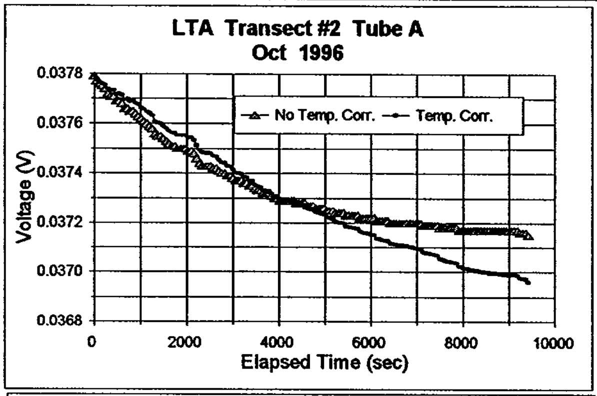
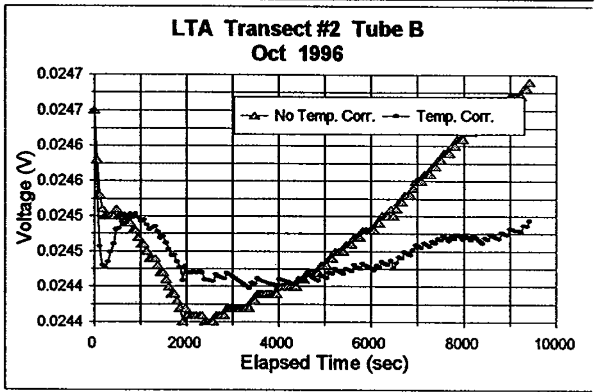
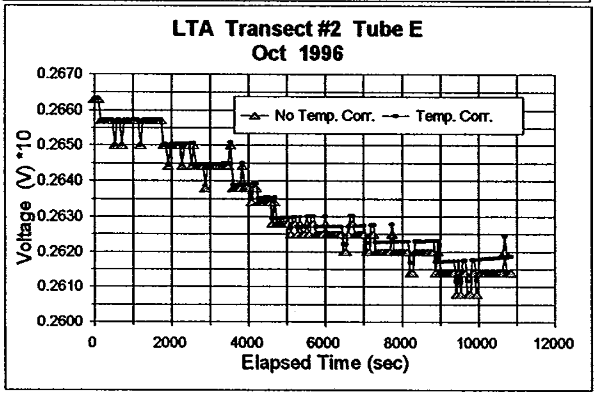
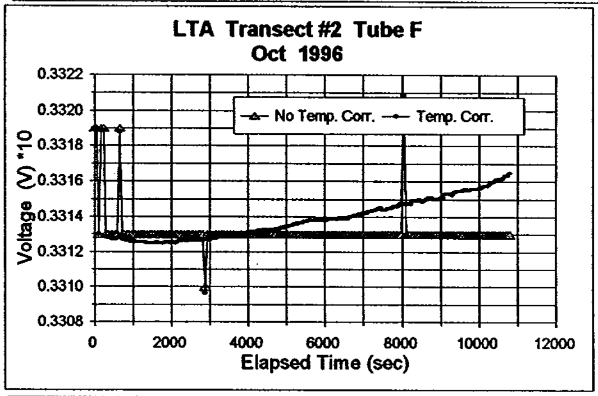
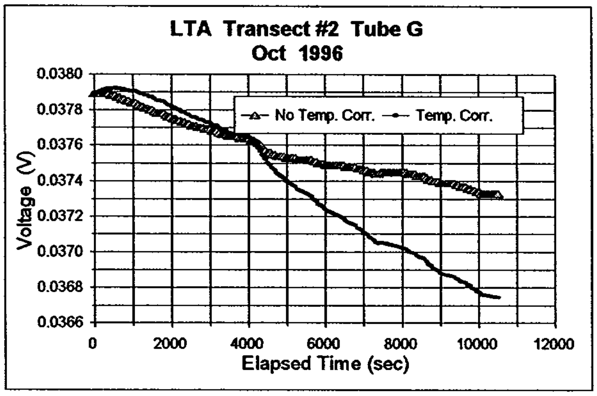
LTA site. Transect #2 October 1996

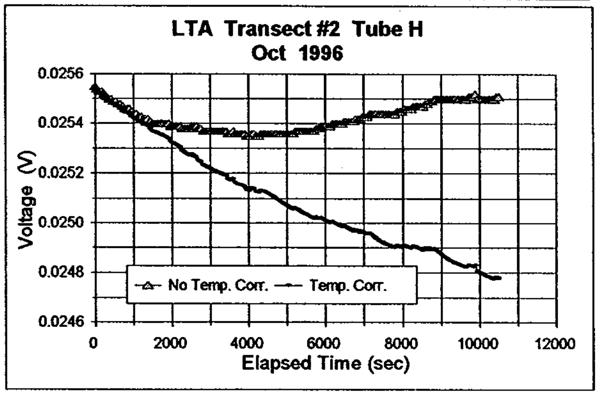




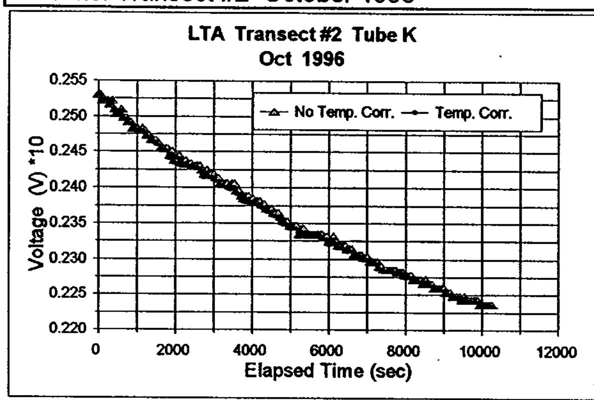


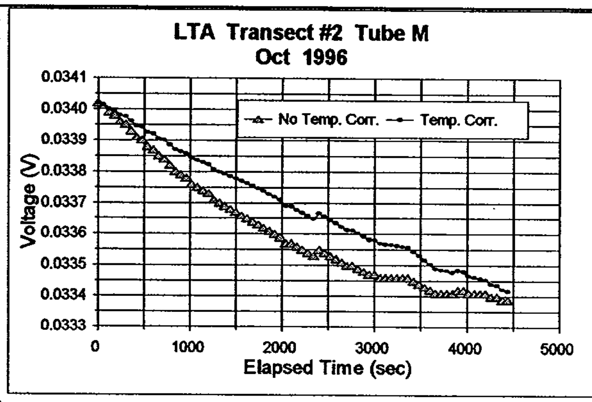


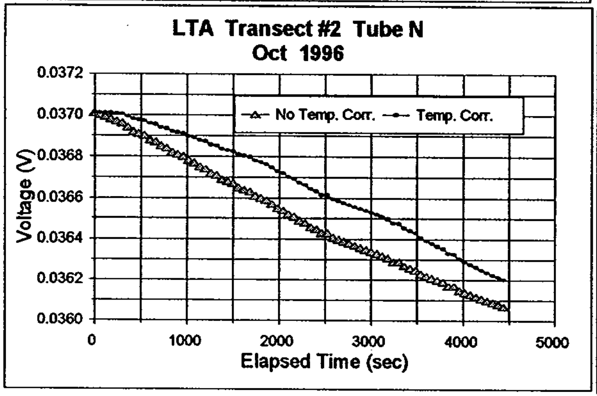


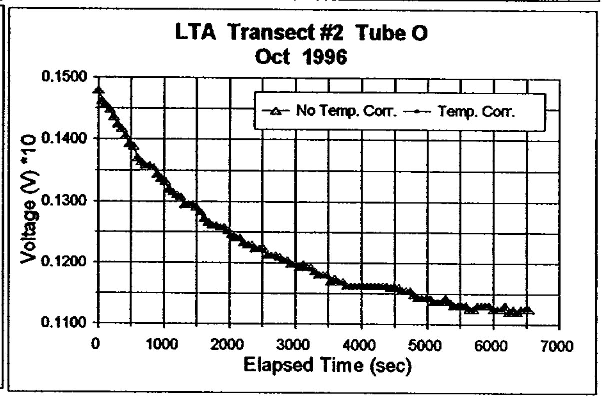


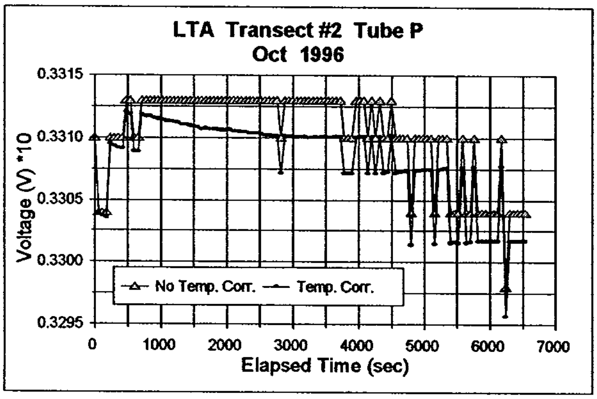
LTA site. Transect #2 October 1996











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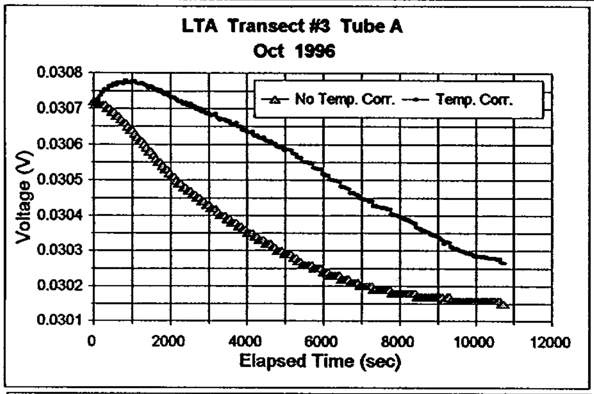

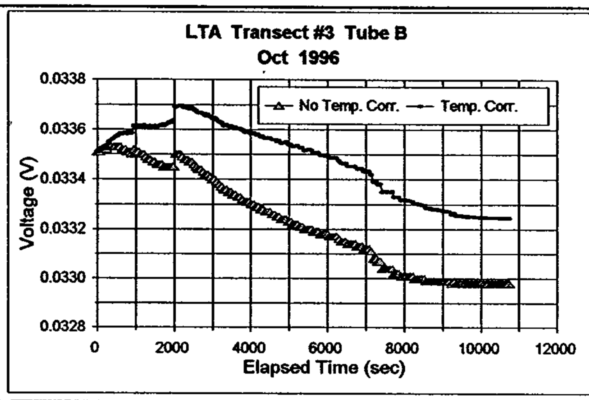

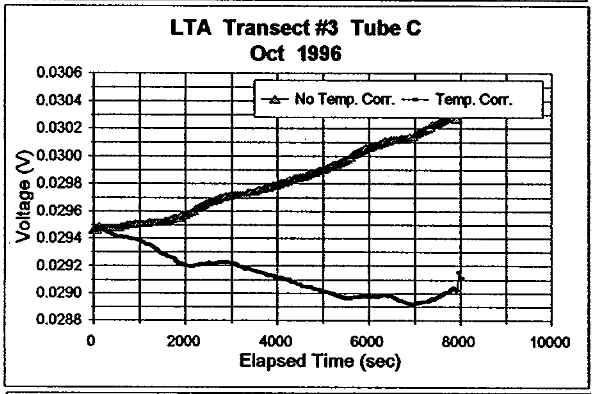

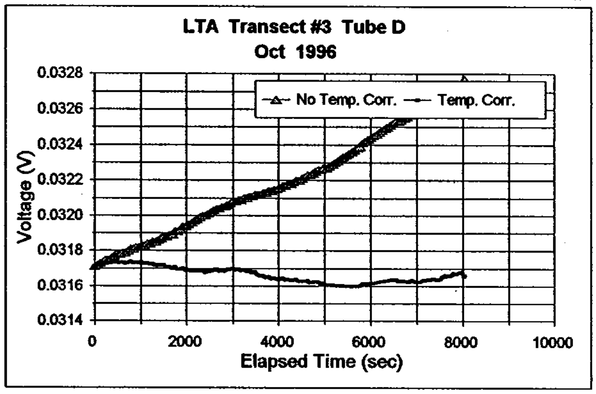

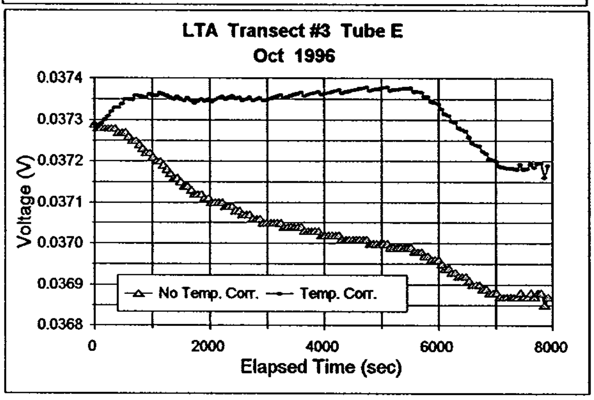

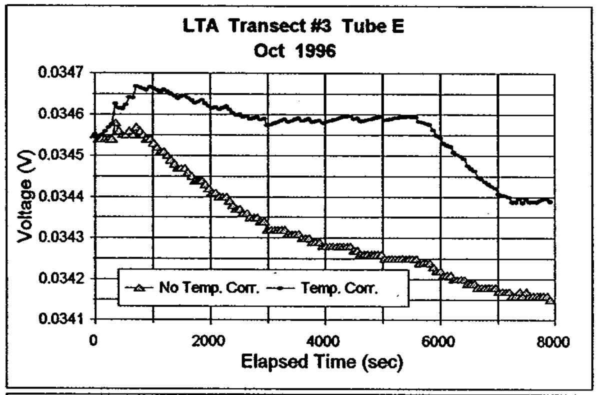

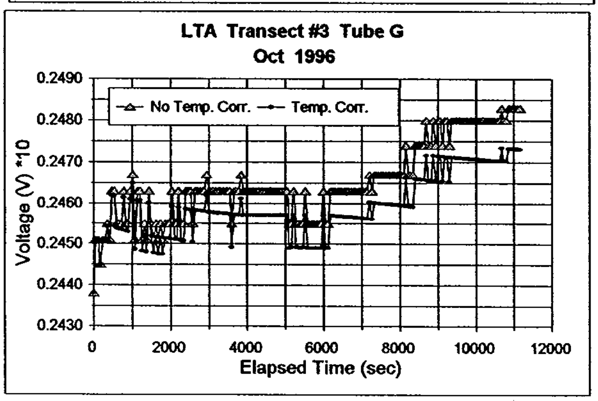

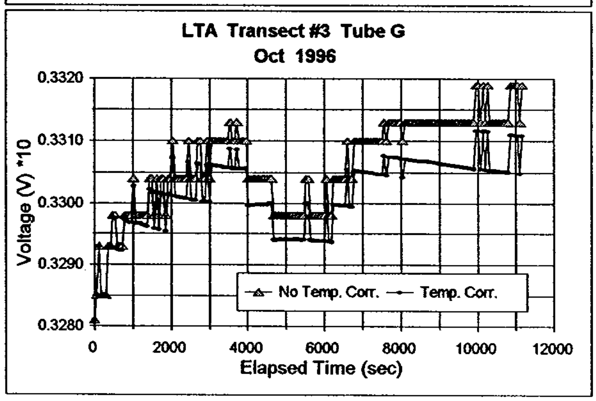

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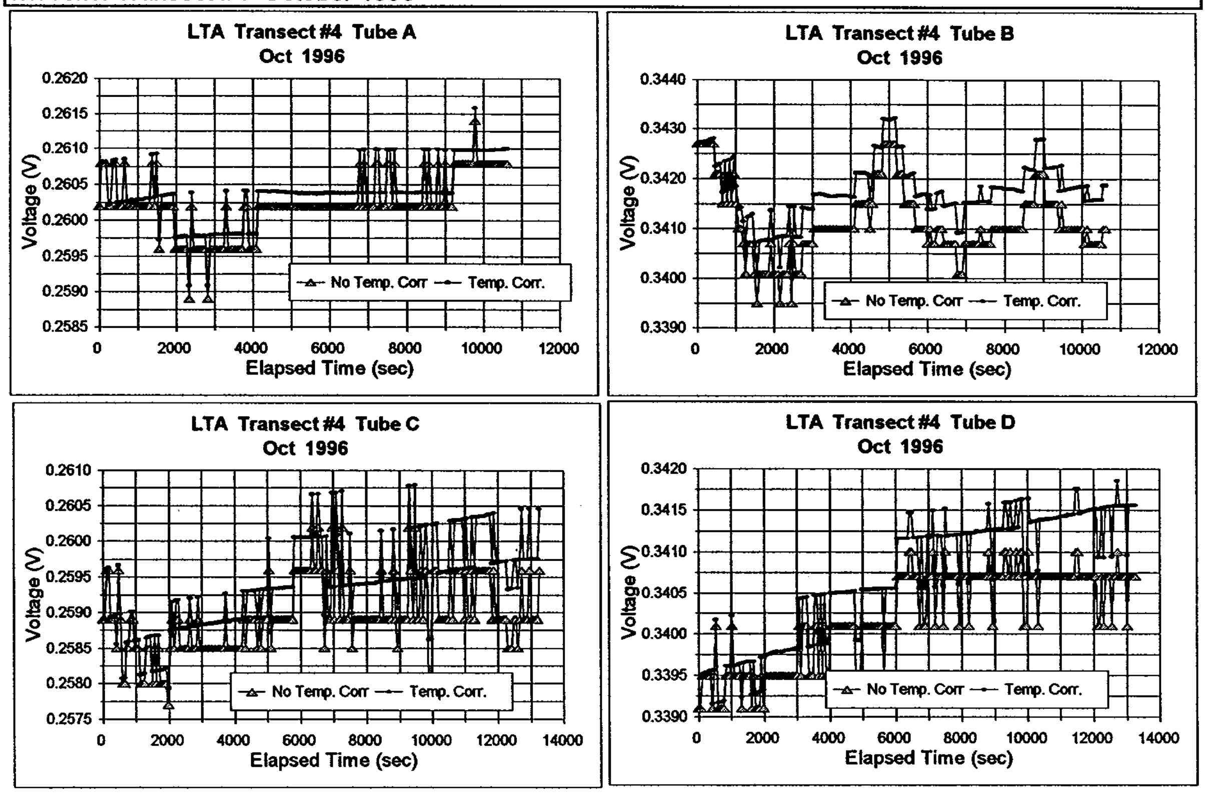

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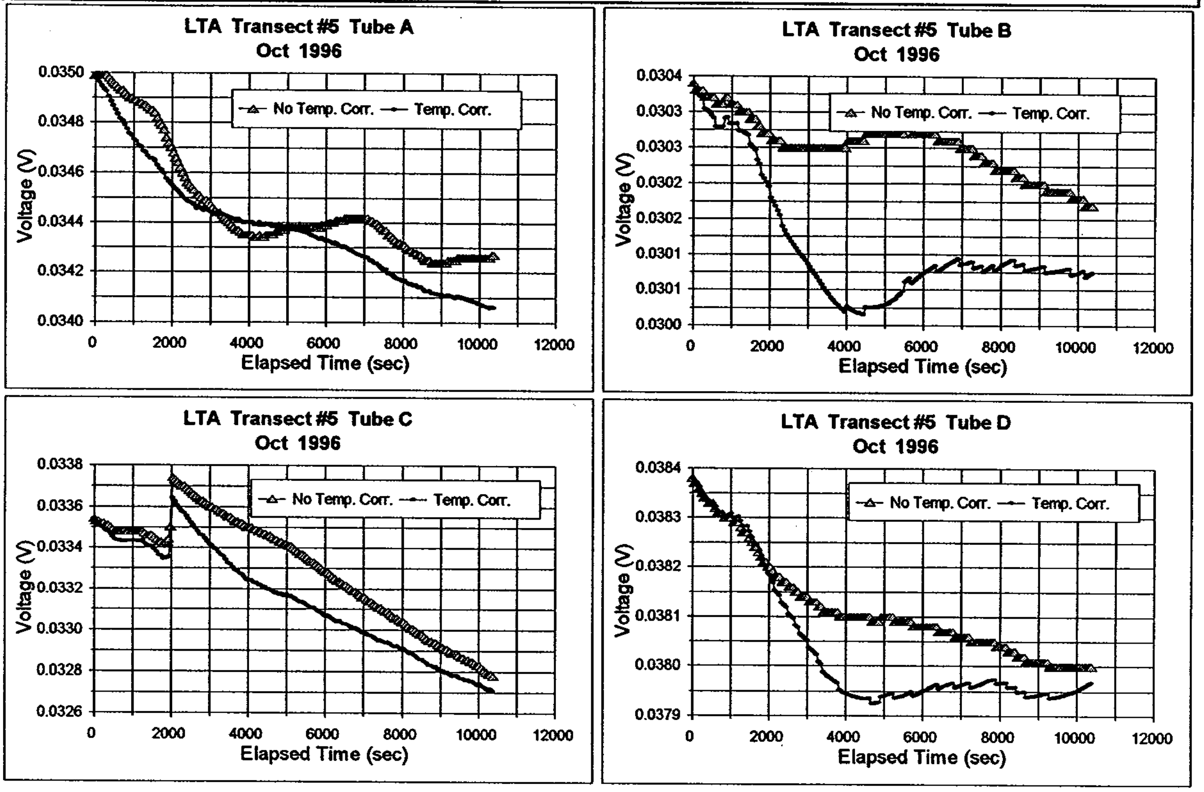

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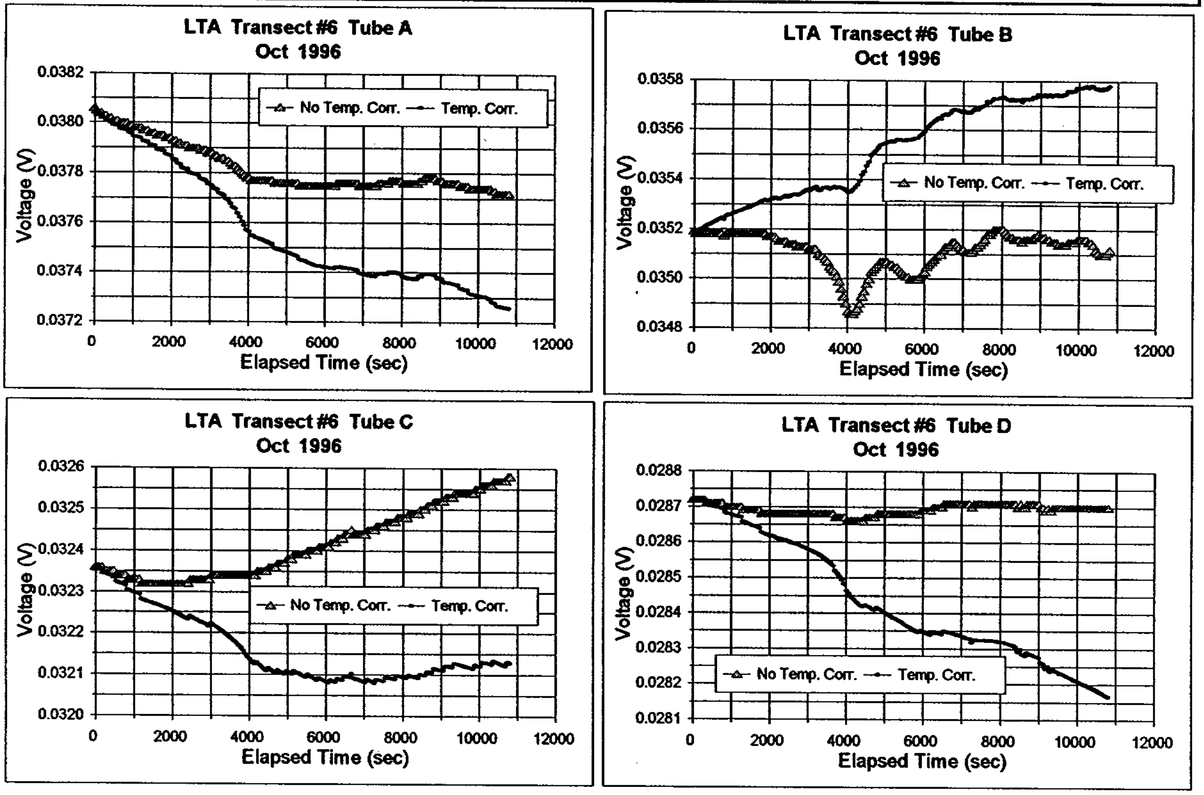

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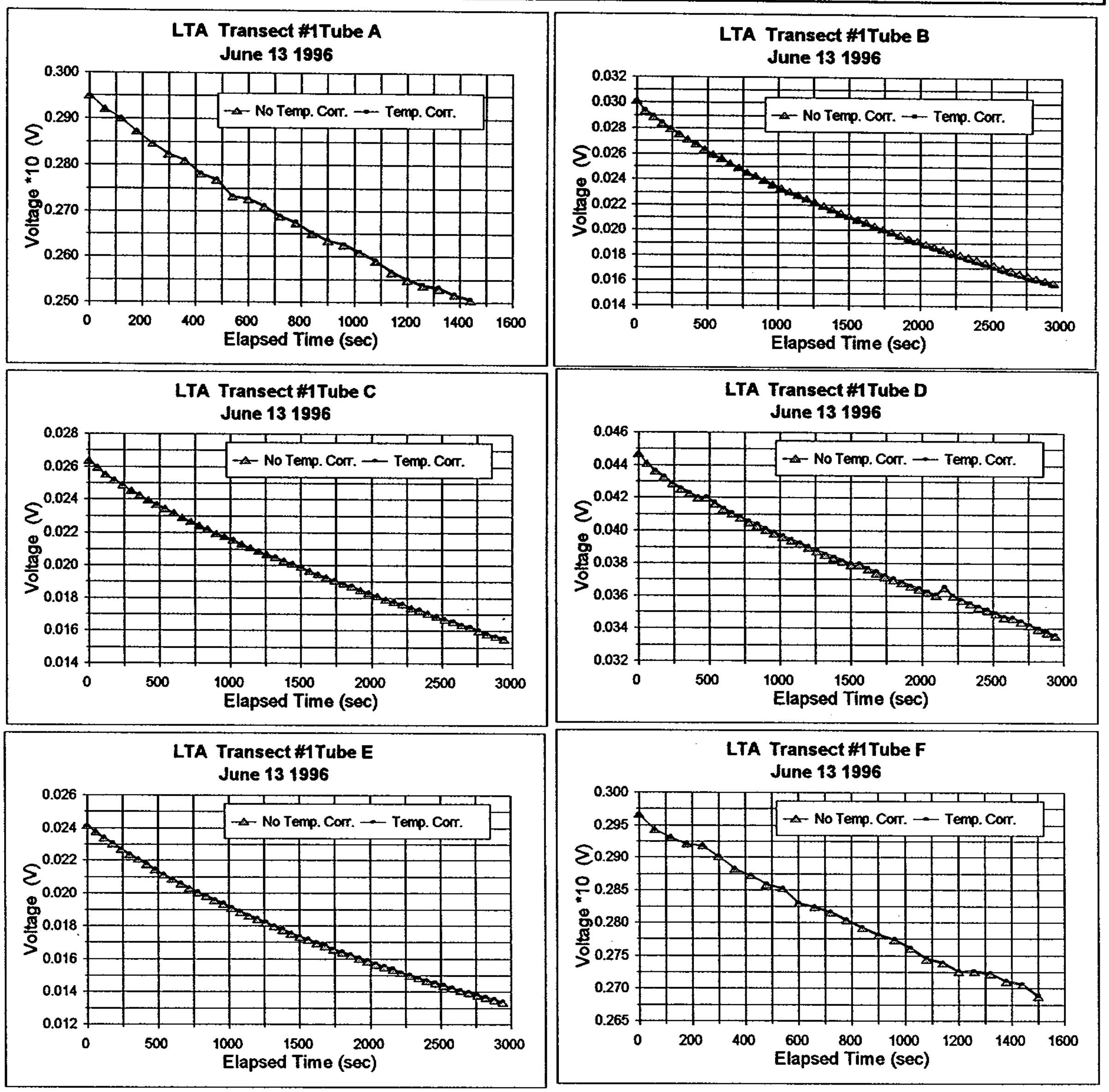

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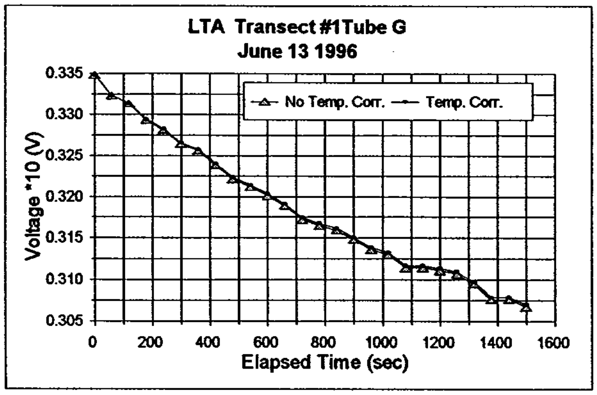

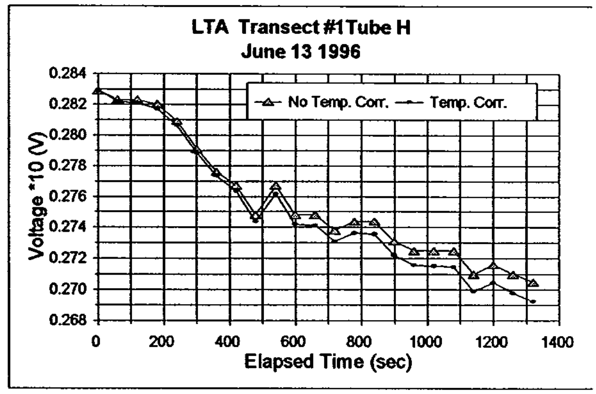

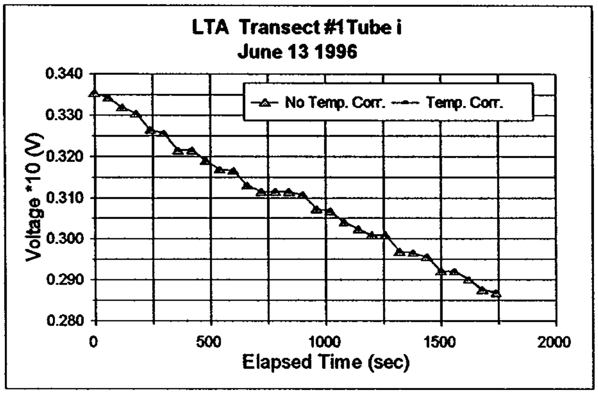

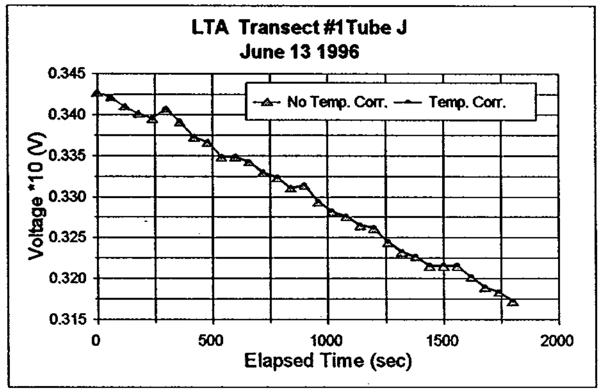

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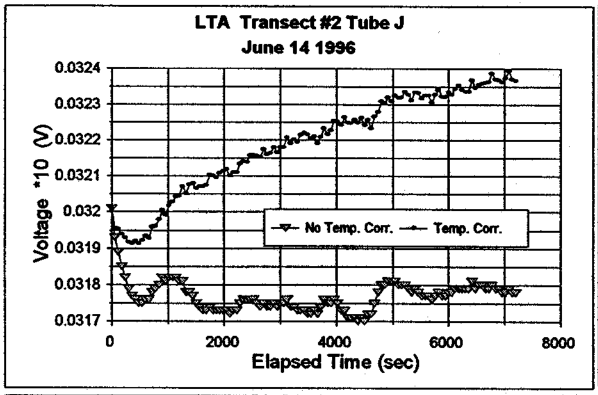

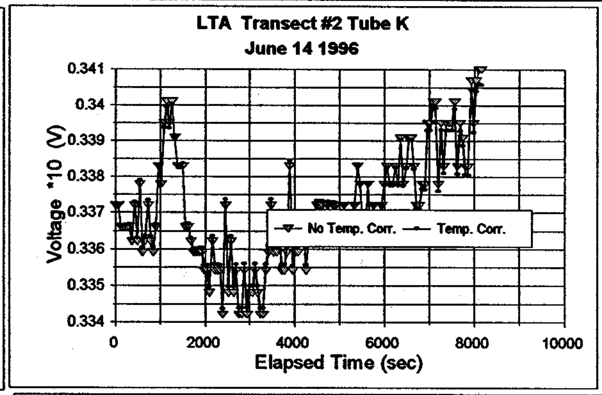

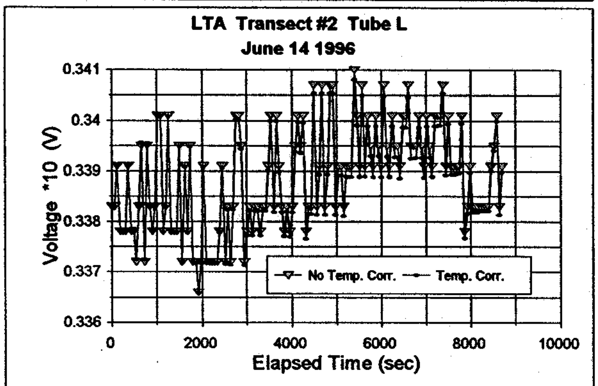

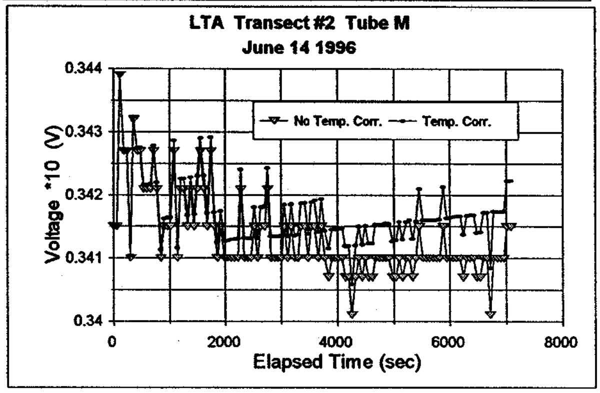

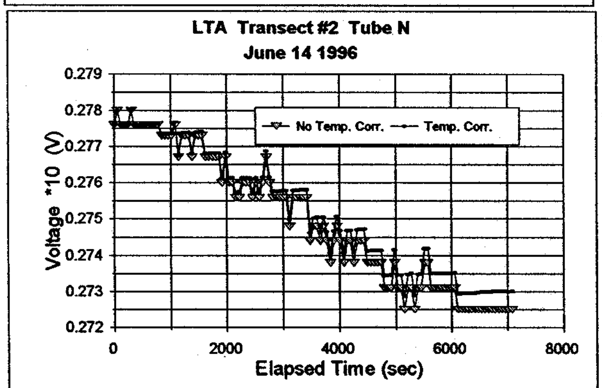

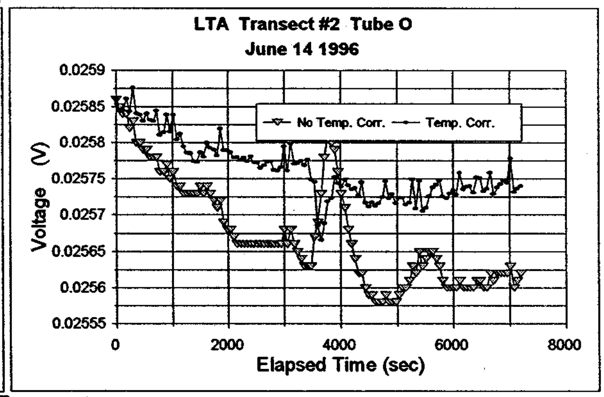

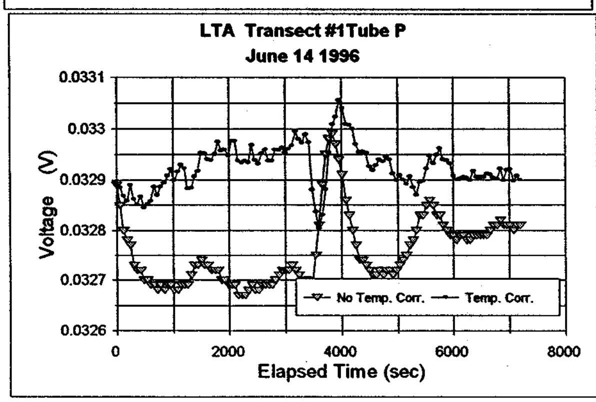

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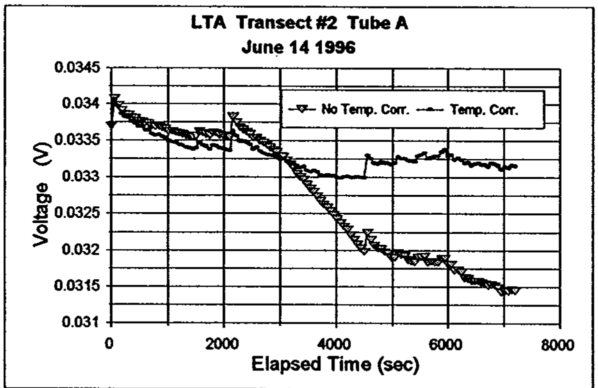
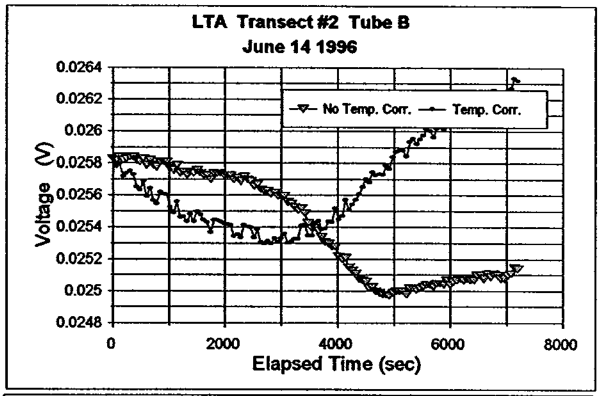
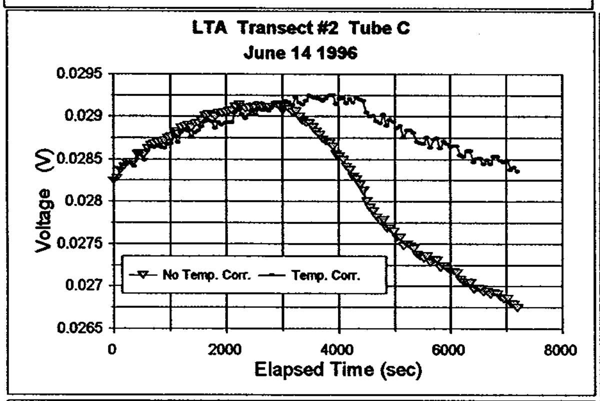
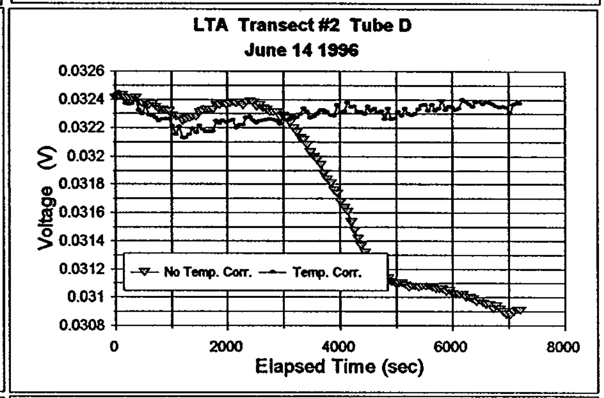
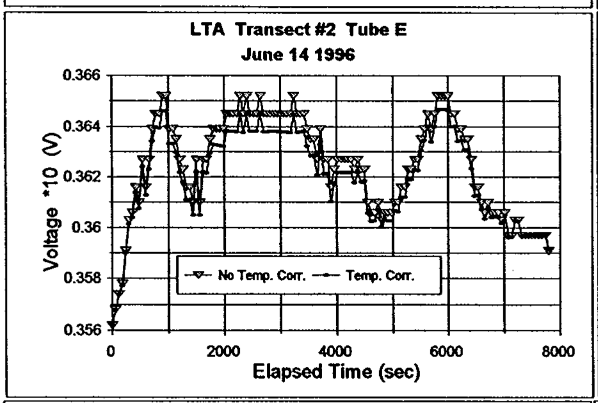
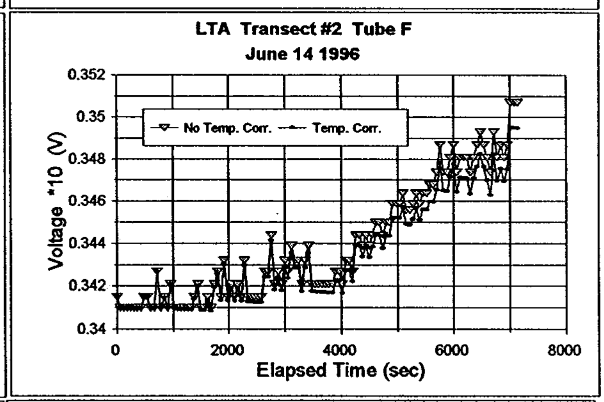


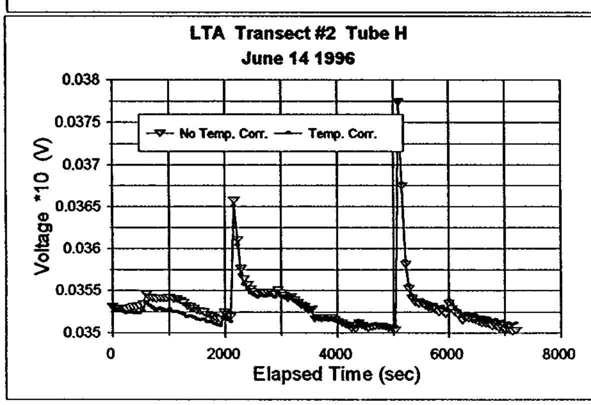


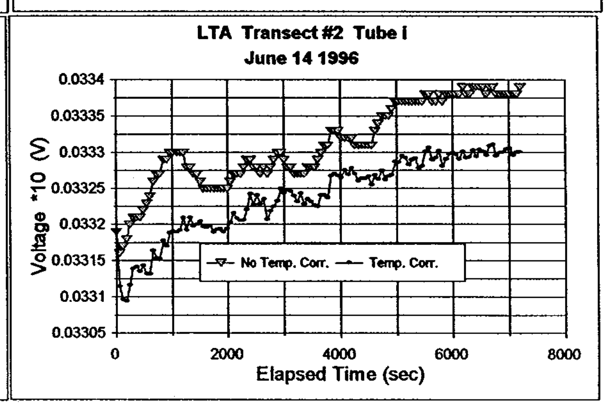




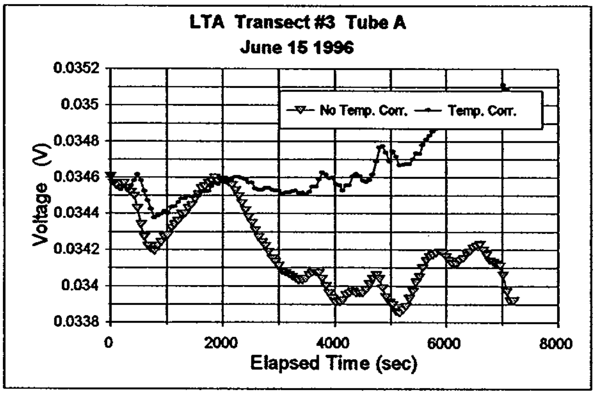


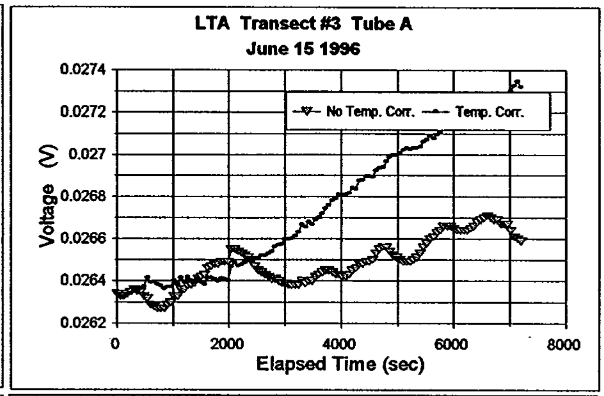


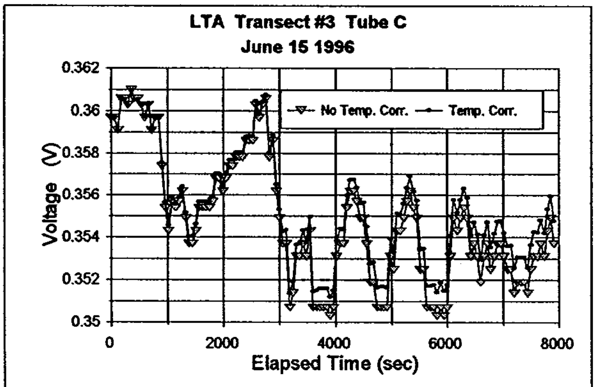


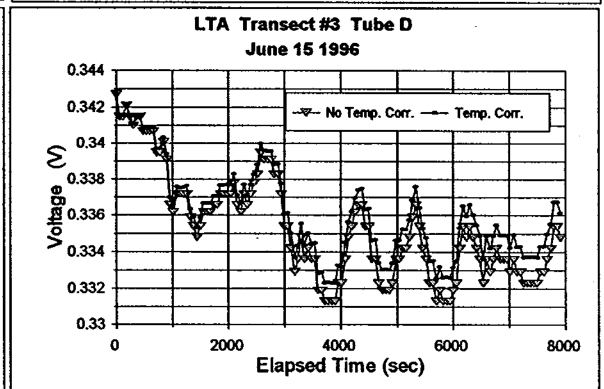


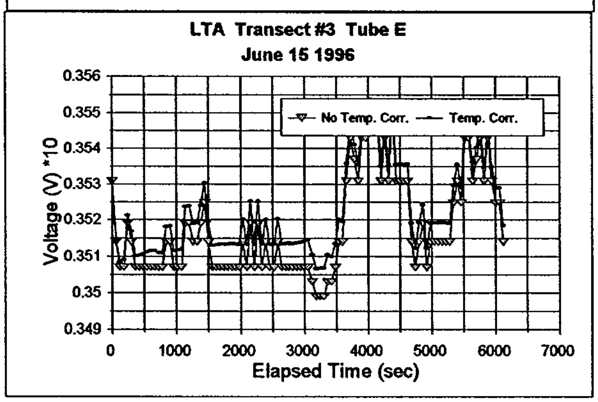
LTA site. Transect #3 June 1996

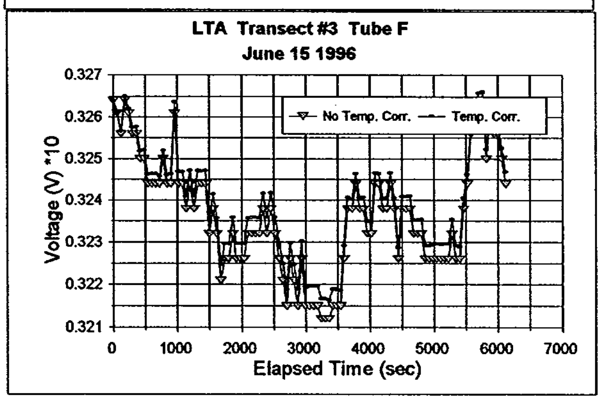


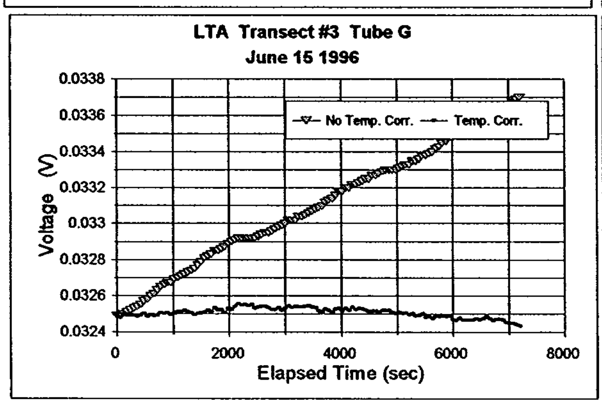


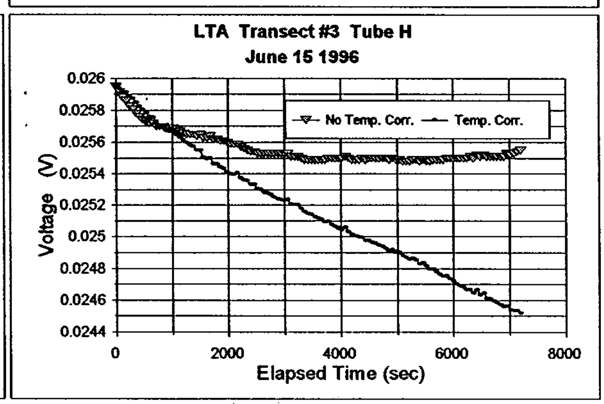












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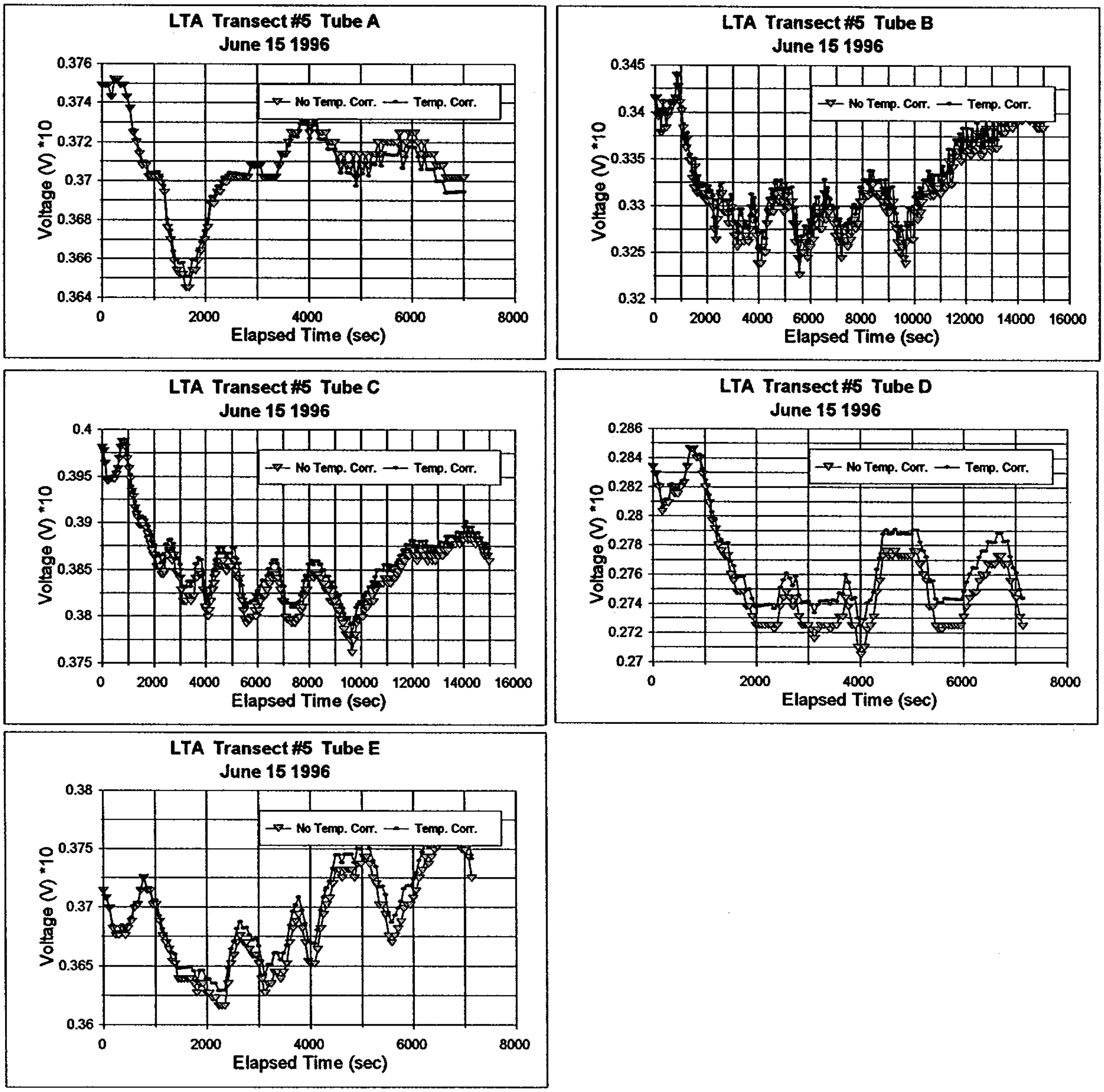

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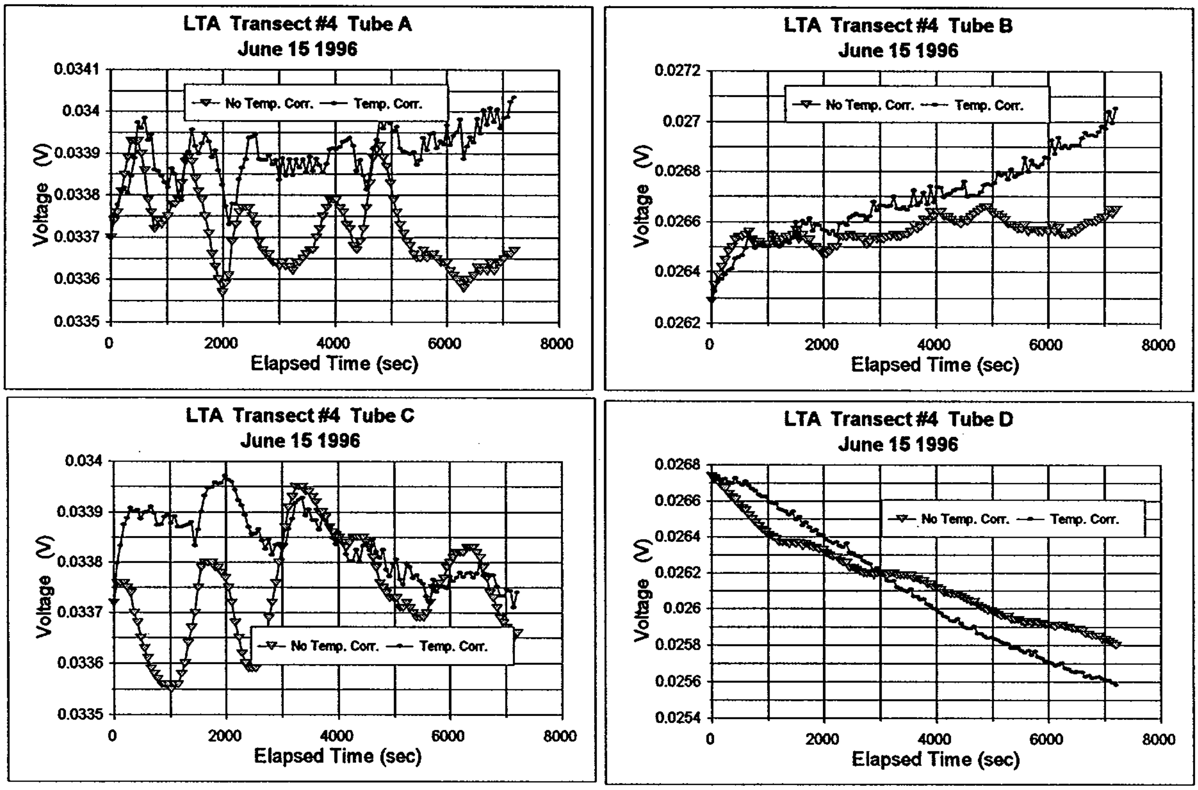

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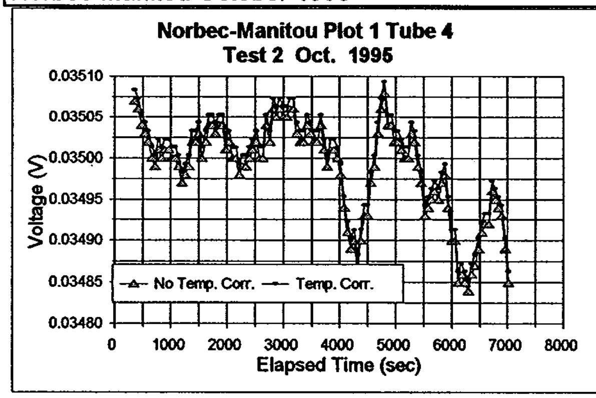

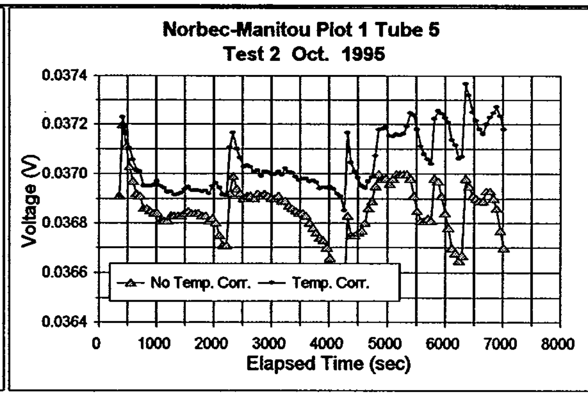

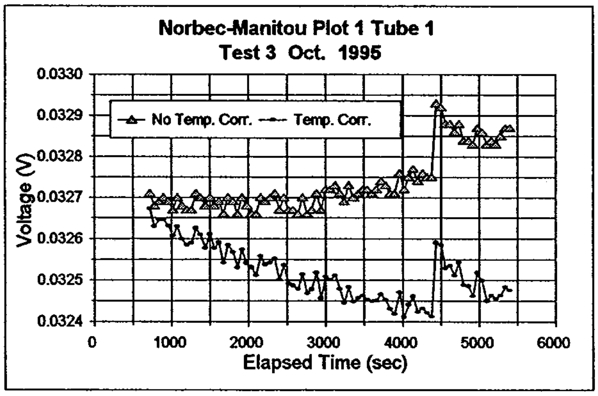

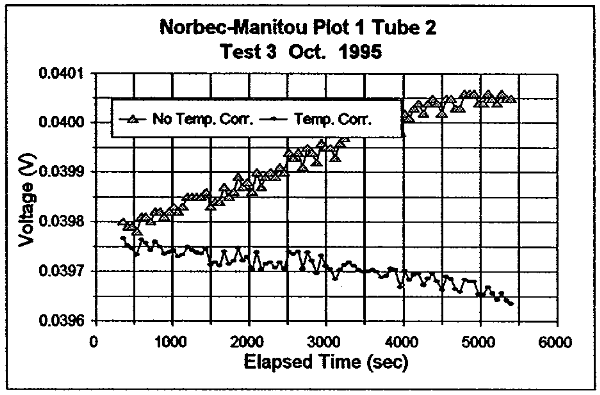

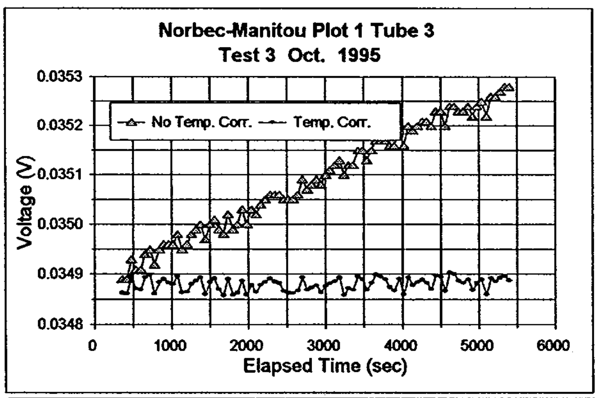

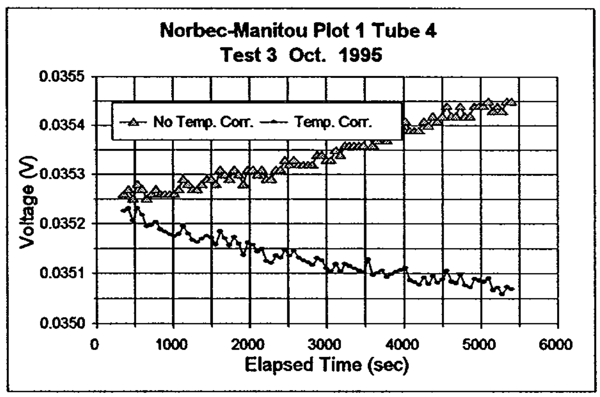

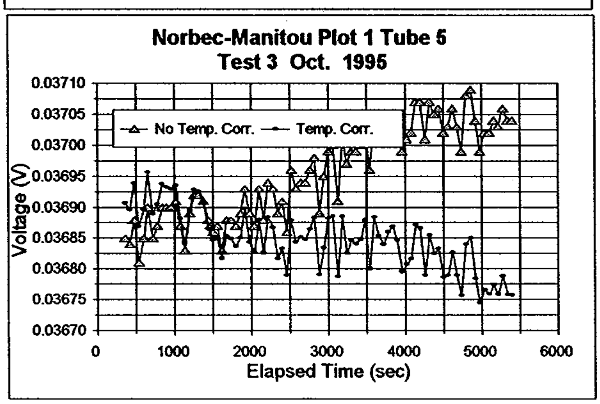

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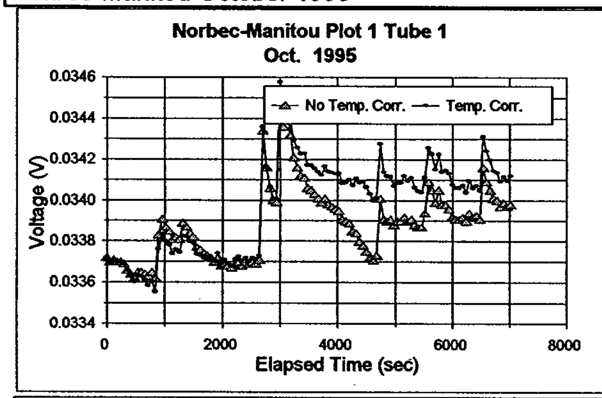

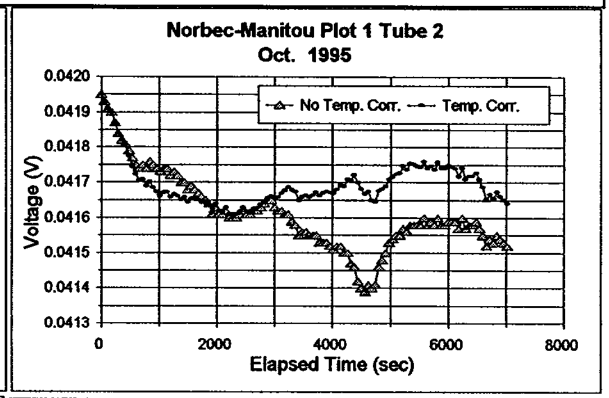

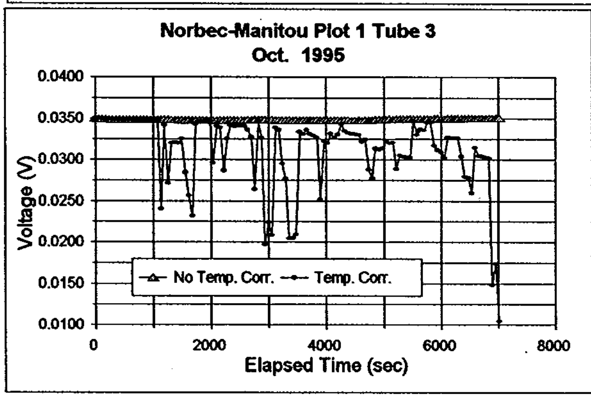

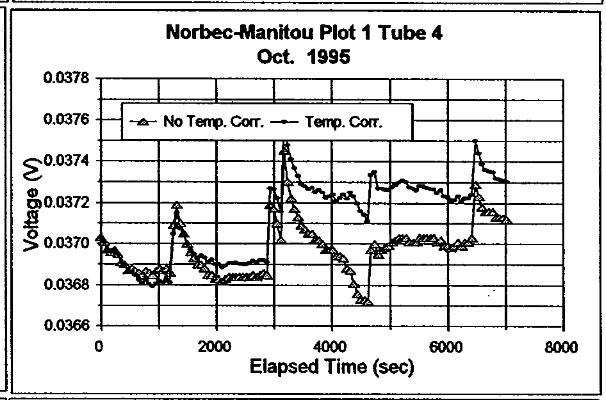

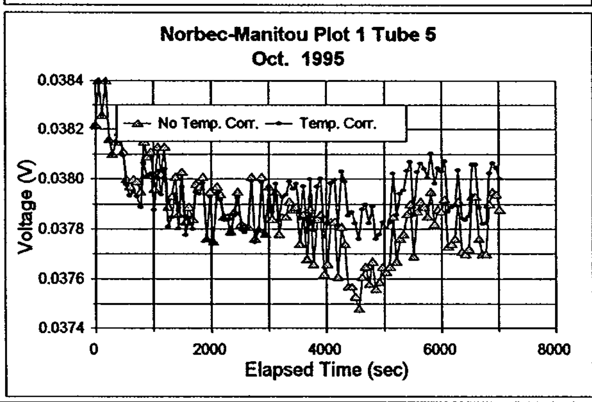

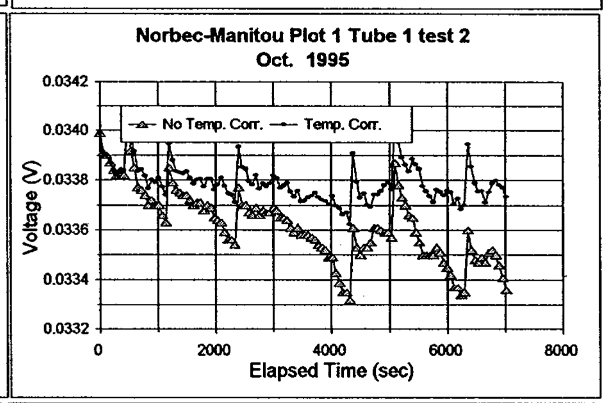

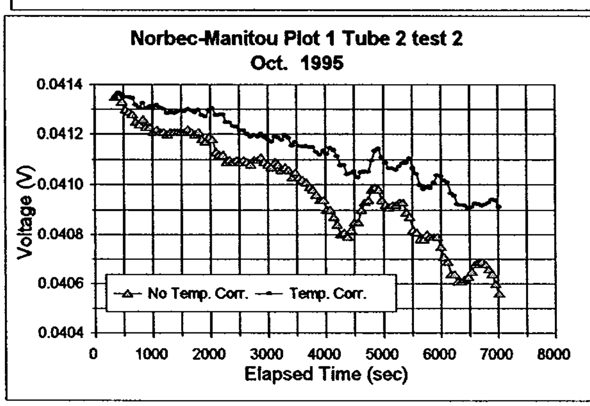

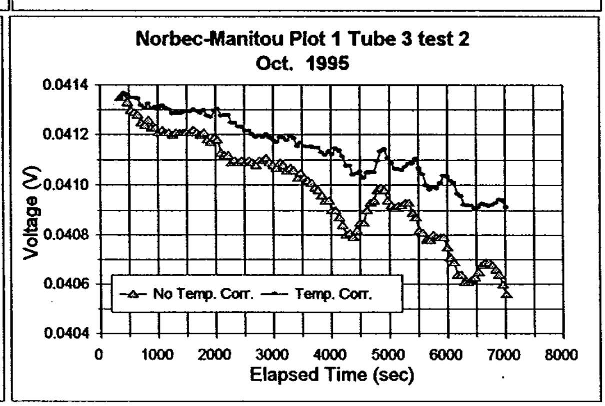

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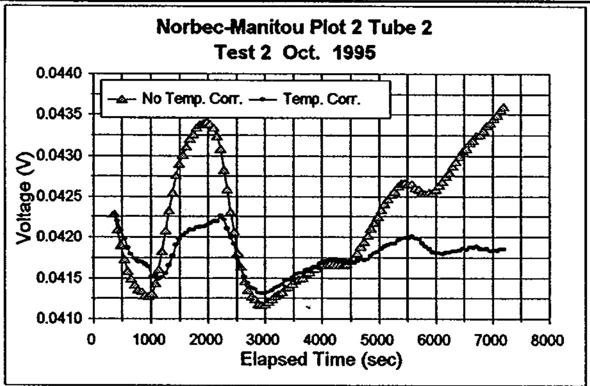

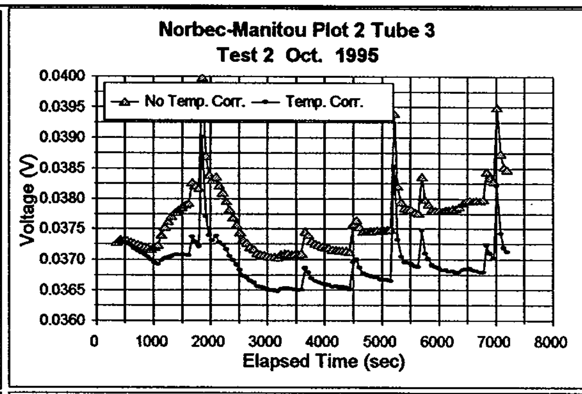

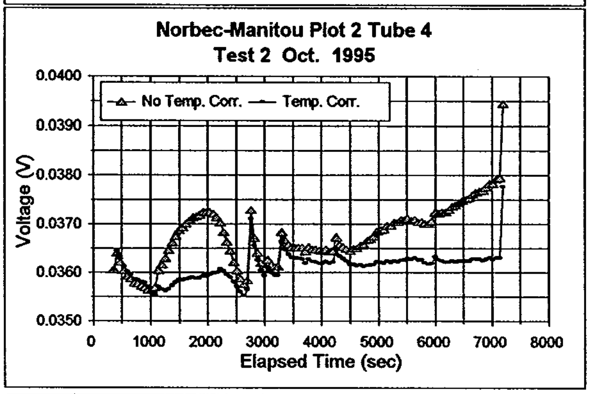

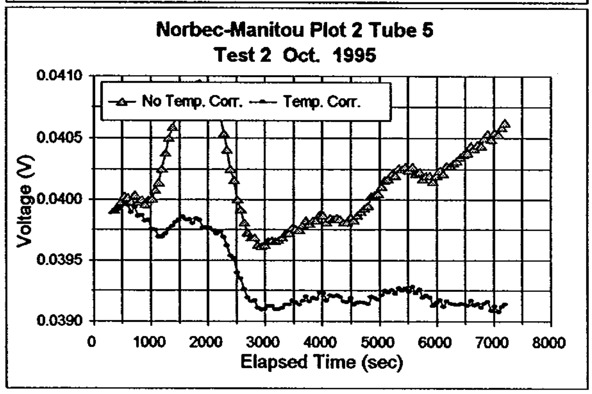

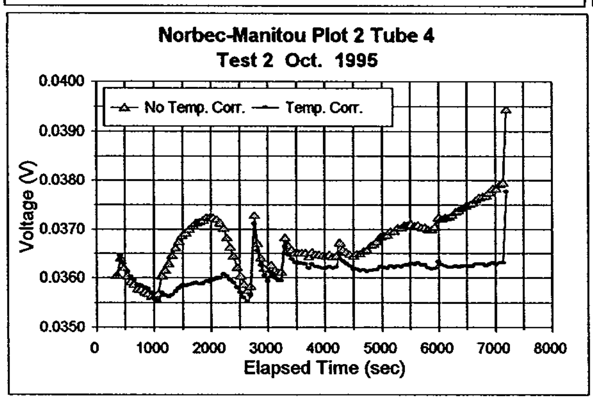

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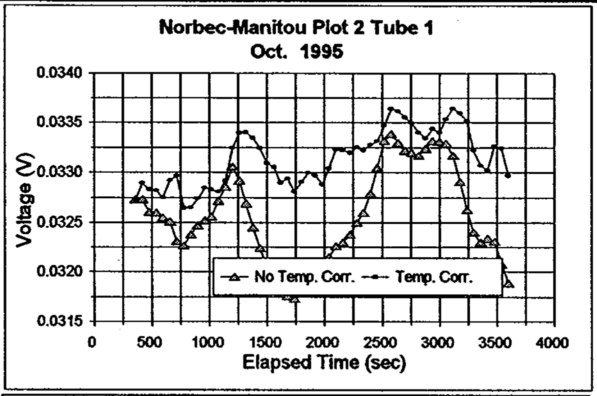

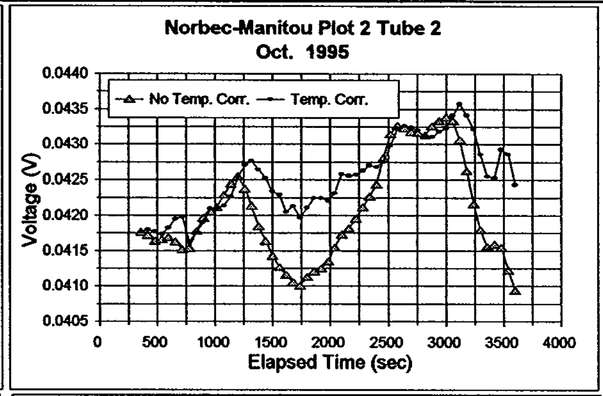

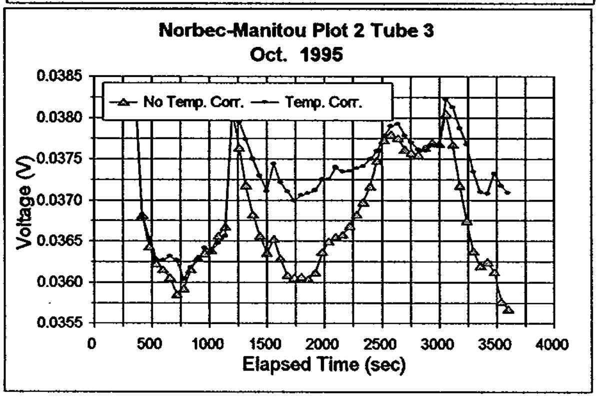

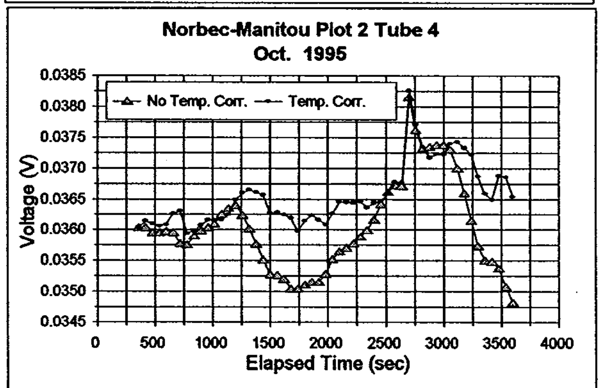

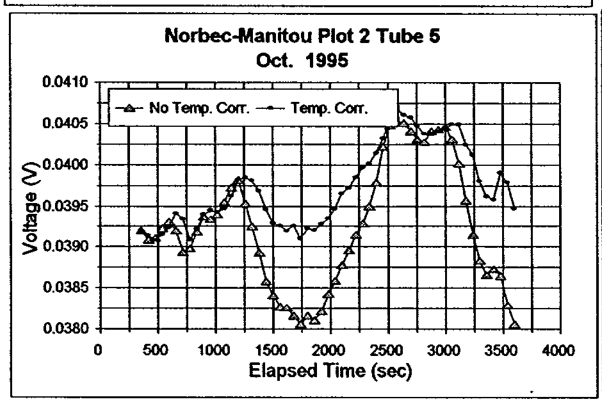

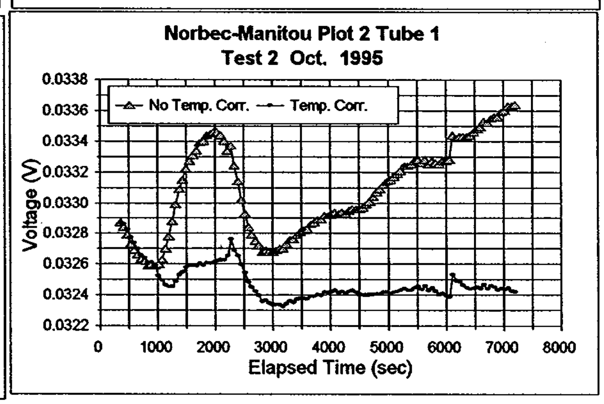

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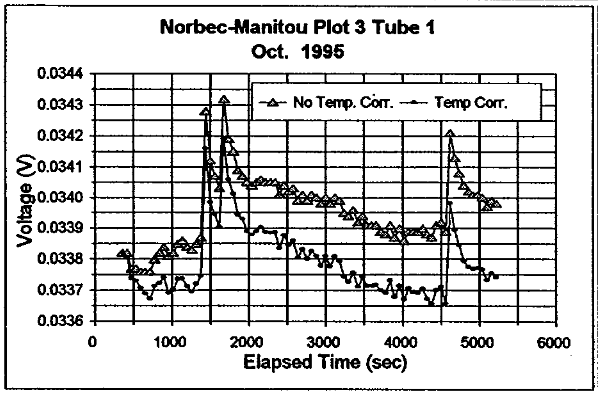

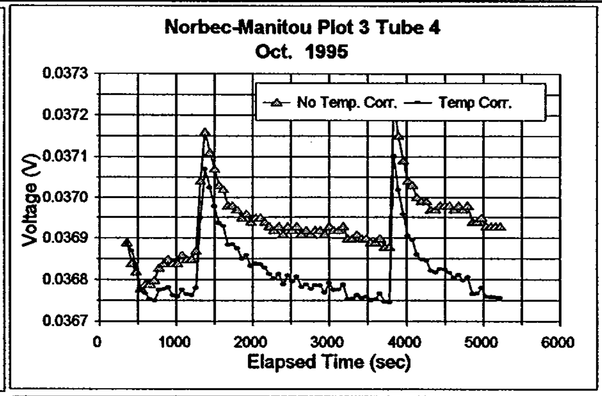

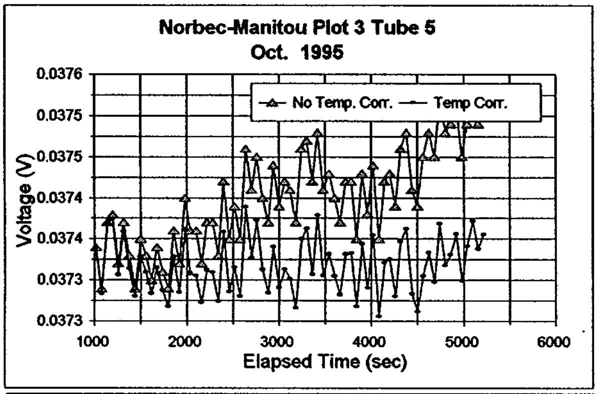

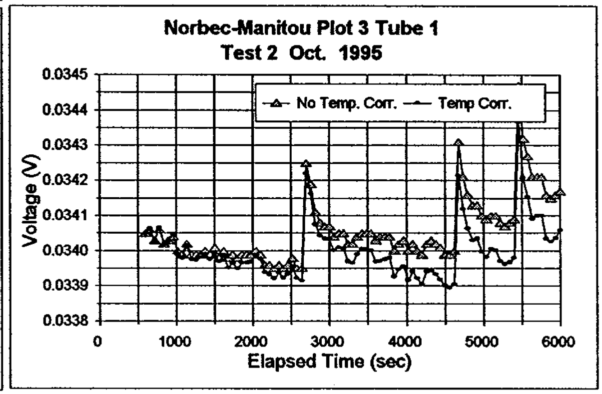

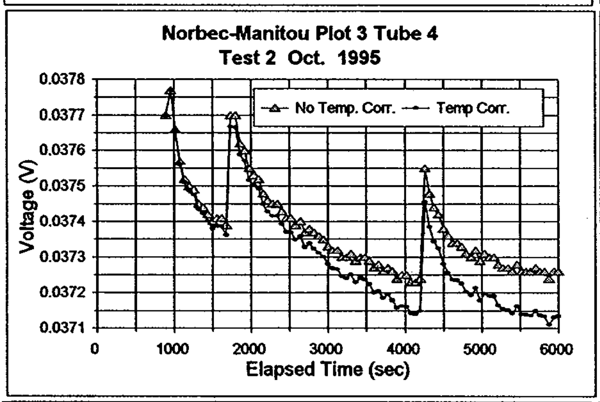

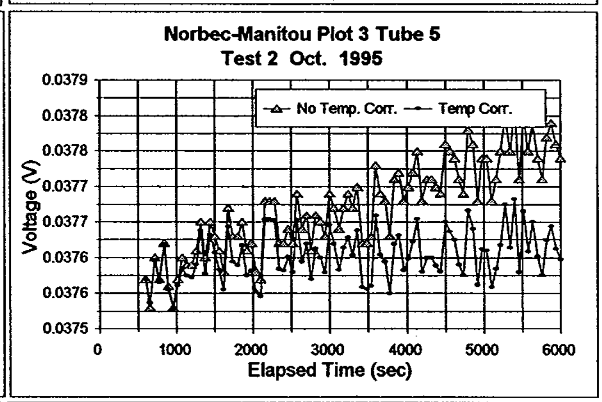

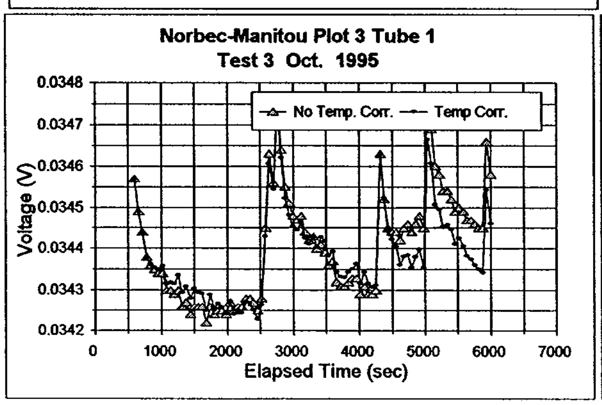

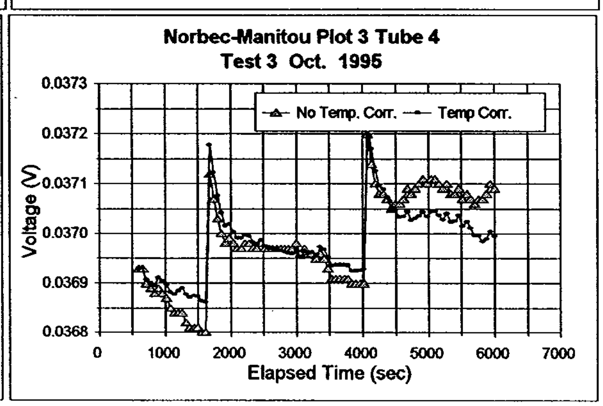

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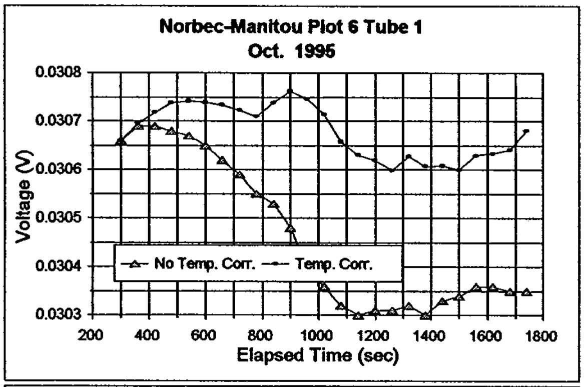
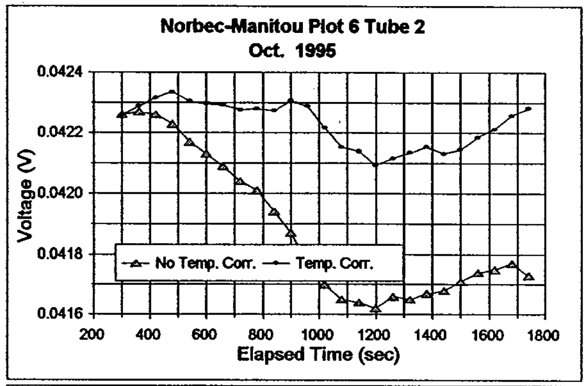
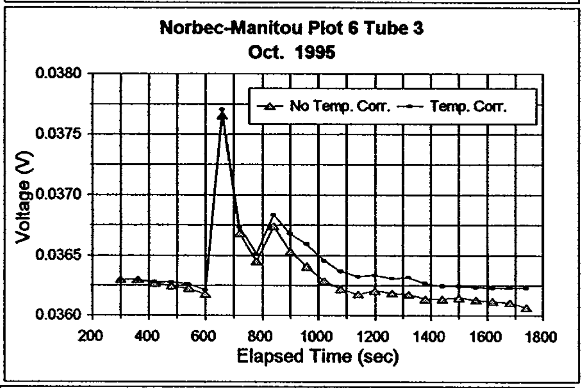
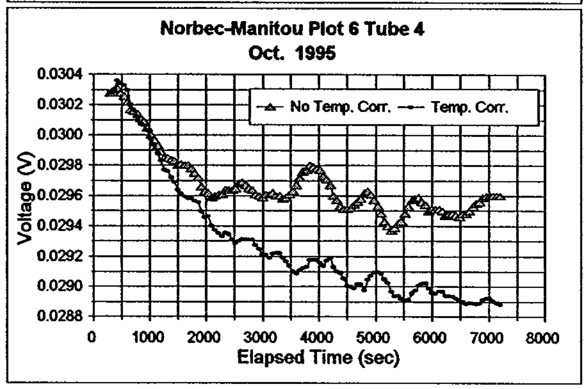
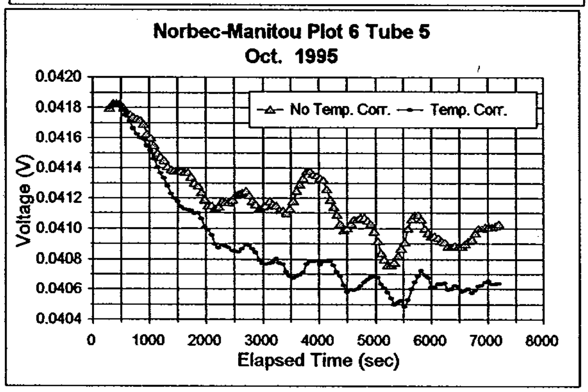
Norbec-Manitou Control Plot - Exposed Tailings. October 1995



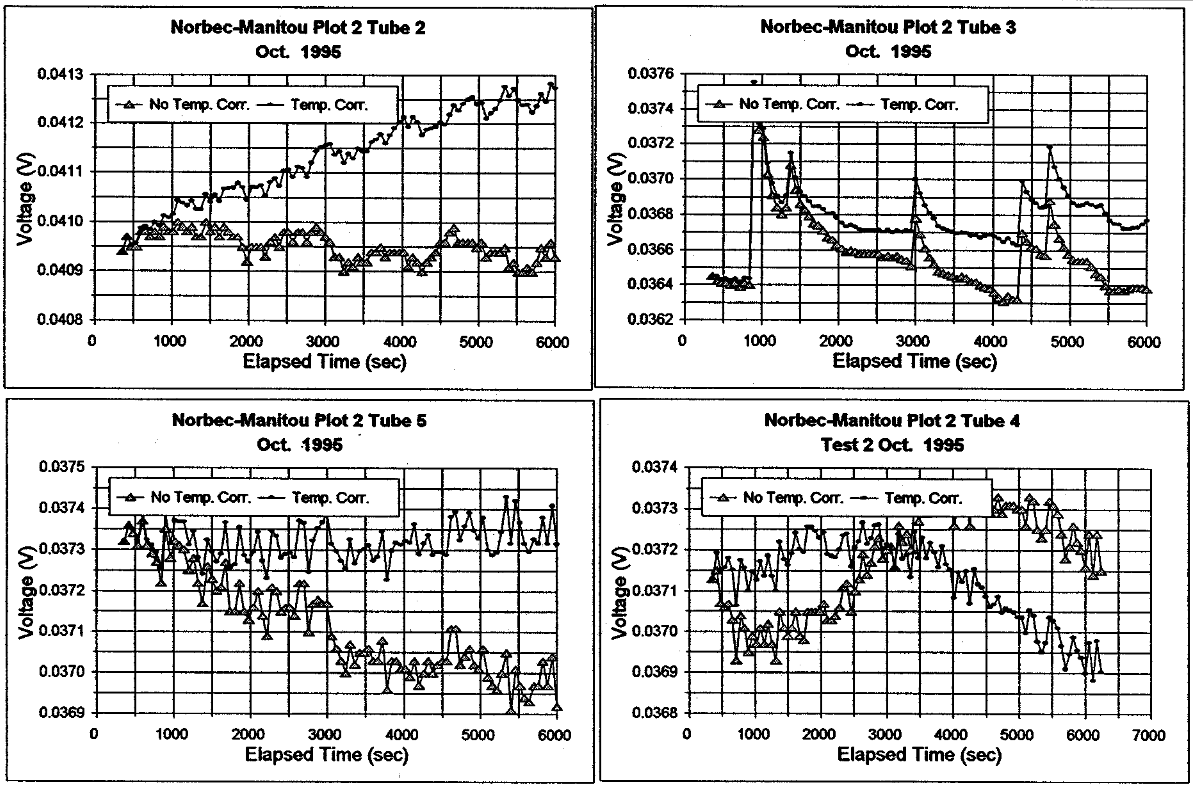




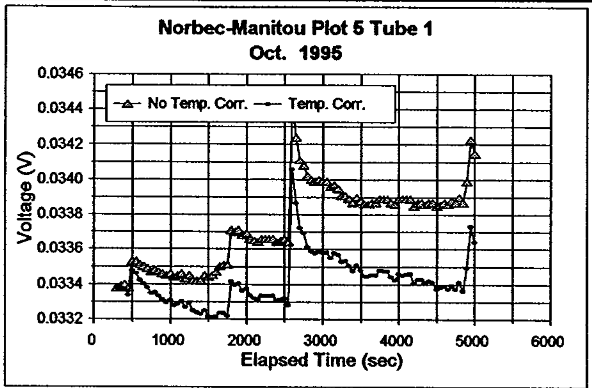


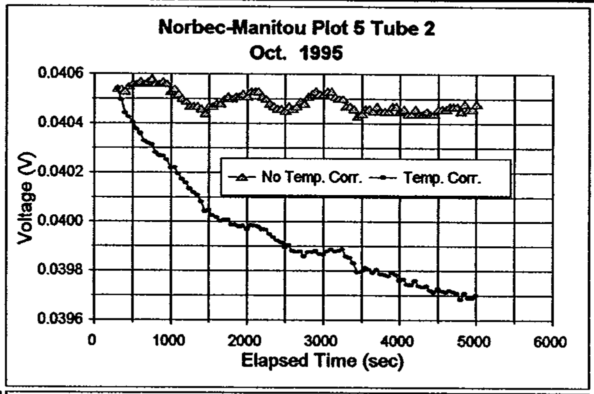


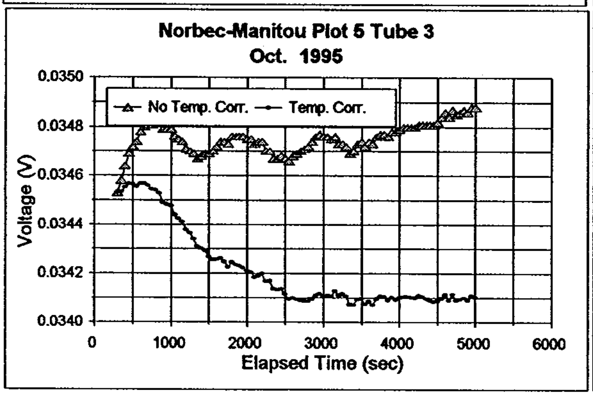
Norbec-Manitou Plot 4. October 1995

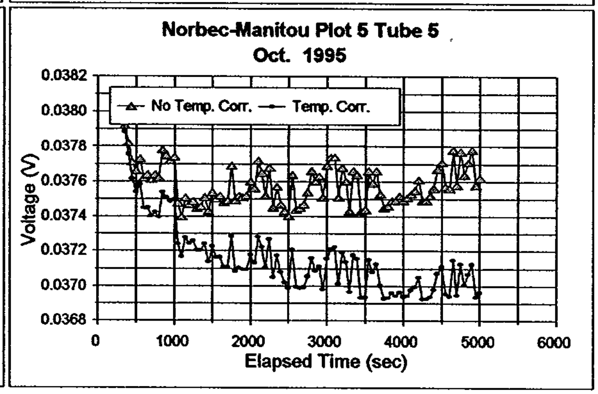


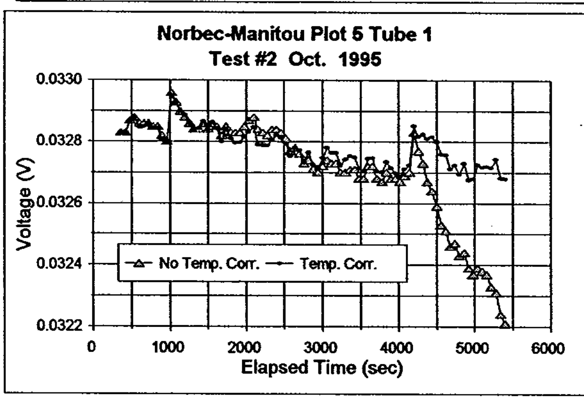
Norbec-Manitou October 1995

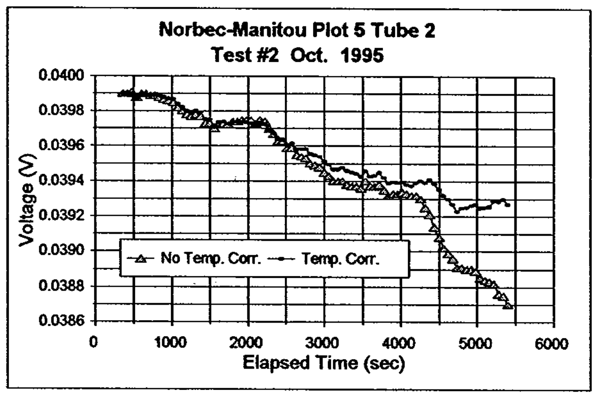




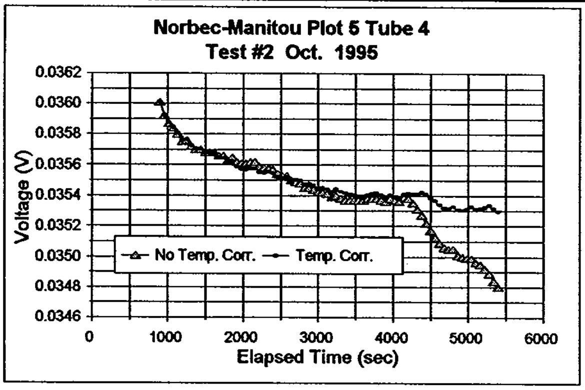


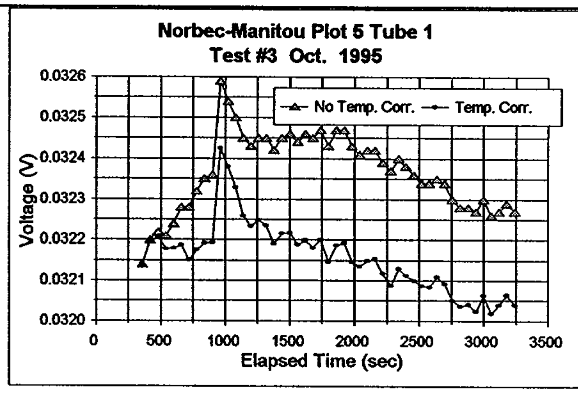


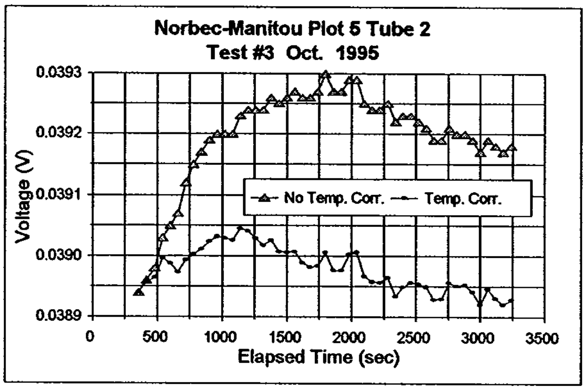


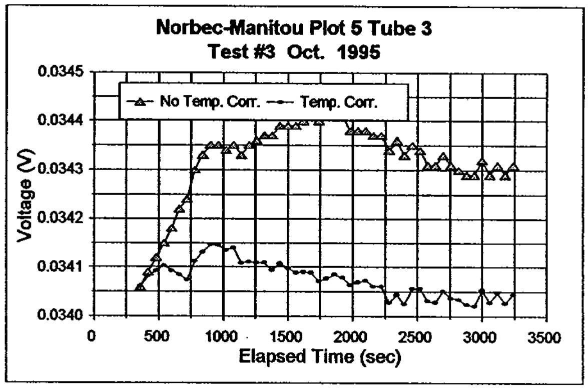


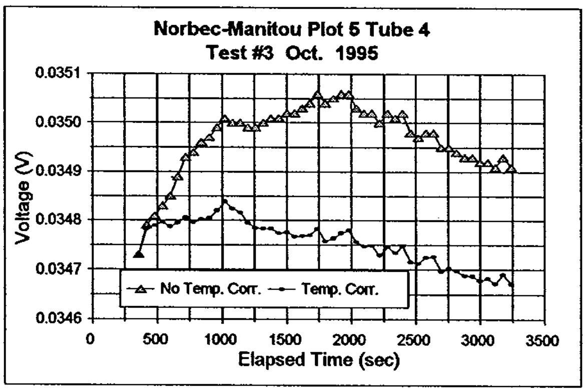
Norbec-Manitou October 1995



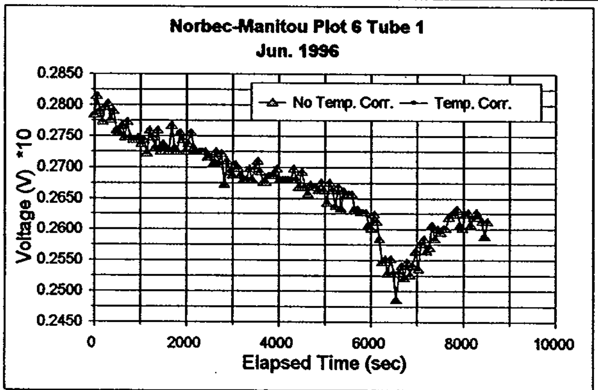


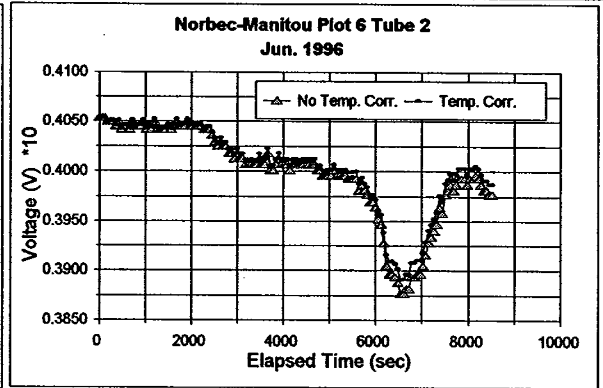


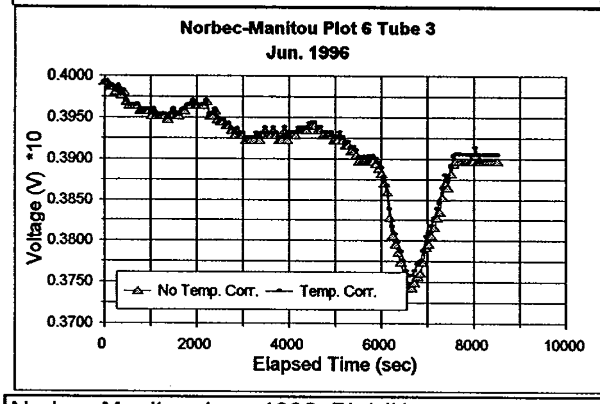


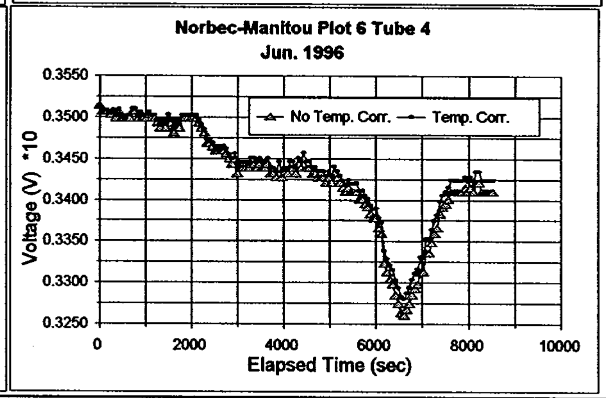


Norbec-Manitou June 1996. Plot #6 Non-covered tailings

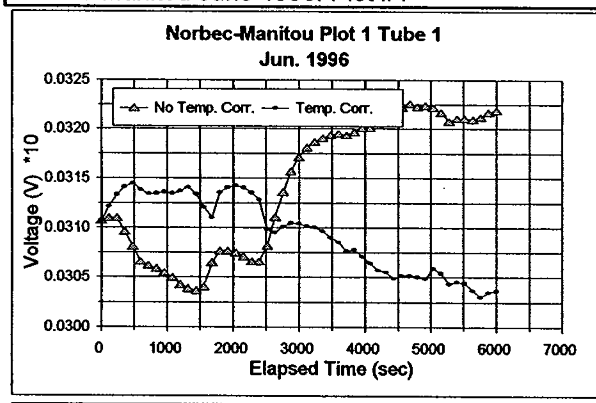


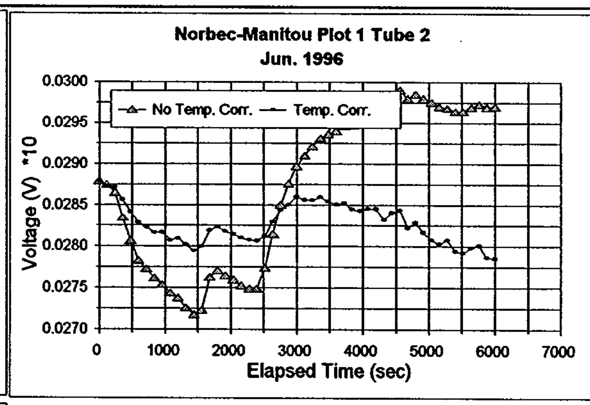


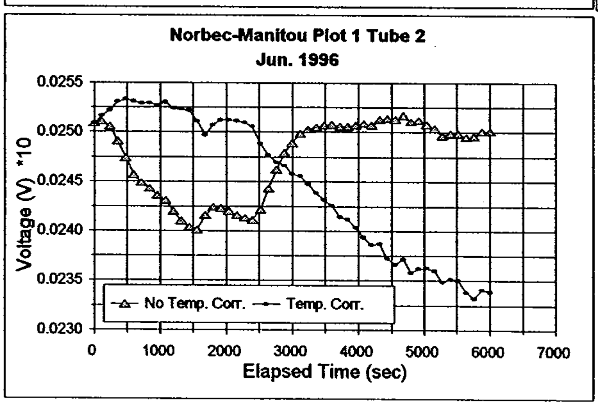




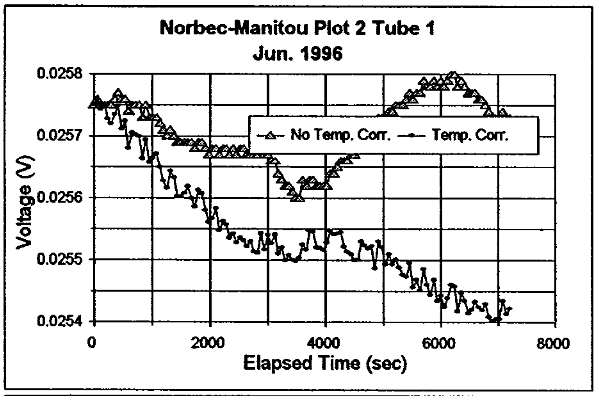
Norbec-Manitou June 1996. Plot #1

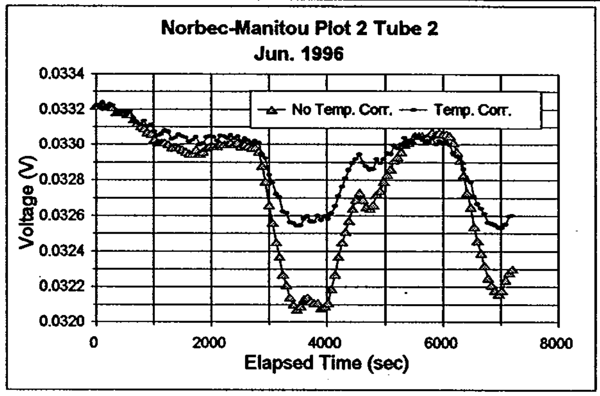


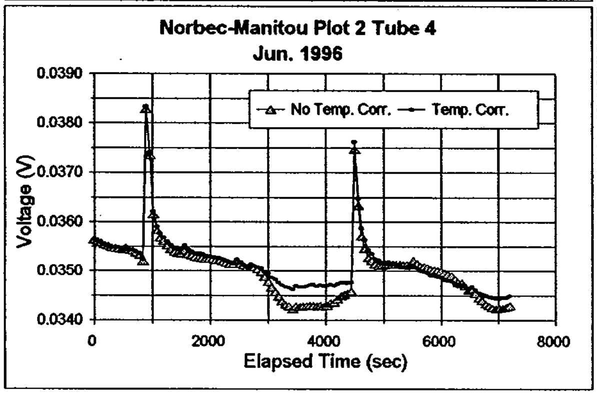


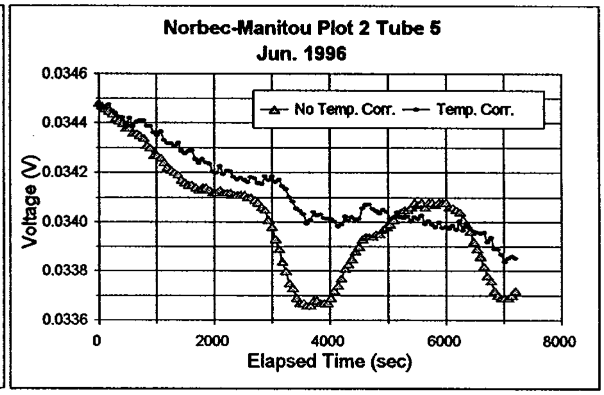


Norbec-Manitou June 1996. Plot #2

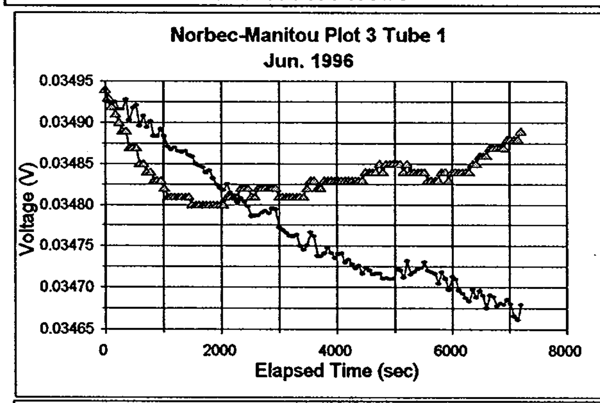


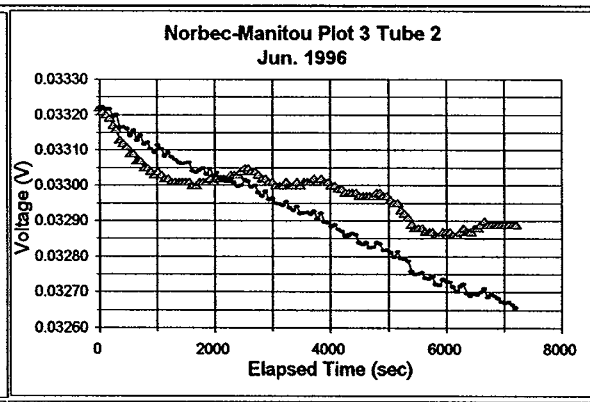


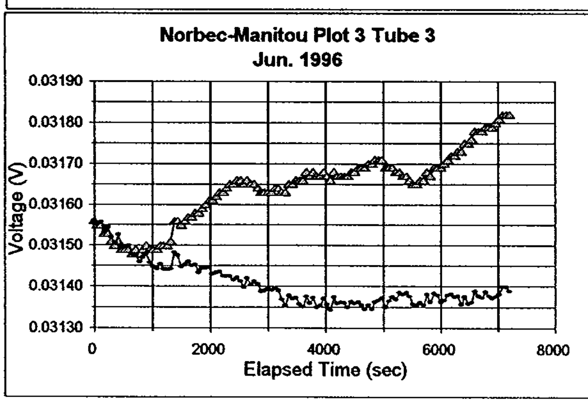


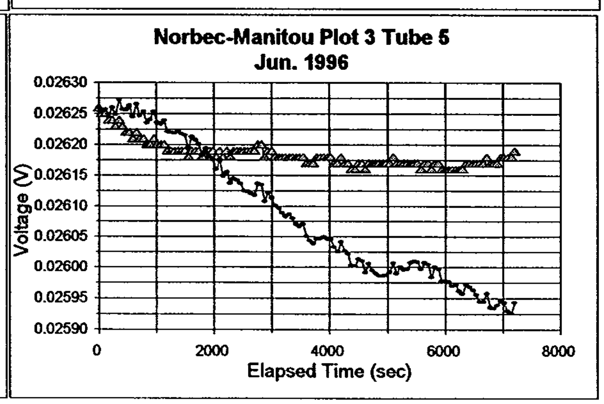


Norbec-Manitou June 1996. Plot #3

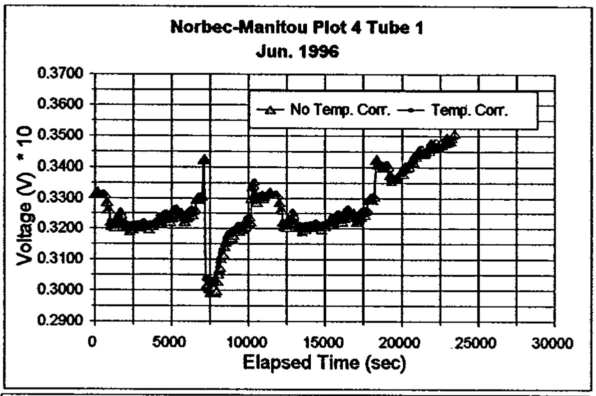


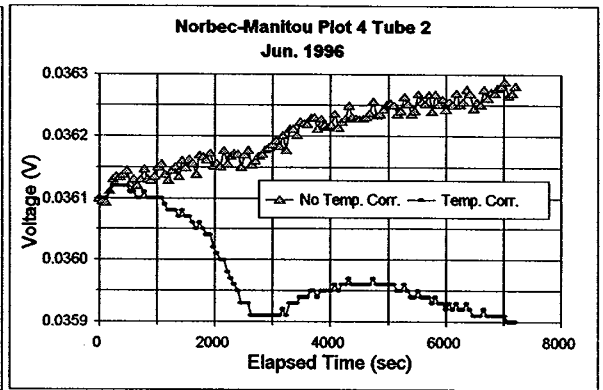


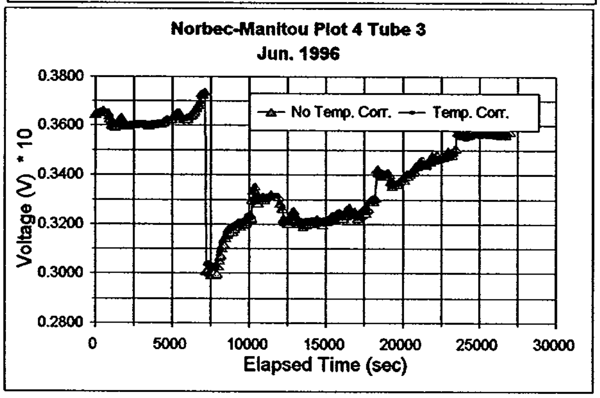


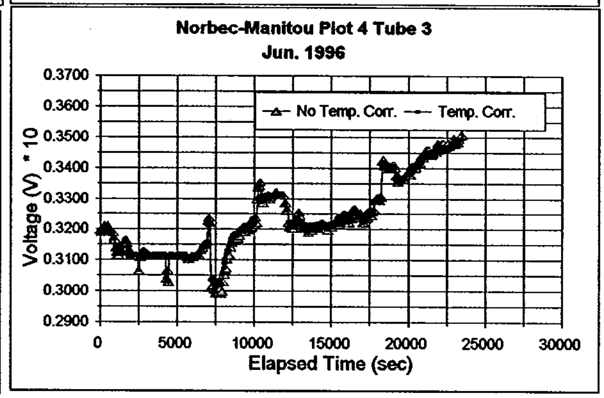


Norbec-Manitou June 1996. Plot #4

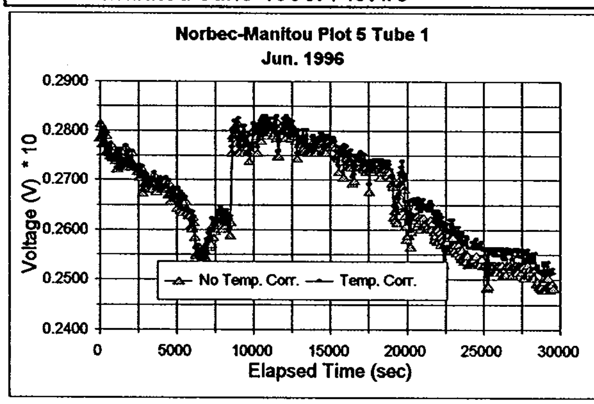


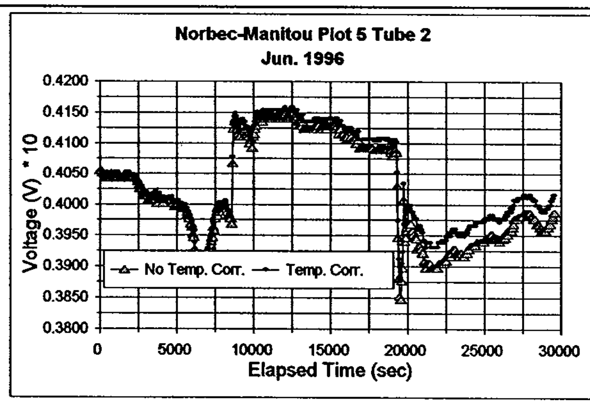


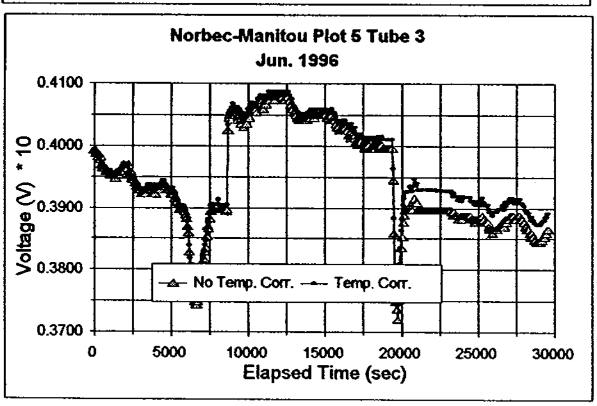


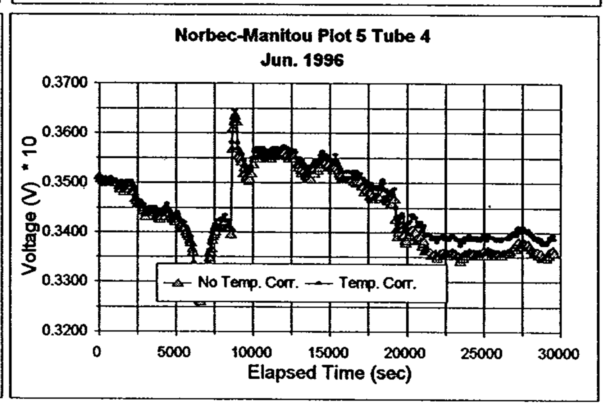


Norbec-Manitou June 1996. Plot #5

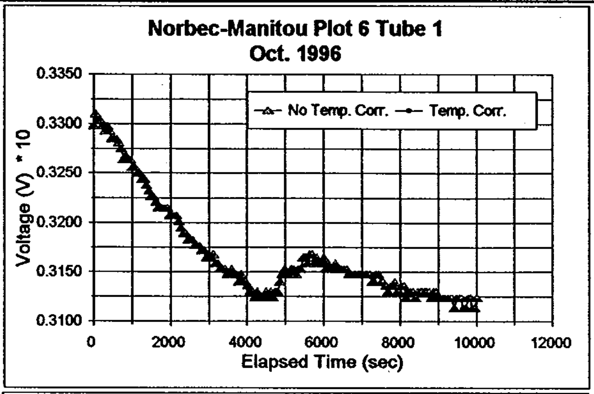


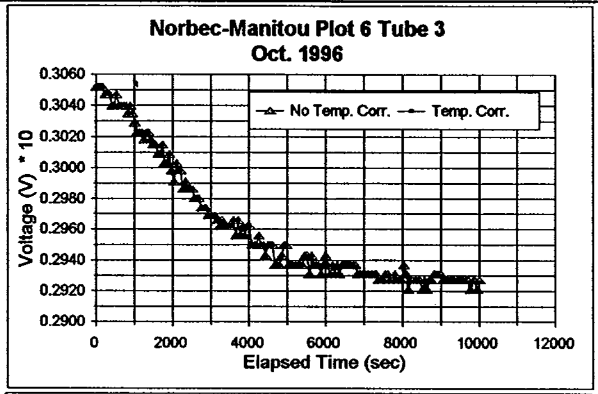


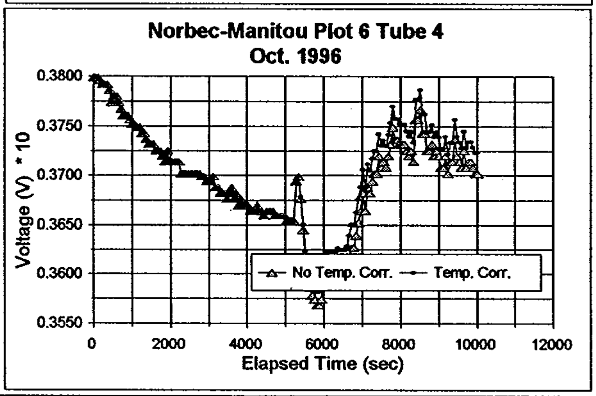


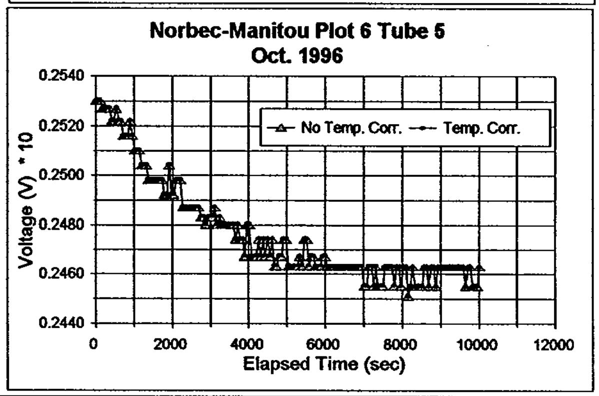


Norbec-Manitou OCT 1996. Plot #6 non-covered tailings

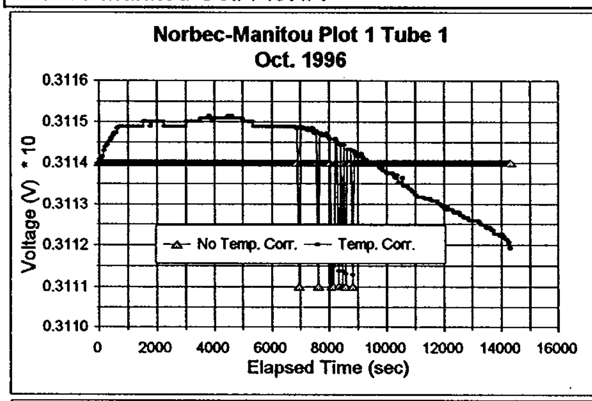


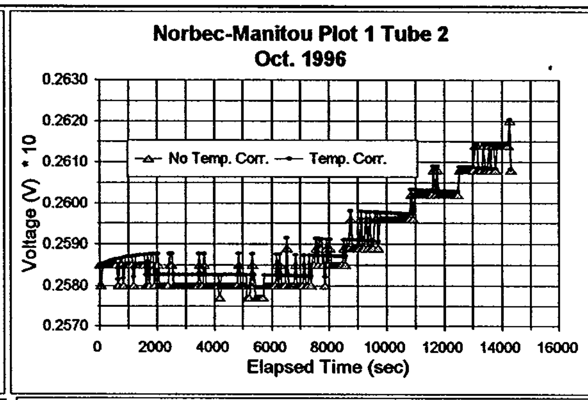


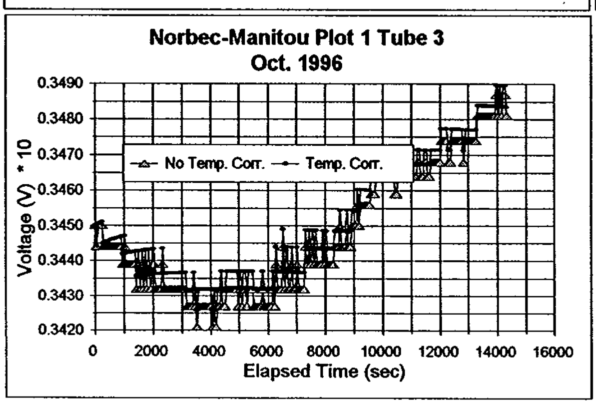


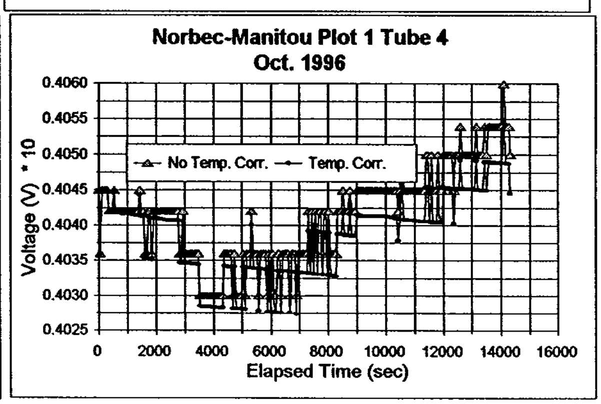


Norbec-Manitou Oct. Plot #1

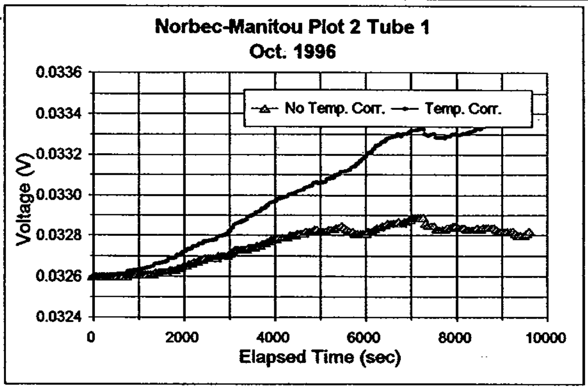


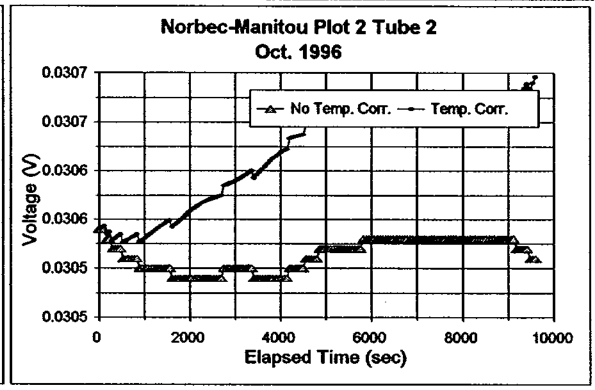




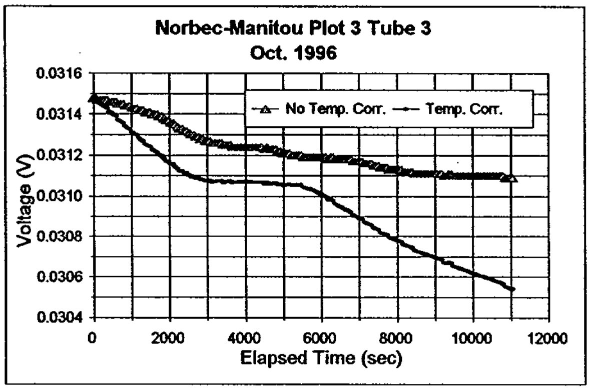


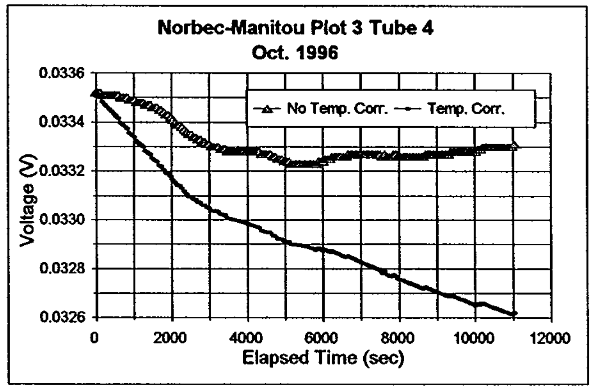
Norbec-Manitou Oct. Plot #2



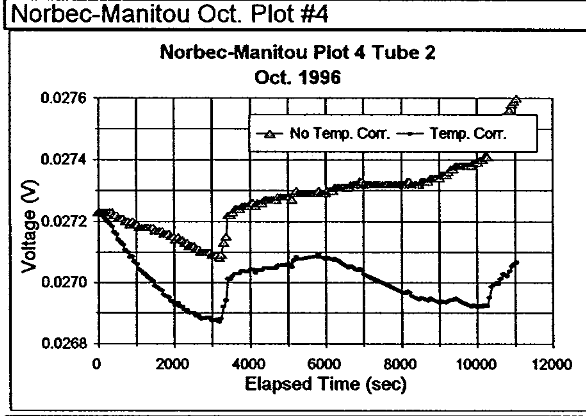


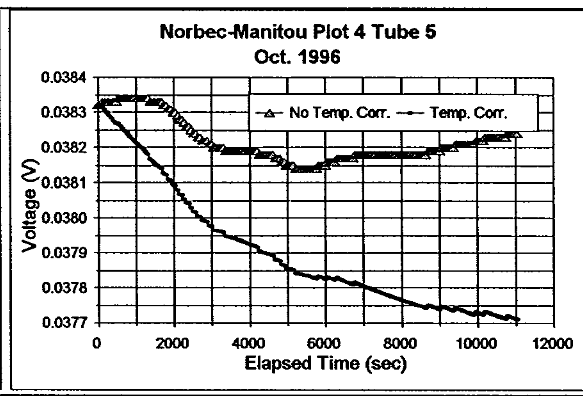
Norbec-Manitou Oct. Plot #3





Norbec-Manitou Oct. Plot #4





Norbec-Manitou Oct. Plot #5