ELECTRICAL RESISTANCE HEATING FOR THAWING OF FROZEN URANIUM TAILINGS IN A URANIUM TAILING MANAGEMENT FACILITY

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ABSTRACT

The Rabbit Lake In-Pit Tailings Management Facility contains frozen layers of tailings due to sub-aerial deposition during successive winter operations. Thawing of the frozen layers is required to ensure full consolidation of the tailings prior to closure and to regain disposal space presently occupied by ice. Electric resistance heating (ERH), which has been used to heat soil for bitumen extraction and remediation of volatile contaminants, is being evaluated as a thawing mechanism. Two bench-scale experiments were performed in late 2009 and early 2010 wherein ERH was tested on about 0.3 cubic metres of frozen tailings. Thawing occurred in both experiments with negligible geochemical effects, demonstrating the viability of ERH as a tailings thawing mechanism. An in-pit field trial was performed from July 2010 until April 2011. Thermal and electric data collected throughout the trial indicate that thawing has occurred as was predicted based on the bench-scale experiment.

1. INTRODUCTION

The Rabbit Lake In-Pit Tailings Management Facility (RLITMF) at Cameco Corporation's Rabbit Lake Operation contains approximately 7.4 million cubic metres (Mm^3) of uranium tailings, as of the end of 2010. Approximately 1.8 Mm^3 of the tailings deposited within the facility prior to the end of 2006 is frozen due to sub-aerial deposition in the coldest periods of winter between 1986 and 1999. The sub-aerial deposition method resulted in the creation of relatively thick frozen layers each winter. These frozen layers were then covered by on-going tailings deposition in the following summer effectively insulating the surface to prevent thawing during the short summer. The result was alternating layers of frozen and non-frozen materials throughout most of the tailings facility, as illustrated in Figure 1. Thawing must be performed prior to decommissioning of the facility to ensure full consolidation of the tailings, which is required to minimize groundwater flow through the tailings. The advantage of thawing tailings during operation is that useable tailings storage space can be recovered for immediate use.

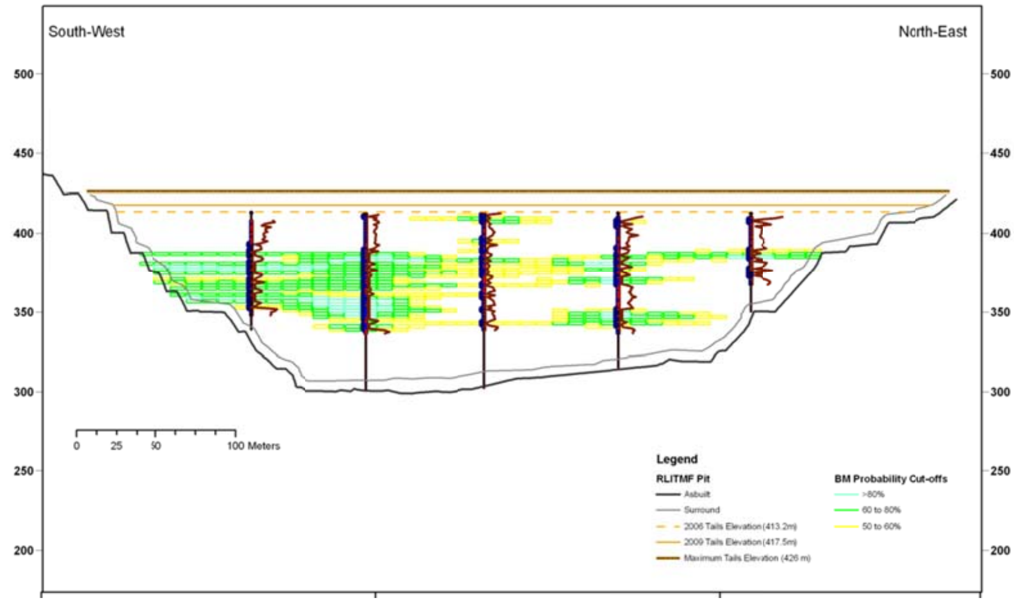


Figure 1 – Vertical and lateral distribution of frozen layers along longitudinal section of the RLITMF inferred from 2006 borehole data

Various strategies have been pursued for thawing or reduction of freezing in the past [1]; these efforts focussed mainly on warm tailings injection. Since 1999, the majority of tailings deposition has been performed by injecting the slurry 30 to 60 m below the tailings surface. Work performed in 2007 and 2008 included a warm water injection trial to assess the effectiveness of warm water injection [2]. Findings indicated that, while warm water injection resulted in thawing and showed no adverse geochemical effects, it was non-uniform, allowed little spatial control, and had poor thermal and energy efficiency. During the analysis of data from the warm water injection trial, the concept of electrokinetic (EK) technology was identified as another possible thawing mechanism. EK technology has been used for soil remediation, dewatering and consolidation, but it has not, to our knowledge, ever been utilized for soil thawing.

Preliminary bench-scale trials demonstrated that EK technology could be utilized to thaw frozen soils due to heat generated by electrical resistance. The potential advantages of electrical resistance heating (ERH) include: higher energy efficiency due to direct application of the heat in the target area (as opposed to heating water which is then injected); more uniform thawing due to heating throughout the electrical field; and greater spatial control of the thawing process. Two bench-scale experiments were performed in late 2009 and early 2010 to assess the effectiveness of ERH as a thawing mechanism in frozen uranium tailings [3]. A positive outcome from the bench-scale testing prompted a field trial to be conducted within the RLITMF from July 2010 to April 2011 in order to assess the large-scale thawing effectiveness of ERH in-situ.

This paper presents an overview of the second bench-scale experiment along with an overview of the in-pit field trial design, operation and a summary of the electrical and thermal data gathered throughout the operating period.

2. FREEZER EXPERIMENT

2.1 Background and Objectives

There has recently been a renewal of interest in the use of EK technology for consolidation or dewatering of tailings [4, 5]; however, none of these has examined the issue of heat generation during the EK process.

Research of particular relevance to the Rabbit Lake tailings was conducted by Shang *et al* [5], although it was also for the purpose of enhancing consolidation. Key findings of the investigation included:

- Electrokinetic dewatering was effective in samples tested and had the added benefit of generating a temperature increase that could potentially be used to thaw tailings (although the test was performed on unfrozen tailings).
- Electrode design is critical to the implementation of electrokinetic dewatering technology (i.e. non-corrodible versus corrodible), and electrode selection should be based on practical considerations such as cost, effectiveness, environmental impact, operation scale, treatment criteria and other factors.

The control of pH at the anode is crucial to minimizing geochemical changes in the treatment area. Polarity reversal had been shown to be an effective measure to minimize pH changes during electrokinetic treatment [6].

Based on these findings, it was decided to carry out a focused, bench-scale trial to test the utility of ERH to melt ice within frozen Rabbit Lake tailings. The overall objectives of the test program were to:

- Demonstrate that thawing could be achieved in conditions similar to in-pit conditions;
- Determine if any detrimental geochemical effects, such as increased metal solubility, would occur during thawing; and
- Develop sufficient technical knowledge to facilitate the design and planning of a pilot-scale test in 2010.

2.2 Laboratory Methods

A plan was developed to conduct two controlled tests in a laboratory setting using standard domestic deep-freezers for containment of tailings. The scope of the freezer experiments included:

- Modification of the freezers to allow the placement and freezing of tailings at a uniform temperature of -2^{o}C by placing a steel insert inside to ensure containment of the tailings, and electrically insulating it with epoxy to promote electrical current transfer through the tailings mass;
- Application of direct current (DC) ERH to enable power adjustment capability to increase the temperature of the tailings to just above 0^{o}C, if possible, without exceeding 35^{o}C, above which geochemical changes could begin to occur;

- Installation of instrumentation to monitor temperature, pH and oxidation reduction potential (ORP) throughout the experiment at various locations in the tailings mass;
- Minimization of pH changes at the electrodes by reversing electrode polarity at regular intervals;
- Collection of pre- and post-experiment tailings solids and porewater samples for geochemical analyses; and
- Determination of optimum electrode spacing and power requirements for a full-scale field application.

1.1.1. Experimental Setup

The electrodes in freezer were placed approximately 54 cm apart and nearer to the centre of the freezer to minimize or eliminate any edge effects that could occur along the freezer insert (Figure 2). The electrodes were comprised of hollow steel rods with an outer diameter of 1.8 cm. The bottoms of the electrodes were set approximately 10 cm above the base of the freezer.

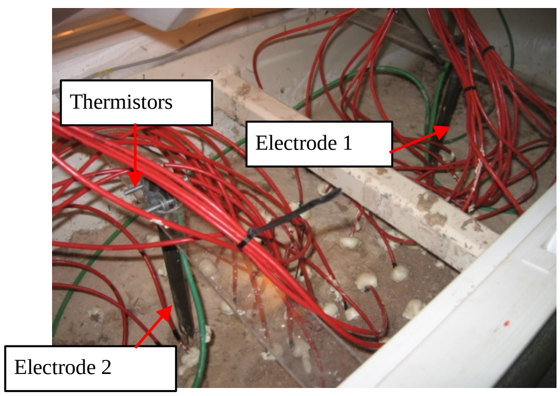


Figure 2 – Experimental setup (pre-thawing) showing the locations of electrodes and thermistors (red wires) on the tailings surface

A closely gridded temperature monitoring system was installed in the freezer to adequately quantify the temperature changes which occurred within the tailings mass as a result of ERH processes. Thermistors were PVC encased to reduce any potential electrical interference from the instrumentation.

A total of 45 thermistors were installed within the tailings mass in five rows (Figure 3). Expanding foam insulation was used to secure the thermistors within the tailings. Twenty-eight thermistors were installed to a depth of about 30 cm (a-series), and 17 were installed to a depth of about 10 cm (b-series) in five rows. While all five rows contained A-series thermistors, only the inner three rows contained both the A-series and the B-series thermistors. Each of the thermistors was connected to a datalogger system. The datalogger was programmed to record thermistor temperatures at 15 minute intervals. Loggernet software was used to view the data.

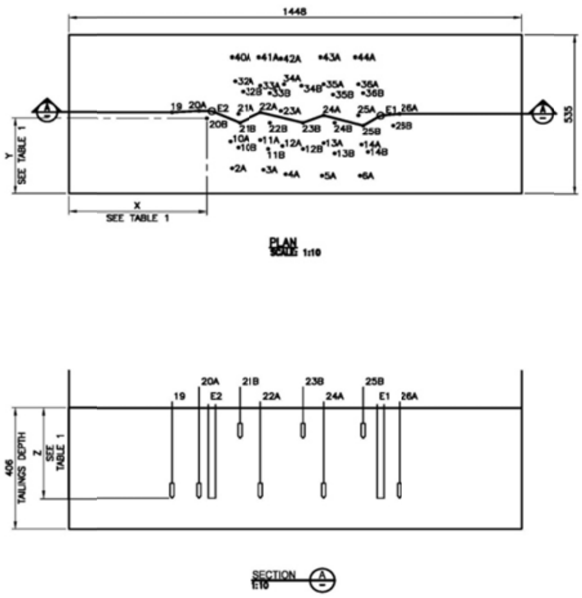


Figure 3 – Freezer experimental setup showing instrument locations in plan and profile views.

2.2.2. Experimental Observations

Baseline temperatures were established over a 15 hour time period prior to the experiment ("I" – Figure 4b). The freezer was operational throughout the establishment of baseline and was turned off just before the EK system was turned on. The ERH system power was turned on at 09:00 February 2, 2010 at 626 V, with a polarity reversal interval of 5 minutes. The amperage began to increase between 30 and 45 minutes after the power was turned on. The experiment amperage reached 0.25 A approximately 17.5 hours after the EK application began, which equates to about 150 W at 646 V. The applied voltage was then decreased as required to maintain approximately 150 W for the remainder of the experiment ("II" – Figure 4a).

The thermistors showed consistent, linear temperature increases almost immediately following application of EK power (Figure 4b). The b-series thermistors (~10 cm depth) located centrally between the electrodes were the first to show positive temperatures at an average elapsed time of about 20 hours. The a-series thermistors (~30 cm depth) in the central zone between the electrodes followed the b-series within about 15 hours (35 hours elapsed time). The lateral a-series thermistors were the final set to indicate positive temperatures. All thermistors were indicating positive temperatures by about 66 hours into the testing. As the melting point was approached, the rates of temperature rise decreased as the latent heat of fusion was overcome and then resumed their initial rate heating rates as the ice became more fully melted ("III" – Figure 4b).

2.2.3. Interpretation of Bench-Scale Testing Results

Electrical Resistance Heating Effect

As demonstrated in Figure 3, all thermistors within the frozen tailings indicated positive temperatures within approximately 66.3 hours of testing. The thermistors also indicated that the system began to overcome the latent heat of fusion at a temperature of about -0.7 ^{o}C and the melting point of the tailings appeared to be about -0.2 ^{o}C ("III" – Figure 3b).

The observed temperature trends within the frozen tailings revealed four distinct periods in which the different areas with the tailings mass overcame the latent heat of fusion ("III" – Figure 3b). The observed thawing pattern was consistent with the typical current density pattern between two electrodes in a homogenous medium, as illustrated in Figure 5, wherein the greatest heating effect is observed in the centre. The blue lines represent current flow and the red lines represent current equipotentials. The current density was greatest, in the area directly between the electrodes and decreased with distance from the electrode centerline axis. While heating should have been uniform with depth, there was about a six hour delay between the b-series (~10 cm depth) temperatures and the corresponding a-series (~30 cm depth) temperatures. One potential reason for the delay is that the a-series thermistors were located at the same elevation +/- 2 cm as the bottom of the electrodes. As such, tailings below the electrodes would have been considerably cooler; therefore would have slowed the rate of thawing in the tailings located at the bottom of the electrokinetic field.

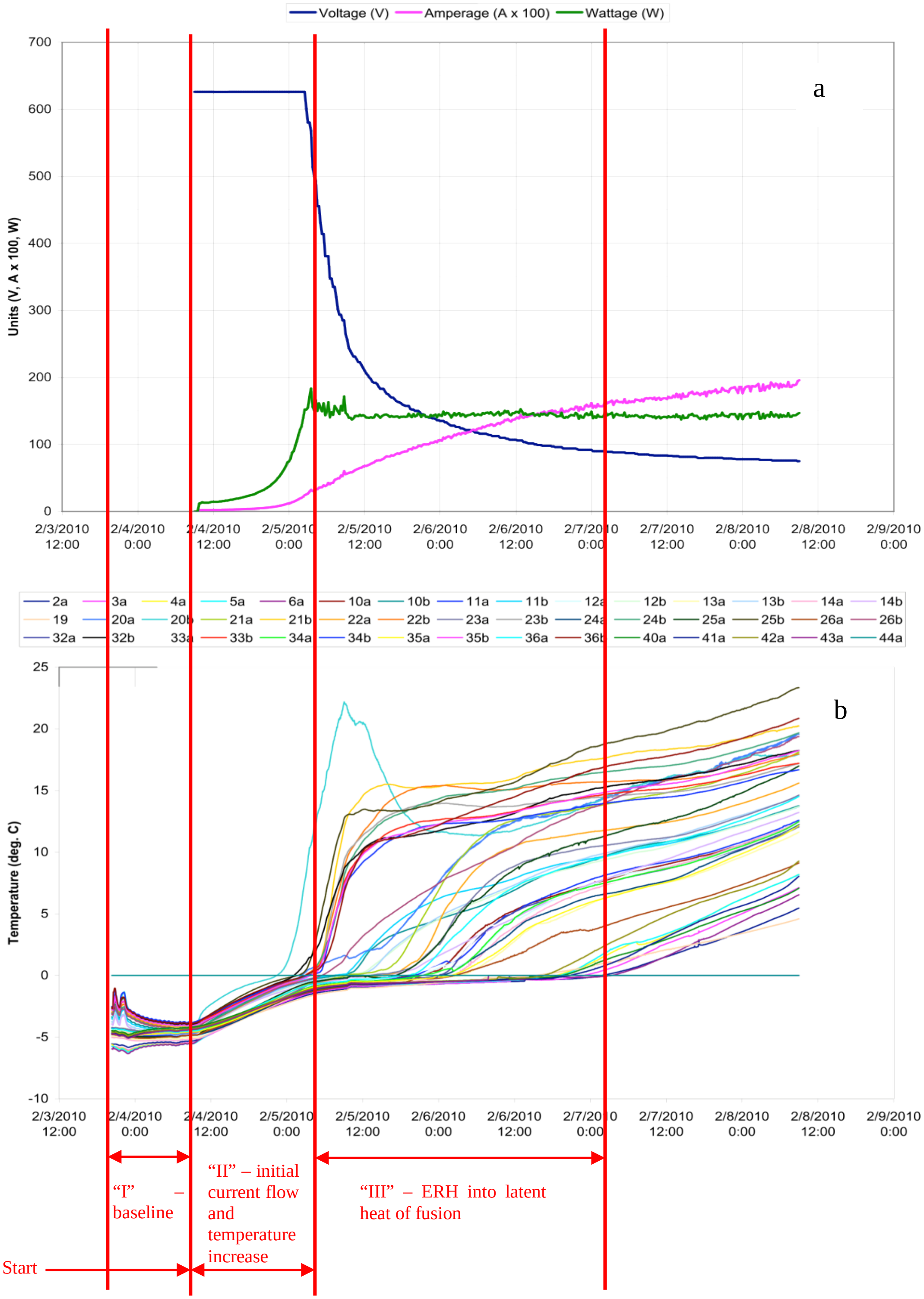


Figure 4 – Comparison between a) experimental parameters (voltage, wattages, amperage) and b) measured tailings temperatures and time for Experiment B. Red vertical lines labeled "I" through "III" approximately coincide with major observed changes as ERH progressed and are referred to within text.

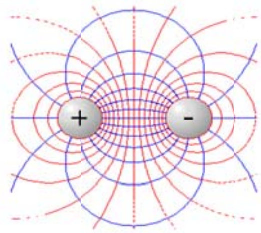


Figure 5 – Typical electrical current density pattern in a homogeneous medium [7]

It was observed that, as thawing progressed, the tailings began to consolidate as shown by expelled porewater pooling on the tailings surface (Figure 6).

Figure 6 – Post thawing layer of water on top of tailings in freezer

Geochemical Effects

Long-term stability of elements of concern (EOC), such as arsenic (and iron, molybdenum, nickel, radium, uranium), within tailings solids at Cameco operations has been demonstrated for tailings discharged as oxic (redox ~ 200 mV) and moderately alkaline (pH ~ 8.5 to 10.5) slurries. This is largely due to long-term stability of secondary arsenic-bearing iron hydroxide (e.g. ferrihydrite) precipitates [8]. As such, one of the primary objectives was to manipulate the electrokinetic experiment such that, with the exception of temperature, there would be no, or very minimal, observed changes to the tailings geochemistry relative to established, in-pit conditions. Within the experiments, a target maximum tailings temperature of 35^{o}C was set. This was based on previous kinetic studies on the long-term fate of ferrihydrite within tailings at the Deilmann Tailings Management Facility at Key Lake Operation indicating that pure ferrihydrite is stable at temperatures of approximately 25^{o}C and does not show considerable recrystallization until temperatures of at least 50^{o}C [9].

With respect to pH, previous studies on Rabbit Lake tailings indicated that ferrihydrite is geochemically stable over a pH range of approximately 4 to 11 and at temperatures lower than about 24^{o}C [10]. As a result, experimental criteria included maintaining the tailings temperatures lower than 35^{o}C during thawing, regularly monitoring tailings pH, and measuring redox values in an effort to maintain and minimize any geochemical changes within the tailings. Temperature changes within the tailings were controlled by reducing the voltage in the system, whereas increasing the frequency of polarity reversal was used to control pH and ion migration within the tailings mass during ERH.

Tailings cores from the freezer were collected at the end of the experiment and porewaters were extracted [2] for geochemical analyses (pH ("final pH"), major ions, metals and radionuclides (Table 1)). When compared to a baseline pH of 7.40, which was measured on pre-test tailings from the RLITMF used to fill the freezer, the final pH values in these tailings were quite similar. The final pH values were also within the range of in-pit tailings values from drill multiple drill programs, indicating that the application of electrokinetics in conjunction with polarity reversal had negligible adverse effects on tailings pH.

Table 1 – Measured concentrations of pertinent Rabbit Lake tailings porewater parameters before and after-ERH application

Geochemical Parameter	Baseline Concentration (n=1)	Freezer Average Final Concentrations (Range: n=3)	RLITMF Drilling Historical Minimum Concentrations	RLITMF Drilling Historical Maximum Concentrations
Final pH (pH units)	7.40	7.96 (7.77 – 8.09)	6.64 (n=1046)	12.51 (n=1046)
As (⌈g/L)	153	70 (64 – 75)	58.0 (n=260)	237,000 (n=260)
Mo (mg/L)	7.43	4.34 (4.30 – 4.38)	0.56 (n=226)	149 (n=226)
Ni (mg/L)	0.0140	0.020 (0.017 – 0.021)	0.001 (n=237)	1.738 (n=237)
R_{226} (Bq/L)	13	24 (19 – 30)	7.0 (n=183)	220 (n=183)
U (⌈g/L)	13900	8240 (7940 – 8560)	4.8 (n=191)	16650 (n=191)

Similar to pH, the baseline and final concentrations of EOC (Table 1), as well as other major ions, metals and radionuclides within the initial tailings porewaters and solids, were found to be comparable with long-term porewater concentrations within the RLITMF. None of the samples from the freezer revealed a consistent change in concentration relative to one another or to baseline, indicating that frequent and consistent polarity reversal is an effective means of mitigating the potential for geochemical changes [3].

3. IN-PIT FIELD TRIAL

3.1 Background and Objectives

Following the success of the bench-scale testing, an in-pit field trial was planned in order to assess the effectiveness of ERH at a field-scale level and confirm the results of the freezer experiment.

3.2 Field-Trial Design & Set-up

The primary field-trial design components consisted of the following:

- Four electrodes, each approximately 73m in length, comprised of NW-size drill casing (mild steel, 88.9mm outer diameter, 76.2mm inner diameter);

- Four 250m lengths of 750kcmil aluminum cable;
- Two 170A/50kW DC power distribution systems (PDS) and a master control centre (MCC), powered by an 8000kW diesel generator;
- Four three-bead thermistor strings; and
- Four 23-bead thermistor strings.

The field-trial was located in the southern end of the RLITMF where there was maximum frozen layer thickness. The electrodes were installed in a grid pattern of about 10m by 12 m (Figure 7) to a target depth of about 72m. The lowermost 3m of the electrodes were seated in the competent, non-frozen, consolidated tailings below the lowermost frozen layer shown in the profile. This section of the electrodes was also epoxy-coated to reduce electrical conductivity and prevent the heating of the deeper non-frozen tailings, thereby improving efficiency. The upper 30m of the electrodes were also epoxy-coated for the same purpose, as the tailings were predominantly non-frozen in that area. The non-coated (active) portion of the electrodes targeted the bulk of the frozen tailings, which were primarily located between depths of about 30m to 70m.

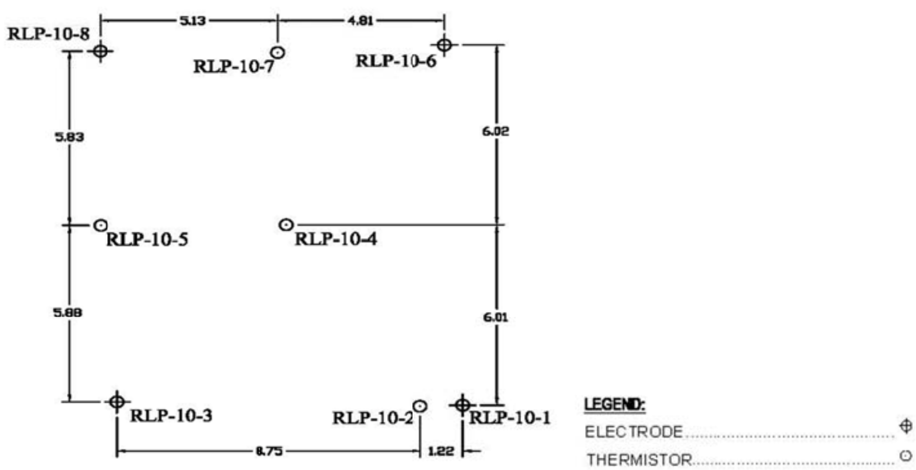


Figure 7 – Field layout of electrodes and thermistors

Electrode spacing was designed to achieve complete thawing within the trial area over a period of three months based on an assumed frozen porewater content of 50% and an estimated bulk tailings resistance of 1.9 ohms.

Aluminum cables were used to connect the electrodes to the 50kW DC power supplies. One power supply was connected to electrodes RLP-10-1 and RLP-10-3; the other was connected to RLP-10-6 and RLP-10-8 (Figure 7). Polarity reversal was set to occur automatically every five minutes.

Thermistor strings with three sensors were installed inside each electrode (labelled as RLP-10-1, RLP-10-3, RLP-10-6, and RLP-10-8 in Figure 7) to ensure that electrode temperatures could be monitored and controlled at a maximum of 35°C. Thermistor strings with 23-sensors were installed at various locations within the electrode grid (labelled RLP-10-2, RLP-10-4, RLP-10-5, and RLP-10-7 in Figure 7) to measure in-situ temperature profiles within the tailings. Dataloggers were used to record temperature data at 30 minute intervals.

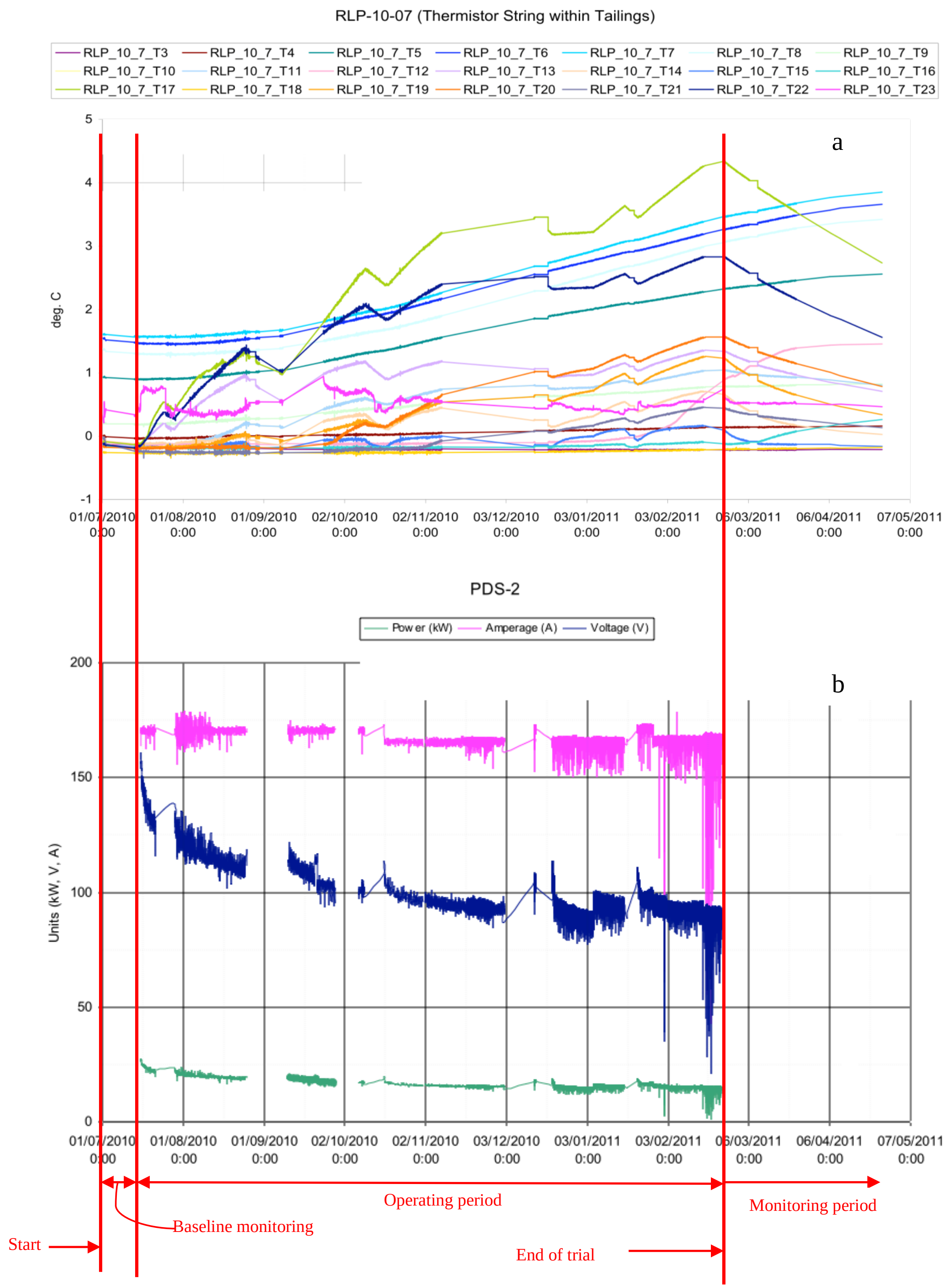
Borehole RLP-10-1 was visually logged and photographed; samples were obtained at regular intervals for geochemical and geotechnical baseline laboratory testing.

3.3 Field Trial Operation & Observations

A voltage of 155V was initially applied to the electrode pairs, resulting in a current of 170A and an initial power input of about 27kW as illustrated in Figure 8. Based on a predicted tailings resistance of 1.9 ohms, it was anticipated that power input would be 50kW; however the actual in-situ resistance of the tailings was only about 1 ohm. The maximum current output of the power supply units was 170A, therefore, the actual power input level was just over half of the predicted level. Despite the lower power level, the resistance of the tailings began to decrease as a function of the heating process as it did in the freezer test. The voltage decreased correspondingly along with the power, which gradually decreased the power input to about 15kW by the end of the trial.

The intent at the outset of the trial was to operate the system from mid-July 2010 until mid-October 2010. However, due to the overall power application being less than half of that planned, and due to unplanned equipment outages (represented in Figure 8 as gaps or jumps in the data), the planned operating period was extended. The revised plan entailed operating the trial until the end of August 2011.

Thermistor RLP-10-7 was located mid-way along the centreline between electrodes RLP-10-6 and RLP-10-8. The location of RLP-10-7 best represents the target thawing area in that thawing would be considered complete once all thermistor sensors in that area registered positive temperatures. As such, the results presented herein focus primarily on the dataset from RLP-10-7 and the corresponding electrical dataset from electrode pair RLP-10-6 and RLP-10-8 (PDS 2).


RLP-10-07 (Thermistor String within Tailings)
RLP_10_7_T3
RLP_10_7_T4
RLP_10_7_T5
RLP_10_7_T6
RLP_10_7_T7
RLP_10_7_T8
RLP_10_7_T9
RLP_10_7_T10
RLP_10_7_T11
RLP_10_7_T12
RLP_10_7_T13
RLP_10_7_T14
RLP_10_7_T15
RLP_10_7_T16
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RLP_10_7_T19
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RLP_10_7_T21
RLP_10_7_T22
RLP_10_7_T23
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4
3
2
1
0
-1
01/07/2010 0:00
01/08/2010 0:00
01/09/2010 0:00
02/10/2010 0:00
02/11/2010 0:00
03/12/2010 0:00
03/01/2011 0:00
03/02/2011 0:00
06/03/2011 0:00
06/04/2011 0:00
07/05/2011 0:00
PDS-2
Power (kW)
Amperage (A)
Voltage (V)
b
Units (kW, V, A)
200
150
100
50
0
01/07/2010 0:00
01/08/2010 0:00
01/09/2010 0:00
02/10/2010 0:00
02/11/2010 0:00
03/12/2010 0:00
03/01/2011 0:00
03/02/2011 0:00
06/03/2011 0:00
06/04/2011 0:00
07/05/2011 0:00
Operating period
Monitoring period
Baseline monitoring
Start
End of trial

Figure 8 – Comparison between a) measured tailings temperatures and time throughout the field trial and b) electrical parameters (voltage, wattages, amperage)

Thermistor responses within the trial area were consistent with the heating pattern that was observed in the freezer test. Heating of non-frozen tailings layers was observed immediately upon start up in thermistor strings RLP-10-2 and RLP-10-7, which were located in areas of higher current density. Thermistor RLP-10-4, located in a lower current density area, showed heating of some non-frozen layers upon start up. Thermistor RLP-10-5, located in an area of very low to zero current density, did not indicate heating of non-frozen layers occurred until about 15 days after the ERH application began

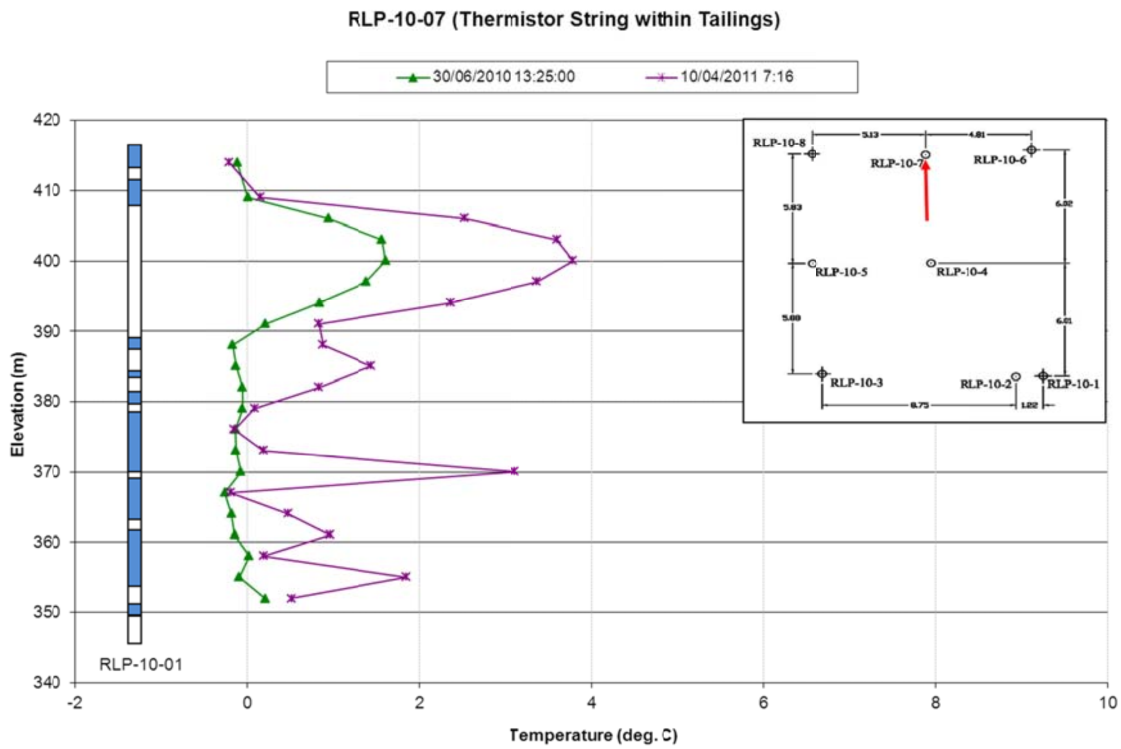

Figure 9 – Baseline and final tailings temperature profiles in RLP-10-7 relative to the frozen/non-frozen tailings stratigraphy logged in RLP-10-1 (blue colour = frozen)

Figure 9 shows baseline and endpoint temperatures in a vertical profile at RLP-10-7. Thirteen sensors on this thermistors string were located in the active zone of the electrodes. At the beginning of the trial, 11 of the sensors showed negative temperatures and by the end of the trial only two were showing negative temperatures. As illustrated in Figure 8a, no temperatures within the electrodes or the tailings mass exceeded 35^{o}C during the trial.

Operation of the field trial ended prematurely in mid-April 2011 due to the failure of three of four electrodes. Preliminary analysis performed on a portion of electrode RLP-10-1 indicated that localized corrosion at the joints of the NW casing caused the failures.

3.4 Field Trial Results

COMSOL™, a multi-physics finite element analysis simulation software, was used to help predict the thawing effects of the ERH application during the in-pit field trial. The model was originally constructed based on the parameters and effects measured and observed in the freezer test; it was then refined with field trial temperature and electrical data.

Model parameters of particular sensitivity included latent heat and tailings resistivity of frozen and non-frozen tailings. It was estimated that 30% of the latent heat required to thaw the frozen layers was pre-supplied based on the initial thicknesses of the frozen and non-frozen layers and their initial temperatures at the time of deposition. The resistivity values used for non-frozen and frozen tailings were estimated from the freezer test and from mixing laws.

Based on the above estimations, preliminary modeling results indicate that at least 70% of the frozen mass within the trial area was thawed during the trial and that the energy efficiency was between 58% and 86%. A follow-up drilling and testing program is planned for the summer of 2011 to physically define the extent of thawing and to better define latent heat and resistivity parameters. The 2011 summer drilling program will also allow for sample collection and geochemical testing of tailings within the trial area. A detailed geochemical analysis will follow. Geochemical effects in the tailings are not anticipated based on the results of the freezer experiment.

3.5 Field Trial Conclusions To Date

Preliminary assessment of the field trial data indicates that ERH is an effective, controllable and predictive thawing mechanism within the RLITMF. Design modifications to the power supply units are required to ensure appropriate voltage and current levels can be maintained to achieve the optimal thawing rate. In addition, work is required to decrease the corrosion susceptibility of electrodes.

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