

# GEOCHEMICAL AND GEOTECHNICAL CHARACTERISTICS OF FILTER-PRESSED TAILINGS AT THE GREENS CREEK MINE, ADMIRALTY ISLAND, ALASKA<sup>1</sup>

Peter D. Condon,<sup>2</sup> and Kerry G. Lear<sup>2</sup>

**Abstract.** The Greens Creek Mine's 3.5M tonne dry-stack tailings pile receives about 800 tonnes of filter-pressed tailings daily. The silt-sized tailings are placed in thin, compacted lifts using a bulldozer and vibratory roller. Carbonate minerals produce a long lag time to acid generation despite a net-neutralization potential of -210 tonnes CaCO<sub>3</sub>/ktonne.

Key influences on pore water compositions include near-surface pyrite and thiosulfate oxidation, vadose zone iron and manganese reduction and saturated zone sulfate reduction. Annual precipitation in excess of 1450 mm poses the largest challenge to achieving design placement densities in this seismically active region.

Despite higher operational costs relative to slurry-tailings disposal, the decision to produce dewatered tailings provided economic and environmental advantages. It reduced the ultimate footprint of the facility, lowered closure and water treatment costs, improved pile stability and reduced environmental liability by allowing half of the tailings to be returned underground for use as structural backfill.

**Additional Key Words:** thiosulfate, sulfate reduction, ARD, Proctor density, costs

---

<sup>1</sup>Paper presented at the 7<sup>th</sup> International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.) Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502

<sup>2</sup>Peter D. Condon, Environmental Geochemist, Kennecott Greens Creek Mining Company, Juneau Alaska 99803; Kerry G. Lear, Geologist, Kennecott Greens Creek Mining Company. 7<sup>th</sup> International Conference on Acid Rock Drainage, 2006 pp 350-364

DOI: 10.21000/JASMR06020350

<http://dx.doi.org/10.21000/JASMR06020350>

## Introduction

Kennecott Greens Creek Mining Company (KGCMC) operates an underground mine located on the northern end of Admiralty Island approximately 30 kilometers southwest of Juneau, Alaska (Fig. 1). The mine produces concentrates containing Zn, Ag, Au, and Pb from volcanogenic massive sulfide ore which is hosted by Triassic (220 MA) calcareous argillite and metavolcanic rock (phyllite) (Taylor, et al., 1999). The deposit was discovered in 1975 and full production began in 1989. The mill currently processes approximately 2000 tonnes of ore and 1500 tonnes of tailings per day. Tailings from the mill are filter-pressed to about 12% (wt) moisture and approximately 50% are returned underground for use as structural backfill. The remaining tailings are trucked 13 kilometers to a dry-stack tailings disposal facility where they are spread in thin lifts with a bulldozer and compacted with a vibratory roller. Figure 2 is an aerial photograph of KGCMC's dry-stack tailings pile.

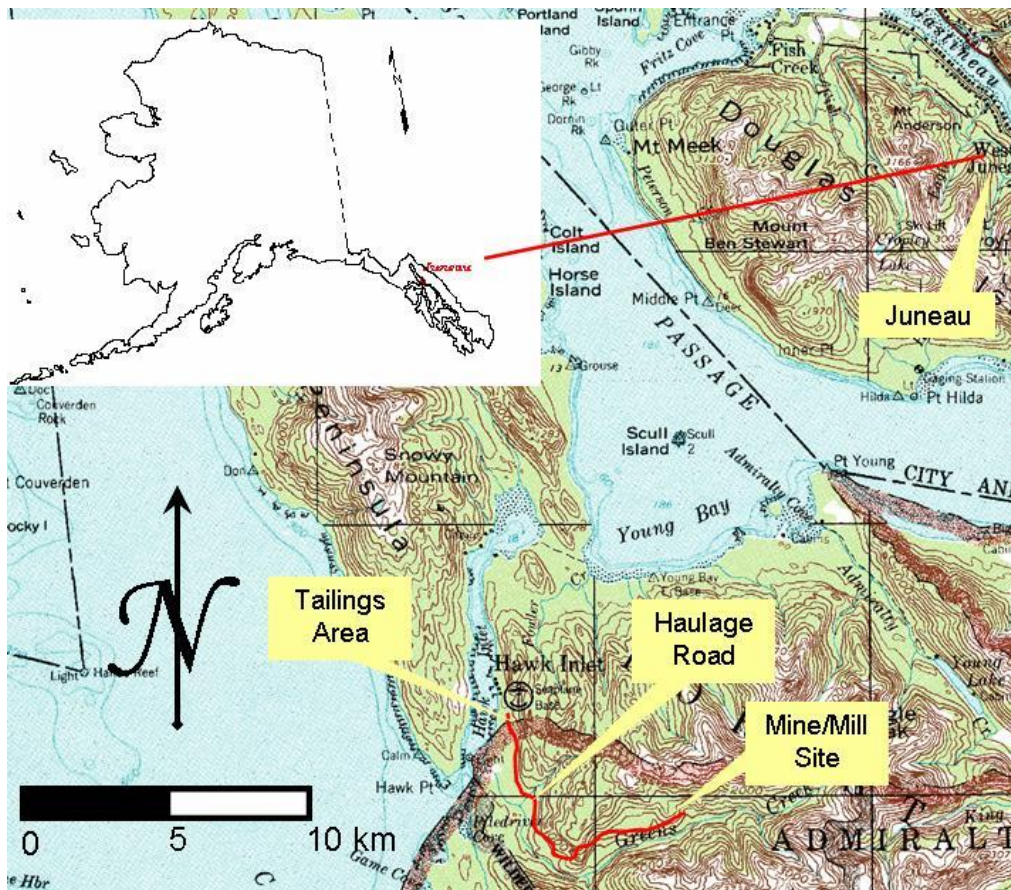


Figure 1. Location map for the Greens Creek Mine

The mine opted for the unconventional dry-stack tailings disposal method, which has considerably higher operational costs, because the projected mine life was relatively short (ten years) and the estimated capital cost for a traditional slurry-type tailings pond was more than seven times that of the dry-stack option (SRK, 1987). Traditional slurry type tailings also would

not have met underground structural backfill density requirements, and a 78% decrease in footprint (60 ha to 10 ha) using dry-stack tailings had valuable environmental and economic advantages (USDA, 1988).



Figure 2. Aerial photograph of the Greens Creek dry-stack tailings pile in May 2005.

Discovery of new reserves has extended the estimated total mine life from the original 10 year at 725 tonnes/day to 15 years of active operation with an additional 10 years of estimated mine life at 2200 tonnes/day. The extended mine life and higher operational costs decrease the net savings of avoiding the high capital costs of a traditional tailings dam. However, the operational costs are offset by the lower cost to construct the facility, improved seismic stability and lower anticipated reclamation costs resulting from the smaller footprint.

The lessons learned and technical data collected over the past 17 years at Greens Creek should be of value to anyone considering this type of tailings disposal. Dry-stack tailings disposal poses a unique set of challenges but has aspects that may be appropriate for some mines, particularly those with footprint limitations.

## **Milling and Dewatering**

Massive-sulfide ore is brought from underground workings to the ore pad stockpile in 18 to 35 tonne rubber-tire haul trucks. Ore from different ore zones is blended to achieve a consistent mill feed and is fed at 2000 tonnes/day through a primary SAG and ball mill circuit. The milled ore is sent through a series of gravity, rougher flotation, regrind and cleaner circuits, which ultimately produce four concentrates (Pb, Zn, bulk and gravity Au) and final tailings. The tailings are thickened to 60% to 70% solids in a 17 cubic meter rake drive thickener. Tailings thickener underflow is pumped to three 32-plate Sala filter presses where they are dewatered to 12% gravimetric moisture content and dropped into loadout bays below the presses. Each press uses high pressure air for diaphragm pressing and processes about 3.6 tonnes of filter cake every 8 to 10 minutes. The presses are mounted on load cells, which provide information to monitor fill, press and discharge cycles in addition to the weight of filter cake produced on each complete cycle.

Of the 1500 tonnes of tailings produced daily, half is sent through a batch plant where 5% to 8% cement is added prior to haulage underground for structural backfill. A portion of the backfill is delivered to stopes in 10- and 20-tonne trucks, dumped and compacted in place with a hydraulic ram. The remainder of the backfill tailings is processed through a paste plant where water is added. The resulting paste is pumped to larger stopes where conditions are appropriate for paste backfill.

## **Surface Disposal**

A CAT 970 loader fills 40-tonne, 18-wheel, off-highway tractor-trailer trucks with tailings from the covered loadout area. The haul truck trailers are equipped with hydraulic metal lids to prevent loss of tailings and to keep them dry during the 12 kilometer trip to the dry-stack tailings facility. The haul road from the mine/mill complex (elevation 280m) to the tailings facility (elevation 35m) near Hawk Inlet is a single-lane gravel road with a maximum grade of 10% and turnouts at 0.3 km intervals. All road traffic maintains communication via two-way radios. The road is only used for mine-related traffic and has a maximum posted speed limit of 40 km/hr. Depending on the amount of tailings needed for underground backfill on a given day, as many as 40 round-trips may be required to keep pace with mill production. Two to four trucks are used contingent on demand.

Haul trucks access the tailings pile via rock roads which make up approximately 5% of the 3.5 million metric tonne pile. At current milling and backfill rates the pile receives about 315,000 tonnes tailings and rock per year. The tailings are dumped, spread out in thin lifts with a CAT D6 bulldozer and compacted with a CAT CS563 vibratory roller to a target of greater than 90% of the Standard Proctor density of the tailings. Figures 3, 4 and 5 are photographs of the equipment used to haul, place and compact the tailings. The photographs show the placement methods occurring under ideal weather conditions, which are somewhat atypical.



Figure 3. 40-tonne haul truck dumping a load of tailings.



Figure 4. D6 CAT spreading tailings. Vibratory roller on compacted lift in foreground



Figure 5. Roller-compacted tailings.

Prior to 2005 the mine had no temporary storage capacity for tailings. Consequently, tailings placement needed to occur daily, regardless of weather conditions. The mine now has dry storage for one to two days of tailings production. However, the tailings facility receives in excess of 1450 mm of precipitation annually and weather systems in southeast Alaska often produce heavy rain that lasts for several days. During long periods of heavy rainfall it becomes difficult to maintain access to placement areas, manage erosion and runoff and achieve target densities. The tailings are close to optimum moisture content when they arrive at the tailings pile but quickly gain moisture from rainfall as they are spread and compacted. Areas away from outer-pile surfaces are utilized during inclement weather to minimize the risk of creating soft zones in areas that are critical to pile stability.

The mine performs weekly to monthly density testing using a Troxler nuclear densitometer or Washington balloon densitometer to verify compaction. Calibration of the nuclear-density method to account for the high-sulfide matrix has been problematic. More frequent testing would improve documentation of in-situ densities, but the long duration of wet periods and a small placement footprint rarely present the opportunity to excavate, dry and re-compact tailings. Tailings are placed in a cellular format to allow pore pressures to subside and to reduce the likelihood of having large areas of tailings that do not meet target density. Figure 6 shows standard penetration test data for four bore holes through the pile. The data show the variability in in-situ density that results from placing tailings over a range of weather conditions. The data suggest that with the exception of pre-1994 portions of the pile (e.g. DH-T-05-03A), soft zones (N-values less than 15 blows/35cm) are discontinuous and surrounded by better compacted tailings. N-values greater than 20 likely indicate areas that were placed under ideal weather conditions.

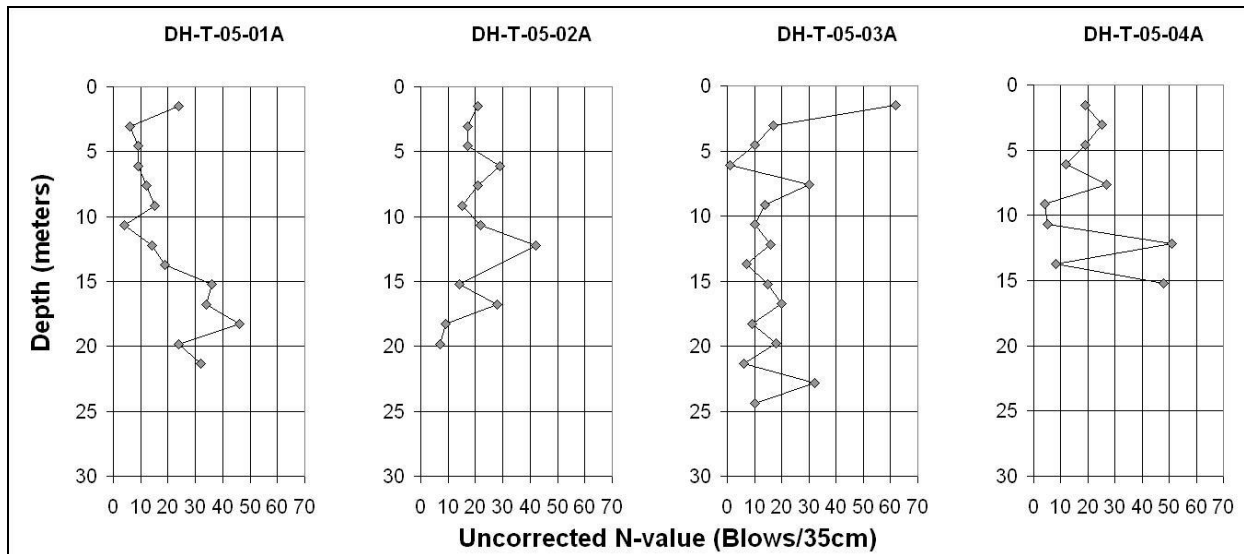


Figure 6. Standard penetration test data (N-values) from tailings-pile bore holes.

The silt-sized tailings erode easily and gullies form rapidly on exposed slopes. Waste rock and sediments from road ditch maintenance are used to protect slopes from erosion and help

limit fugitive dust. Managing runoff has become more challenging as the tailings pile has grown in height (now 25 meters) and area (13 ha). Rock roads and rocked outer slopes accommodate runoff now, but rip-rap channels, liners and piping may soon be required to control drainage prior to construction of the soil cover. Gullies that form on slopes are either cut and re-compacted or filled with compacted tailings or rock. Tailings washed from the gullies are problematic because they are often too wet to place conventionally. They are typically mixed and placed with fresh tailings during dry periods.

At most mines that utilize traditional slurry-type tailings disposal, saturated sediment from ponds and sumps is often sent to the tailings pond. Because KGCMC has adopted the dry-stack method, it is much more difficult to handle large volumes of loose, saturated sediment. The mine's current method of decanting and mixing with fresh tailings is not ideal and the mine is evaluating ways to improve management of these materials. Temporary synthetic covers could reduce infiltration and erosion, but snow removal, wind susceptibility, runoff undercutting and additional labor requirements have prevented large-scale implementation.

### **Geotechnical Characterisitcs**

Size gradations for the tailings produced between 1999 and 2005 are presented in Fig. 7. The tailings are predominantly silt-sized with 80% typically passing the 200 sieve. The clay- sized fraction is approximately 10%. As milling rates have increased up to the current 2000 tonnes/day, a general coarsening of the tailings (less clay, more silt fraction) has occurred. Because the tailings are placed mechanically, no size sorting occurs in the pile. The average Standard Proctor density, specific gravity and optimum gravimetric moisture content are 2.2 g/cm<sup>3</sup>, 3.5 and 13%, respectively. Atterberg limits tests indicate that the tailings are cohesionless to very low-plasticity silt. The average liquid limit, plastic limit and plasticity index are 19%, 16% and 3, respectively (KCCL, 2005b). The average in-situ gravimetric moisture content of tailings in the pile is 16% (KCCL, 2005b) and the porosity is about 40% (USDA, 2003). The average hydraulic conductivity of four in-situ tests is 1.9x10<sup>-6</sup> cm/s (EDE, 2002). The friction angle for compacted tailings is approximately 40° (KCCL, 2005a).

The foundation stratigraphy generally consists of about a meter of amorphous to fibrous peat overlying 1 to 5 meters of locally liquefiable marine and glaciofluvial sand and gravel, which overlie up to 30 meters of interbedded marine and glacial silt, clay and sand. Bedrock consists primarily of siliceous chlorite-muscovite schist, which is locally graphitic and pyritic. The bedrock is exposed at the surface in the northwest and southeast corners of the pile footprint. The facility relies on the marine silt and clay in the foundation, bentonite/soil slurry walls along the perimeter, and 80 mil HDPE synthetic liner over bedrock in the southeast corner of the pile to direct contact water to drains and collection sumps. An upward groundwater gradient under most of the footprint prevents the downward migration of contact water in the foundation. Site waters are collected and treated prior to discharge to Hawk Inlet under the mine's NPDES permit.

Approximately one-third of the pile is underlain by a network of gravel finger drains, which were placed directly over peat prior to original tailings placement in 1989. These drains do not prevent conveyance of head pressures between the pile and the foundation, and the maximum saturated thickness in this area is 10 meters. The remaining two-thirds of the pile (south, east

and west flanks) are underlain by a series of blanket drains and finger drains that do dissipate head pressures between the pile and the foundation. Despite having a free-draining base in these areas, the tailings saturate to about 4 meters, likely reflecting the high moisture-retention ability of the silty tailings and a general decrease in hydraulic conductivity with depth.

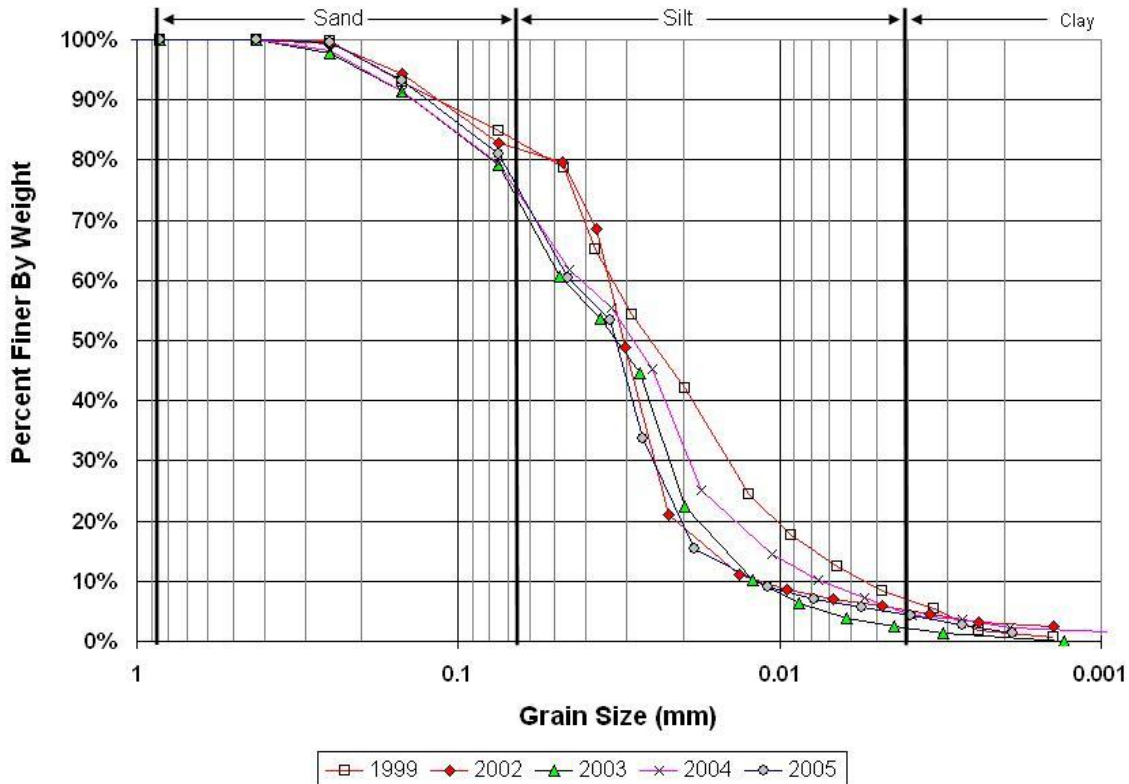


Figure 7. Size gradations of Greens Creek tailings.

The mine is located in an area prone to seismic activity. The maximum design earthquake (MDE) used for closure purposes is a magnitude 7.0 event with a recommended peak ground acceleration of 0.3g, which is 75% of the maximum credible earthquake ground motion based on deterministic analysis of random earthquakes near the site (KCCL, 1998). The probability level of the MDE is 1/10,000 years. The recommended MDE ground acceleration conforms to criteria proposed by the International Commission on Large Dams (ICOLD, 1995).

Materials that may liquefy in the MDE include portions of the sand unit underlying the peat beneath the pile, significant portions of the pile constructed between 1989 and 1993, and isolated zones in the pile which were placed after 1994 (KCCL, 2003). KGCMC adopted improved foundation drain and tailings placement criteria in 1995. In 1998, the liquefiable sand was removed along the western flank of the pile and a dense-tailings buttress was constructed on the stable foundation in that area. Liquefaction of the sand unit under the southern portion of the pile may lead to displacement of the mass to the south during a MDE (KCCL, 1999). Potential displacements would not breach the containment but would likely cause damage to the composite soil cover that will be constructed on the pile when the site is reclaimed. It may be



possible to construct a buttress similar to that which was built on the west side of the pile if the pile is expanded to the south. In either case KGCMC will maintain contingencies for repair of the cover in the closure plan for the facility. Identification and removal of the liquefiable sand in the foundation prior to construction and strict adherence to compaction specifications would have reduced significantly the risk of pile deformation.

In retrospect, the risks related to deformation of a slurry-type tailings pond would be greater than those for the current dry-stack pile. The likelihood of tailings liquefaction would be much greater and the consequences of a dam failure would be far more severe. Repair costs would also be considerably higher due to the larger footprint and greater potential deformation.

### **Geochemical Characteristics**

The tailings consist primarily of quartz, sericite, pyrite, dolomite, magnesite, calcite, chlorite and lesser amounts of sphalerite, galena, tetrahedrite, barite and the barium feldspar, celsian. Secondary minerals include gypsum, hexahydrite and amorphous iron oxyhydroxides. Acid-base accounting (ABA) analyses presented in Fig. 8 indicate that the tailings are potentially acid generating but have a substantial neutralization potential. The average acid-generation potential, neutralization potential, and net-neutralization potential for the samples shown in Fig. 8 are 527, 317, -210 tonnes CaCO<sub>3</sub>/ktonne, respectively. Analyses of weathered tailings demonstrate that carbonate minerals produce a long lag time to acid generation (greater than 17 years and probably considerably longer) (KGCMC, 2003). Despite the long lag time, oxidation of sulfides and neutralization of acidity by carbonate minerals in the tailings produce pore water that is alkaline but high in SO<sub>4</sub><sup>-2</sup>, Ca, Mg, Zn, As, and Se.

Geochemical zones have developed in the tailings pile. Near the surface of the pile where oxidation rates are high and the tailings are unsaturated, the pore water is high in sulfate, calcium, magnesium. Concentrations of Cu, Zn, Se, Cd, Ni and Pb are variable. Thiosulfate, which is derived from residual process water, persists with concentrations locally exceeding 2000 mg/l (determined by ion chromatography) within one meter of the surface. Samples of pore water containing thiosulfate can have a pH as high as 8 when extracted from the tailings pile, but when the sample is allowed to oxidize the pH can decrease to less than 4. The water remains clear and no precipitates form. Thiosulfate is not added as a reagent in the milling and extraction process. For a description of the formation and fate of thiosulfate in sulfide milling and flotation circuits see Silver and Dinardo (1981). Oxidation of thiosulfate and pyrite at the pile surface produces a substantial amount of acidity, which is neutralized in-situ by carbonate-mineral dissolution. The oxidation products contribute to a high dissolved load in surface runoff.

Deeper in the pile, but above the water table, redox levels decrease and iron, manganese and arsenic concentrations are elevated in addition to the constituents found in near-surface water. Below the water table, microbial sulfate reduction has a dramatic effect on water compositions. Saturated zone water has a distinct hydrogen-sulfide smell, high alkalinity and low metals concentrations. Thiosulfate is either absent or occurs at much lower concentrations (<75 mg/l) in the saturated zone and deeper portions of the unsaturated zone, presumably removed by a combination of microbial and non-biological processes. Water pumped from perimeter and foundation drains contains a mixture of tailings pore water, runoff and groundwater. Dissolution

of Fe- and Mn-bearing soil horizons contributes these metals to groundwater as conditions beneath the pile become more reducing. Examples of different pile-water compositions are provided in Table 1.

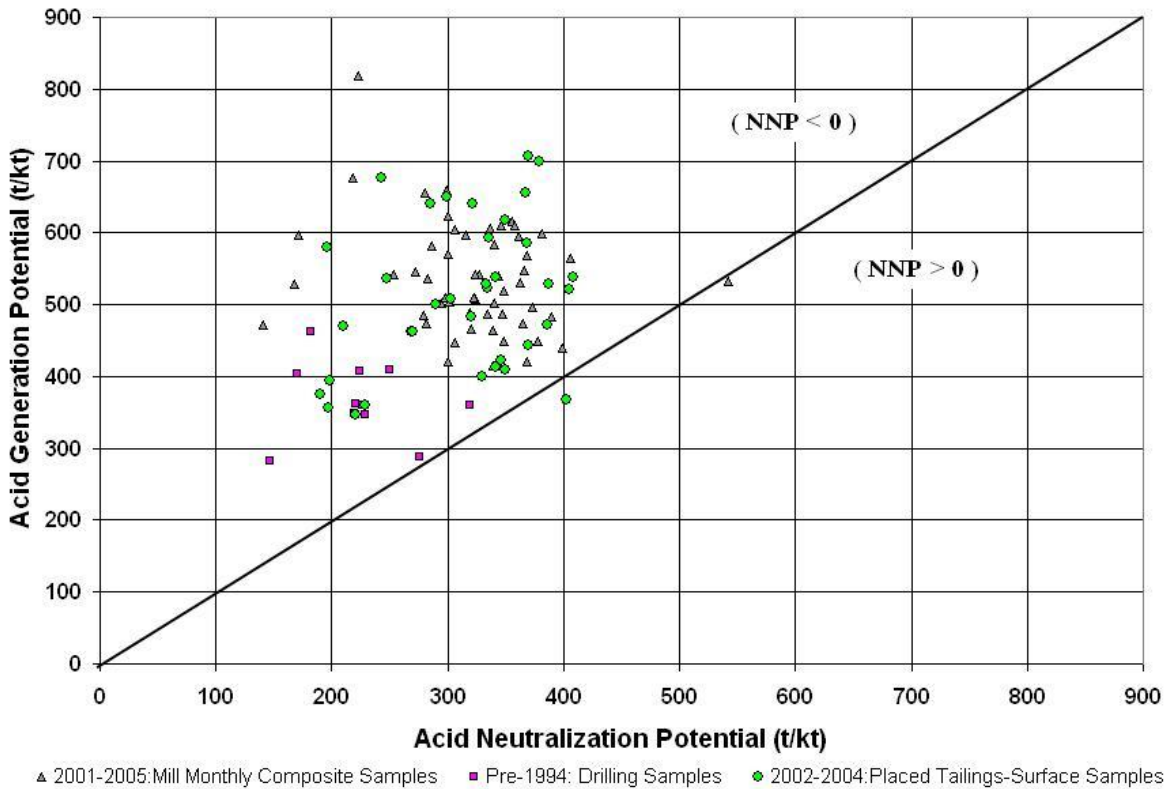


Figure 8. Acid-base accounting data for Greens Creek tailings.

Sulfate-reducing bacteria metabolize organic carbon provided by the mine's sewage sludge, which is placed in the tailings pile in accordance with the mine's waste management permit. Other potential sources of bioavailable carbon include flocculants, other processing reagents and organic compounds in water expelled from the peat in the foundation.

As the pile grows, the water table and redox boundary move. In some locations the oxidized zone becomes reduced, mobilizing Fe, Mn, As, and sorbed metals. KGCMC also places approximately 380 cubic meters of pressed, iron-hydroxide sludge from the mine's high-density sludge co-precipitation water treatment plant in the tailing pile each year. Remobilization of iron, arsenic and coprecipitated metals from dissolution of the sludge under reducing conditions contributes to the dissolved load in the pore water. Selecting a water treatment scheme that matches the anticipated conditions for the sludge is advisable.

Table 1 Examples of tailings pile water compositions.

Zone	Unsaturated	Unsaturated	Saturated	Foundation Drain
Depth	3 meters	6 meters	18 meters	14 meters <sup>1</sup>
ID	SW01-01	SL-T-02-05	PZ-T-00-01	Wet Well 2
Date	7/5/01	6/16/03	9/29/04	8/17/04
pH	8.0	7.3	7.9	6.9
Alk. (mg/l CaCO <sub>3</sub> )	<5.0	NA	585	284
Cond. (µS/cm)	5020	3880	2850	2400
ORP (mV)	111 <sup>2</sup>	-134 <sup>3</sup>	-300 <sup>4</sup>	-36 <sup>5</sup>
H <sub>2</sub> S (mg/l)	<0.1 <sup>2</sup>	<0.1 <sup>6</sup>	>5.0 <sup>4</sup>	<1.0 <sup>7</sup>
Calcium (mg/l)	837	466	175	340
Magnesium (mg/l)	349	182	224	130
Sodium (mg/l)	62	330 <sup>2</sup>	125	34
Potassium (mg/l)	60	19	48	12
Iron (mg/l)	<0.1	15	<0.1	16
Sulfate (mg/l)	2410	2200 <sup>9</sup>	940	1220
Thiosulfate (mg/l)	~1300 <sup>10</sup>	<5	69 <sup>11</sup>	<3 <sup>12</sup>
Chloride (mg/l)	15.5	17.9 <sup>13</sup>	42.2	17.6
Nitrate (mg/l)	0.6	0.7	<0.5	<0.5
Ammonium (mg/l)	NA	<0.1	14	2.96
O-phosphate (mg/l)	<.002	<0.8	<1.5	<0.15
Manganese (µg/l)	68	176	181	3270
Arsenic (µg/l)	34	213	14	21
Antimony (µg/l)	20.4	NA	3.7	0.4
Copper (µg/l)	247	7.4	9.8	1.9
Lead (µg/l)	2.2	5.8	<0.5	<0.03
Zinc (µg/l)	55.2	419	11	439
Nickel (µg/l)	7.1	28.7	3.3	31.5
Cadmium (µg/l)	1.7	<0.2	<0.5	<0.1
Chromium (µg/l)	1.3	3.2	6.7	0.3
Mercury (µg/l)	0.055	NA	<0.2	<0.02
Selenium (µg/l)	145	NA	14	2

<sup>1</sup> The drain wet well is at the base of the pile, 14 meters below the mid-slope of the pile.

<sup>2</sup> Sampled 7/15/01;

<sup>3</sup> Sampled 6/16/03;

<sup>4</sup> Sampled 1/30/03;

<sup>5</sup> Sampled 11/25/02

<sup>6</sup> Sampled 5/9/03;

<sup>7</sup> Sampled 4/23/02;

<sup>8</sup> High sodium concentration in this sample may reflect ion exchange with bentonite used during well installation;

<sup>9</sup> Sampled 10/16/03

<sup>10</sup> Estimate based on charge imbalance, 4 pH unit decrease upon sample oxidation and ion chromatography results from samples from other areas on the pile; <sup>11</sup> Sampled 5/19/05

<sup>12</sup> Sampled 2/16/05;

<sup>13</sup> Sampled 10/16/03

Maintaining a low water table in the pile is necessary to ensure geotechnical stability, but the resulting unsaturated zone may allow oxidation of a greater volume of tailings compared to traditional saturated, slurry-type tailings. The lack of sandy zones caused by size sorting helps reduce gas permeability in the unsaturated zone. Reduced permeability and consumption of oxygen near the surface appears to limit oxidation of the unsaturated tailings. This change in redox chemistry is supported by the presence of grey (unoxidized) tailings and pore water thiosulfate close to (< 1 meter) the surface.

### **Closure**

When the pile reaches design configuration, a 2-meter, composite soil cover will be placed over the tailings. Key cover design aspects include a low-permeability, saturated layer that will limit oxygen and water ingress and a thick growth medium that will prevent freezing of the saturated layer, accommodate growth of spruce and hemlock and provide a means for shedding water off the pile. The cover will accommodate flow from the top of the pile and its 3H:1V slopes. Water treatment will continue as long as necessary to meet NPDES discharge standards after closure.

In 2003 the United States Department of Agriculture Forest Service provided its record of decision of an environmental impact statement for expansion of the tailings pile (USDA, 2003). A requirement of the decision was to determine if it is feasible to promote long-term sulfate reduction in the pile through carbon addition. Promoting sulfate reduction would reduce the metal load in the site drainage and may eliminate the need for active water treatment prior to discharge to Hawk Inlet or drainages adjacent to the site. KGCMC assembled a team of company, academic and consultant researchers to participate in the study, the results of which will be presented at a later date.

### **Costs**

The decision to use the dry-stack tailings method was based on economic assumptions at the time of initial mine permitting. At that time, selecting the dry-stack method represented an 85% savings in estimated capital costs. The actual inflation adjusted capital costs to construct the 10 ha facility and install the filter presses were \$12M and \$5M, respectively. KGCMC incurred additional capital costs of approximately \$7M to develop placement areas after 1994 because design modifications called for localized removal of foundation peat and sand, installation of higher-capacity drains, lining of bedrock exposures, and extension bentonite/soil-slurry walls. In areas underlain by marine silt and clay where a synthetic liner was not required, modified site preparation cost approximately \$0.5M/ha. Areas that received a synthetic liner cost about \$1M/ha. The total inflation adjusted capital costs for the site are approximately \$24M.

With a ten-year estimated mine life, the higher operational costs of filter-pressing and dry-stack tailings disposal were worth the benefits of a smaller tailings footprint, reduced capital costs and improved mine-backfill capability. The mine also avoided the several-year delay that would have been required to construct the larger facility. The total estimated mine life has been extended an additional 15 years over the original estimate, which has reduced some of the cost savings of avoiding construction of the larger tailings dam.

From 1989 through 2004 KGCMC milled approximately 6.4M tonnes of ore and produced 4.6M tonnes of filter-pressed tailings, half of which was placed in the dry-stack pile. The remainder was used as structural backfill underground. Operational costs to dewater tailings are \$1.4/tonne of tailings produced, including labor, materials and maintenance. Haulage and placement costs are \$1.9/tonne and \$1.2/tonne of tailings placed, respectively. These costs also include labor, maintenance and fleet replacement commitments. The haulage fleet is replaced approximately every 10 years (750,000 km) and the D6 bulldozer is replaced at 10 years (27,000 hrs) and compactor 7 years. The total cost to dewater, haul and place tailings in the surface facility is approximately \$4.5 per tonne.

The cost estimate for constructing the composite soil cover is approximately \$250,000/ha. The reduction in footprint between the two disposal methods offers a significant opportunity for savings on reclamation costs. The 78% reduction in footprint from the slurry-type to dry-stack design reduced the estimated cover construction costs by over \$12M. This savings will decrease to \$8.4M because the extended mine life has led to permitting an expansion from 10 ha to 26 ha for the dry-stack pile. However, the increased mine life would have required expansion of a slurry-type dam at considerable cost.

Another benefit of reducing the footprint of a tailings pile is the reduction in water treatment costs. Water treatment costs at Greens Creek are between \$0.0004/L and \$0.0005/L, including labor, reagents, sludge disposal and maintenance. Approximately half of the treatment cost is labor. KGCMC currently treats approximately 5.3 million liters of water per day. A 60 ha slurry-type tailings impoundment would have added approximately 580 million liters per year to the water balance. Assuming it would not require additional labor to treat more water, the annual savings due to the smaller footprint is between \$115,000 and \$145,000. Reducing the footprint also reduces the amount of water that contacts tailings. Reducing the volume of contact water may increase the options available for low-maintenance post-closure water management and treatment.

## **Discussion**

Dry-stack tailings disposal is most appropriate for small mines and mines with footprint limitations. Higher operational costs may limit the applicability of utilizing filter-pressed tailings at larger mines, however, the benefits of reduced water treatment and reclamation costs should be given proper consideration when comparing tailings disposal options. Filter-pressed tailings offer the opportunity to construct a pile that is more stable than a slurry-type impoundment, although heavy precipitation poses serious challenges with respect to achieving appropriate densities. Use of synthetic covers and temporary dry storage and strict adherence to compaction specifications may be required to ensure geotechnical stability.

Controlling fugitive dust is also a challenge during prolonged dry periods, particularly under freezing conditions. Use of synthetic covers, waste rock or a thin layer of ice may be necessary to control dust when conditions are not suitable for water application.

Despite challenges posed by wet weather and freezing conditions, the decision to use dry-stack tailings at the Greens Creek Mine provided economic and environmental advantages. The information gained and lessons learned by KGCMC have the potential to improve the mining

industry's awareness of dry-stack tailings options and reduce the geotechnical, environmental and financial risks of tailings disposal.

### **Literature Cited**

- Environmental Design Engineering (EDE). 2002. Kennecott Greens Creek Mining Company Stage II Tailings Expansion hydrologic analysis.
- International Commission on Large Dams (ICOLD). 1995. Tailings dams and seismicity. Bulletin 98. ICOLD, Paris, France.
- Kennecott Greens Creek Mining Company (KGCMC). 2003. Tailings and production rock site 2002 annual report.
- Klohn Crippen Consultants Ltd. (KCCL). 1998. Kennecott Greens Creek Mine seismic hazard assessment.
- Klohn Crippen Consultants Ltd. (KCCL). 1999. Kennecott Greens Creek Mine evaluation of tailings pile.
- Klohn Crippen Consultants Ltd. (KCCL). 2003. Kennecott Greens Creek Mine tailings project summary of Klohn Crippen reports – 2003 update.
- Klohn Crippen Consultants Ltd. (KCCL). 2005a. Stage 2 tailings facility expansion stability update.
- Klohn Crippen Consultants Ltd. (KCCL). 2005b. Kennecott Greens Creek Mine 2005 geotechnical investigation field data summary.
- Silver, M. and O. Dinardo. 1981. Factors affecting oxidation of thiosalts by thiobacilli. p. 1301-1309. Applied and Environmental Microbiology. Vol. 41 No. 6.
- Steffen Robertson and Kirsten (COL.) Inc. (SRK). 1987. Upper Cannery Tailings Impoundment capital cost estimates for Greens Creek Mining Company. Technical Memorandum 62202/C.
- Taylor, C. D., S. R. Newkirk, T. E. Hall, K. G. Lear, W. R. Premo, J. S. Leventhal, A. L. Meier, C. A. Johnson, and A. G. Harris. 1999. The Greens Creek deposit, southeastern Alaska : a VMS-SEDEX hybrid, p. 597-600. *In* C.J. Stanley et al. (ed). Mineral deposits, processes to processing, Balkema, Rotterdam.
- USDA Forest Service. 1988. Environmental assessment for proposed changes to the general plan of operation for the development and operation of the Greens Creek Mine Admiralty Island National Monument, Alaska.
- USDA Forest Service. 2003. Greens Creek tailings disposal final environmental impact statement R10-MB-482.