

Mine Waste Management in Wet, Mountainous Terrain: Some British Columbia Perspectives

Part II – Creating, Managing and Judging our Legacy

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Abstract

The mining industry in British Columbia is in the process of constructing a number of large mine waste impoundments contained by large dams, and given robust conditions within the industry, more such facilities are being planned. In many instances, these impoundments are required to maintain a state of permanent submergence to prevent acid rock drainage from the impounded tailings and waste rock. Much has been learned in how to properly characterize and manage these wastes, and how to construct the dams required to contain and flood them. British Columbia has made substantial contributions to this body of knowledge, experience, and evolving practice. What has been learned and incorporated into the construction of these mine waste impoundments will be the mining industry's bequest to future generations. The principles of sustainability mandate that we consider fully, today and in the future, the nature of that bequest, how best to manage it, and how it is likely to come to be viewed, and managed, by future generations, for there is never an inopportune moment to step back and contemplate what we are doing today and planning for tomorrow.

Introduction

In a companion paper, Martin (2011a) addressed challenges, past practices, and recent trends related to the management of mine waste in the wet, mountainous regions of the Canadian province of British Columbia. Societal and regulatory expectations and requirements have evolved over the last few decades, and so too have the mine waste practices implemented to address them. Mine waste management solutions that were awarded permits a few decades ago now no longer appear palatable. The solutions implemented in the past, and being implemented today, will represent the contemporary mining industry's most significant bequest to future generations. This paper examines, based on B.C. experience, how that legacy is being constructed, how it is managed and will have to be managed in the future, and offers speculative comment on how that legacy might be viewed in a hundred years' time.

In consideration of the nature of the mine waste legacy the industry is creating today, an issue that has bedevilled the mining industry, not just in B.C. but worldwide, since before Roman times, remains paramount today: metals leaching (ML) and acid rock drainage (ARD).

Managing the Acid Rock Drainage Issue

The website of Natural Resources Canada (NRCAN), Mine Environment Neutral Drainage (MEND) (see <http://www.nrcan.gc.ca/mms-smm/tect-tech/sat-set/med-ndd-eng.htm>) observes: "*Acidic drainage is recognized as the largest environmental liability facing the mining industry and, to a lesser extent, the public through abandoned mines. ... The target is for new mines to open without long term concerns about acidic drainage upon closure*". In B.C., Provincial ML/ARD guidelines observe that for subaqueous disposal to effectively prevent ARD over the long term, "*the storage location must remain permanently flooded and geotechnically stable*" (Price and Errington 1998). An ever-expanding series of invaluable MEND laboratory and field investigations have provided compelling evidence as to the effectiveness of permanent submergence as a means of ARD prevention, and this is

the solution being implemented for many B.C. mines now in operation that produce potentially acid generating (PAG) mine wastes. The efficacy of one approach, as is so often the case, is often reinforced by an example of what not to do, and from an ARD perspective, the development of the Equity Silver mine in the 1980's provided just such an example.

Equity Silver

Price (2003) provides a summary of the ML/ARD situation at the closed Equity Silver mine, an open pit mine that produced silver, copper, and gold from 1980 through 1994. The tailings impoundment is contained by water-retaining dams, and is maintained in a flooded condition, preventing ARD. The waste rock dumps, however, containing about 70 Mtonnes of rock, are not flooded, and these are a source of ARD requiring ongoing water treatment. To reduce the volume requiring treatment, till covers were constructed over the waste rock dumps, which reduced ARD treatment volumes by about one-third. Despite this, particularly high freshet snowmelt runoff events in 1997 and 2002 led to releases of untreated ARD. The need for perpetual water treatment, the care and maintenance to support it, and the potential for upsets in an actively managed system, are legacies that neither mining companies, local residents, nor regulators care to see repeated if at all possible. That said, in some instances, for example pit highwalls that cannot be flooded at closure, or potentially acid generating (PAG) waste rock dumps for which a submergence solution is infeasible, a long term collect and treat situation may well be unavoidable.

Much has been learned, and continues to be learned, from the Equity Silver experience. A particularly critical lesson was the importance of accounting for ML/ARD prevention, mitigation, and control from the very outset. The lesson was taken to heart in B.C., and as noted by Price (2003), "*British Columbia now has a number of mines where ML/ARD concerns were addressed right from the start and mitigation requirements were an integral part of every phase of the operation*". Two of these mines, which commenced operations just a few years after Equity Silver's shutdown in 1994, are Huckleberry and Kemess, which commenced operations in 1997 and 1998 respectively.

Getting it Right from the Start

Huckleberry Mine is an open pit, copper-molybdenum mine located approximately 86 km southwest of Houston, situated on the south flank of Huckleberry Mountain, overlooking Tahtsa Reach, with a daily mill throughput rate of about 18,000 tpd. The Kemess South Mine is an open pit gold-copper mine, located in the Omineca mountain range of north-central British Columbia, approximately 300 km northwest of Mackenzie. The plant throughput rate was about 54,000 tpd, with milling operations ceasing in early 2011, and the site entering the closure and reclamation phase.

The ML/ARD management plans for the Huckleberry Mine are described by Johnson and Day (1999) and by Lighthall et al. (2007). Stogran et al. (2004) describe the waste management program for the Kemess Mine. The provincial ARD guidelines (Price and Errington, 1998) were being developed and introduced during the planning of both mines. While the specifics between the two were somewhat different to account for site-specific conditions, the ML/ARD management plans incorporated within the initial permits for both mines included the key elements summarized in Table 1. An added feature at Huckleberry, which involved two open pits (Main Zone and East Zone) less than 1 km apart, was integration of ML/ARD aspects into the open pit sequencing, with the Main Zone pit being mined out relatively early on, in order to provide for storage, and eventual flooding, of PAG waste rock and tailings produced from mining of the larger East Zone pit, separated from the Main Zone pit by a till core dam (East Dam). To a significant degree the ML/ARD management plan at Huckleberry drove the mine plan.

The ML/ARD characterization and management programs implemented at both sites, and the data derived from them, allowed for significant optimizations of PAG tailings and waste rock handling at both sites, as discussed further below. The adaptive management and optimization on the basis of ongoing ML/ARD characterization work both validated and demonstrated the value of the B.C. ML/ARD guidelines.

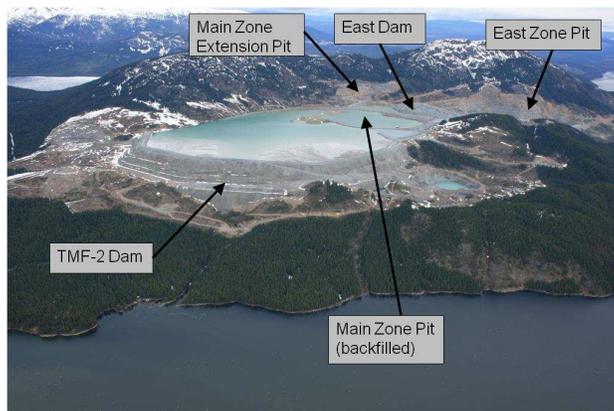


Figure 1: Huckleberry mine site (from Lighthall et al., 2007)

Table 1: Key aspects of ML/ARD management plans: Huckleberry and Kemess

ML/ARD Management Plan Aspect	Huckleberry	Kemess
Permanent submergence of PAG waste rock and tailings	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
Submergence of PAG waste rock within two years of its exposure	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
Continuation of long term kinetic testing commenced prior to mine operations	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
Blast hole sampling to confirm NPAG/PAG prior to waste rock being hauled, and NPAG/PAG boundaries staked in the pit	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
Post-blast sampling and testing to confirm NPAG/PAG segregation to be correct	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
Rigorous field controls and checks to ensure NPAG/PAG waste rock hauled to correct destinations	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
Segregation of waste rock into 7 categories (considering neutral ML and ARD) for haulage to designated areas		<input checked="" type="checkbox"/>
Lithology-specific PAG/NPAG NPR cutoff criteria	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
ML/ARD testing of materials used for downstream shells of the tailings dams to confirm NPAG materials only used	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
Regular ML/ARD management plan reporting to B.C. Ministry of Energy and Mines (MEM)	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>

Waste Rock and Tailings Co-Disposal

Waste rock management planning for Huckleberry and Kemess, the initial permits for both of which mandated submergence of PAG rock within two years' exposure, incorporated co-disposal of waste

rock with the tailings. For Huckleberry, with a compressed site layout as shown in Figure 1, the requirement to haul PAG rock to the tailings facility was not onerous. For Kemess, on the other hand, a 7 km uphill haul from the pit to the tailings facility was required. For both dams, with central clay till core zones raised via the centreline method, the PAG rock was used for temporary upstream support of the till core in advance of the rising tailings beach, as shown in Figure 2. While this is beneficial to support centreline raising, it also results in a material of high hydraulic conductivity in direct contact with the till core zone, which means a hydraulically conductive pathway for seepage to any cracks in the dam cores, or to any pervious horizons at the base of the PAG waste rock. This concern can be mitigated in a number of ways, including providing for a till blanket (either natural or placed) below the PAG waste rock to hydraulically isolate it from the dam foundation, and providing an above water tailings beach to separate the water pond from the waste rock. Regardless of these measures, a robust filter is required to the downstream of the central till core under any circumstances.

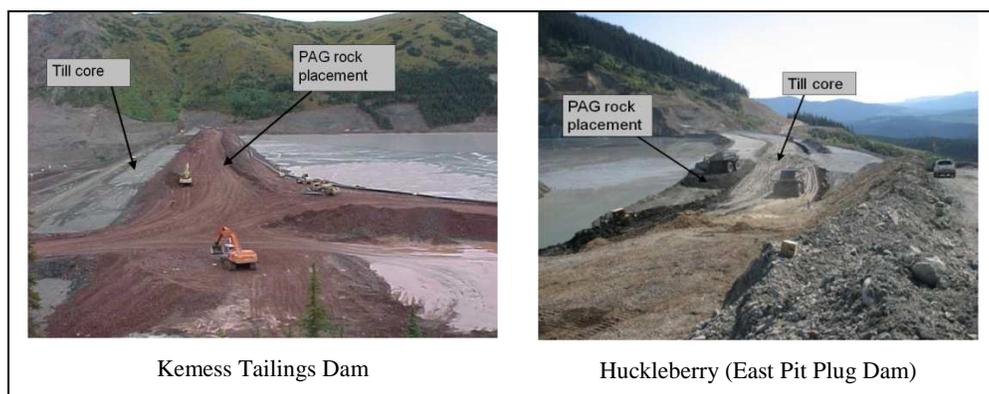


Figure 2: PAG waste rock placement upstream of tailings dam core

A recent project in which the writer is involved demonstrated that, in some instances, tailings and PAG waste rock co-disposal is infeasible. For that project, the volume of waste rock was considerably higher than that of the tailings, and with relatively pervious foundation soils, this would eliminate any seepage reduction benefits of a continuous tailings deposit, with the result that full reservoir pressure could be transmitted into relatively pervious foundations. As such, for geotechnical reasons, tailings and waste rock co-disposal at the scale being proposed will not be implemented for that project.

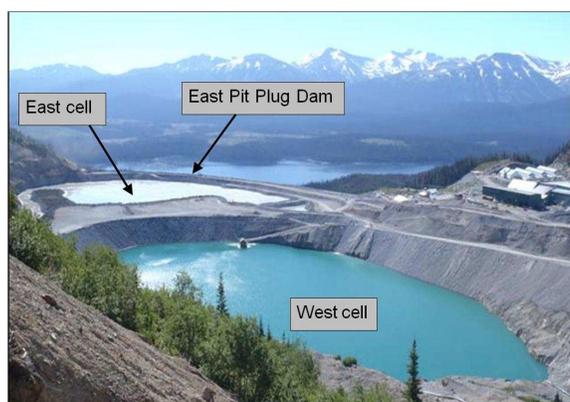


Figure 3: Tailings and waste rock co-disposal: Huckleberry Mine East Zone Pit

In recent years at the Huckleberry Mine, tailings and PAG waste rock have been directed to the mined-out East Zone Pit (see Figure 3). The pit has been divided into two cells, the west cell (foreground, with the reclaim water pond and barge) and the east cell (background), the division defined by a causeway of PAG waste rock. The PAG waste rock retains the tailings in the east cell, which in turn provide for a means of seepage reduction below the dam constructed at the East Pit Plug Dam across the low point along the pit rim, and provide support for centreline raising of that dam.

Waste Rock Stockpile and Rehandle for Pit Flooding

The ongoing ML/ARD testing and monitoring programs and Kemess and Huckleberry yielded data sufficient to convince the regulators that the permit requirement for PAG rock submergence within two years' exposure could be eliminated, which afforded greater flexibility and reduced costs for both mines. In the case of Huckleberry, this made possible the mining of the Main Zone Expansion pit, which in turn required substantial dewatering of the impoundment between the TMF-2 and East Dams, and thus de-saturation of previously flooded PAG waste rock. At Kemess, rather than a 7 km uphill haul, PAG waste rock was short-hauled and stockpiled at an ex-pit dump, underlain by a constructed till liner, for eventual backhaul into the mined-out Kemess pit. That PAG rock backhaul at Kemess was completed in 2011, and the stockpile pad reclaimed, as shown on Figure 4.

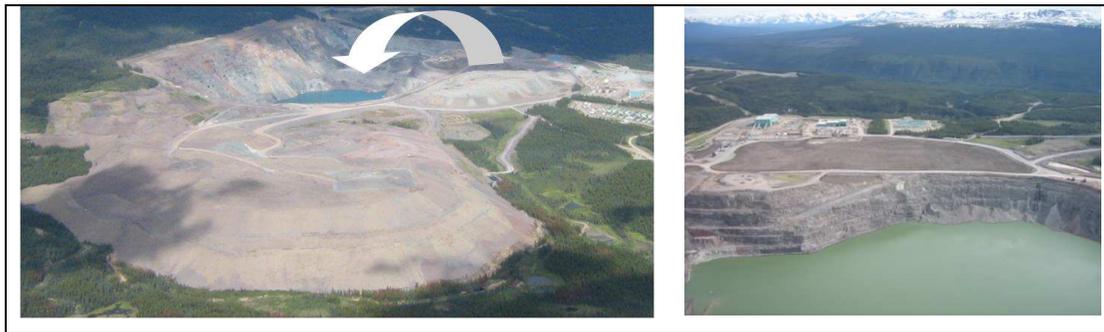


Figure 4: Kemess Mine: PAG waste rock stockpiled and rehandled for pit submergence

Two important points are to be noted here:

1. These optimizations were made possible by the ongoing ML/ARD characterization programs, which formalized and implemented a system of “continuous learning” in terms of site-specific ML/ARD issues. Rather than a “chore”, these programs represented an opportunity for the mine to demonstrate if initial permit conditions were overly conservative, and, if so, propose amendments to the ML/ARD plans, armed with the data to back them up.
2. Throughout this process, both mines worked closely with very knowledgeable and experienced personnel within the B.C. MEM, in order to provide and document the evidence such that the permit terms could be amended, an excellent example of a regulator not just regulating, but facilitating.

There has been much recent cutting back and attrition in the B.C. MEM, with undoubtedly additional such pressures in the pipeline given the governmental budgetary constraints now becoming the norm in many jurisdictions. Any loss of expertise and capacity within MEM could well render the sort of cooperative approach that proved of such benefit to both Huckleberry and Kemess more difficult to enact in the future. Loss of expertise and capacity such as that within the B.C. MEM constitutes a loss to the mining industry in B.C., as well as the public.

Managing the Sulphides: It's All About Process

Another enhancement at Kemess arose from a significant change to the design of the tailings dam. Given the presence of weak, pre-sheared glaciolacustrine soils at residual strength within the dam foundation, a large downstream buttress (see Figure 5) was required to maintain adequate stability. This buttress, from starter dam construction through 2002, was constructed from NPAG waste rock hauled 7 km uphill from the open pit. This represented one of the largest ongoing capital cost expenditures at the mine and, as described by Rasmussen et al. (2004), in 2001 various Kemess departments embarked upon studies to assess the viability of using cycloned tailings sand for downstream shell construction, in lieu of NPAG waste rock. The studies undertaken by Kemess were positive, and determined that NPAG cycloned sand with the requisite low fines content for hydraulic fill placement could be produced. An extensive geochemical characterization study was undertaken to demonstrate that cycloned sand that was both NPAG and lacking in neutral metal leaching concerns could be reliably and consistently produced. It was determined that an additional flotation circuit was required to remove sulphides from the underflow from the first stage of the two-stage cycloning process. It was further determined that of the four ore types processed at Kemess, only hypogene ore could be used to produce cycloned sand that was both NPAG and did not pose a potential neutral metals leaching concern. The design modifications to the dam, related principally to filter blankets and under-drainage control measures required to accommodate hydraulic sandfill placement, are described by Lysay et al. (2007), which chronicles the design evolution of the dam.

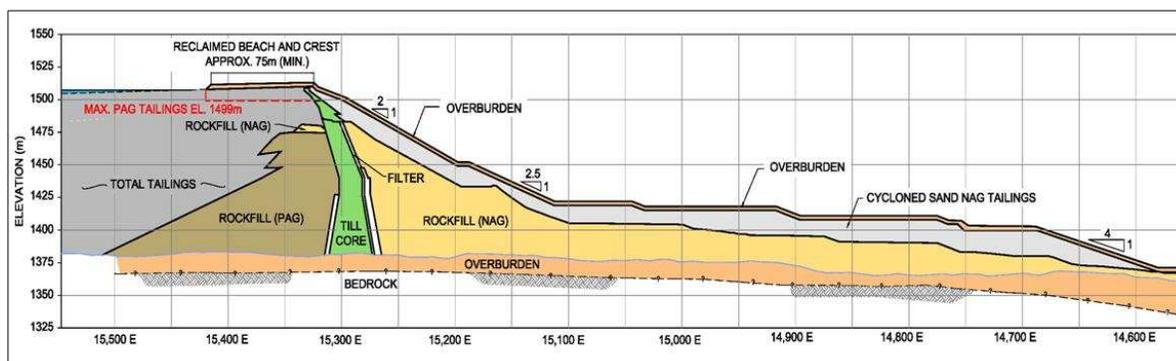


Figure 5: Kemess Mine tailings dam – simplified design section

A noteworthy aspect of the Kemess cycloned sand production was the level of controls put on the process to ensure that the sand produced met the specified requirements for NPR (carbonate-based) > 2. The procedure implemented is illustrated by and summarized within Figure 6. To speed analytical turnaround, a correlation between NPR and the sulphur/carbon ratio was developed, and a control ratio set to correlate with $\text{NPR} = 4$. The cycloned sand control and testing procedures were added to Kemess' ML/ARD management plan, with the result that a comprehensive geochemical as-built record was developed. Once again, the active participation of geochemical expertise within the B.C. MEM was instrumental in guiding and facilitating the studies and test work that supported the permit approval and successful implementation of this design change.

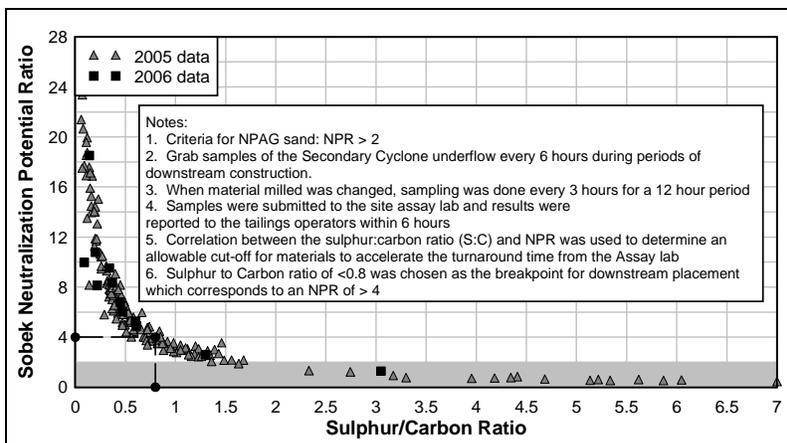


Figure 6: NPAG cycloned sand control procedure used by Kemess

Cycloned sand construction commenced with the commissioning of the cycloned sand plant in October 2002. The dam has since been completed to its final configuration, and reclamation activities are well-advanced. Cycloned sand was also used for upstream support of the annual core raises, in lieu of PAG waste rock which, per the discussion above, was being stockpiled in the ex-pit dump for eventual backhaul to the open pit.

Another benefit of the NPAG cycloned sand system was the ability to develop and maintain an above-water beach of NPAG tailings, lacking metal leaching concerns, between the core of the dam and the water pond. Due to the net annual water balance surplus for the Kemess tailings facility, maintenance of an above-water beach along the entire 1 km length of the dam crest had always been a challenge. However, via cell construction using NPAG tailings, such a beach could be developed and maintained on a consistent basis. An above-water beach between the core and the water pond was also a geotechnical design requirement, and is judged a significant enhancement in terms of long term dam safety when compared with a water pond up against the crest of the dam. The final above-water beach for the tailings facility is shown in Figure 7. A wider beach was specified near the left abutment owing to more fractured volcanic bedrock on that side of the valley. A filter and rockfill sequence was placed over the upstream slope of the beach to provide for erosion resistance against waves, once the reservoir is brought up to its full pool elevation post-closure.

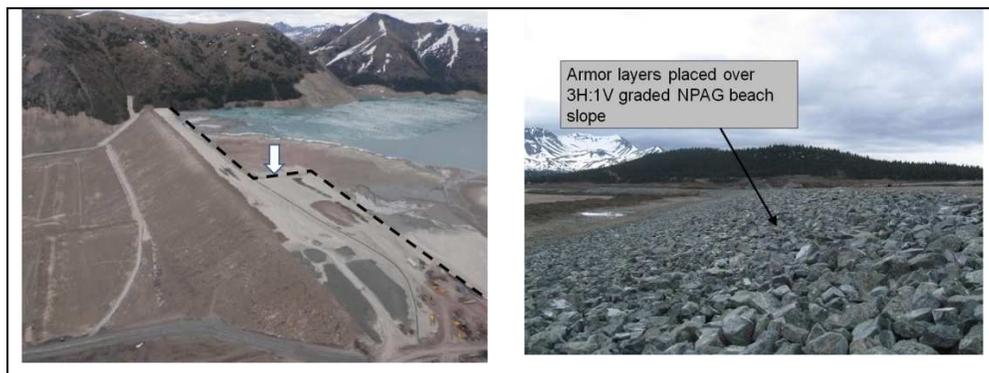


Figure 7: Kemess Mine: above-water NPAG tailings beach for final closure configuration

At Huckleberry, an above-water tailings beach in front of the large TMF-2 Dam was also stipulated as a geotechnical requirement. Huckleberry found that NPAG tailings could be produced from the rougher tailings circuit with some minor modifications to the mill process. The final stage of tailings

discharge to impoundment from the TMF-2 impoundment therefore comprised NPAG tailings, so that the PAG tailings below will either be flooded at closure or, within the plan limits of the above-water tailings beach, below the phreatic surface.

The experiences at Huckleberry and Kemess are representative of contemporary mine waste characterization and management practices for mines in B.C. with potential ML/ARD concerns. The B.C. mining industry and the B.C. MEM are fully entitled to give themselves a pat on the back for ingenuity and resourcefulness in grappling with mining's most significant environmental problem – ML/ARD. Lest such success elicit a smug sense of superiority relative to the predecessors at whose outdated mine waste management (or lack of management) practices we may now disdain, we should give pause. Our predecessors solved the principal mining problems of their time by creating another for future generations to grapple with. The principle of sustainability therefore compels us, at all times, to confront ourselves with the following question: might we be doing likewise?

Managing Our Legacy

It is self-evident that amongst the legacies that the mining industry today will leave to future generations, that with the greatest visibility and liability involves flooded impoundments of PAG tailings and waste rock. As outlined above, the industry has become ever more adept and proactive at their planning, design, construction, operation and stewardship. Although not in business for the purposes of dam construction, in B.C. the mining industry in recent decades has built, and is in the process of building, many large, world-class dams, with yet more on the drawing board. The industry has become ever more experienced and skilled in the in the planning and implementation of closure and reclamation of its mines, and in undertaking such activities proactively and progressively, while operations continue. Designing and operating for closure are neither ideals nor slogans – they are simply how the mining business is now conducted in B.C.

All well and good, but one step remains, a step with which we are only beginning to grapple, and the one that will be of principal and profound interest to future generations: how effectively will we steward these large impoundments and structures once closure and reclamation are completed?

Flooded Impoundments in Mountainous Terrain

Vick (1999) examined the implications of tailings dam safety to the broader dam safety community, and did so in a manner that accentuated the implied choices associated with the preferred ML/ARD prevention technology of today: permanent submergence of sulphidic mine wastes. Vick cited experience that indicated “*stability of most inactive tailings dams can be assured simply by preventing permanent accumulation of surface water stored behind them following the end of their operational life*”. However, this condition favourable to long term stability is precluded by design for the large, flooded waste impoundments that have been constructed to date, are being constructed today, and have yet to be constructed. As such dams and impoundments accumulate, so too does the mining industry's collective liability for them. Using tailings dam failure statistics to estimate an annual probability of failure per tailings dam, Vick (1999) demonstrated with basic probability calculus what should be intuitively obvious. The combination of a given annual probability of failure, an ever increasing inventory of flooded impoundments, and an indefinite period of exposure, as a flooded impoundment is never taken out of service, leads inexorably to a cumulative probability of failure that increases much more rapidly with time for flooded impoundments than for those not in a flooded state. This constitutes the barter that the industry, its regulators, and the public implicitly accept in adopting the ML/ARD prevention technology that is the permanent submergence solution.

The increased dam safety risk associated with a permanent water cover can be ameliorated to some degree via such means as above-water NPAG beaches between the dam and the water pond, and wetland type closure scenarios that maintain saturation rather than a large water cover. Nonetheless, as Vick (1999) observed, tailings impoundments incorporating water-retaining dams and a flooded/saturated condition within the impoundment are not, in geotechnical terms, ever truly closed.

The Status Quo is Not an Option

Maintaining appropriate dam safety stewardship for this ever-growing inventory of large, flooded impoundments poses the mining industry's most significant challenge in managing the legacy it bequeaths to future generations. In B.C., terrain and climatic conditions serve to amplify that challenge. Moreover, it is starkly evident that maintaining the status quo in terms of dam safety stewardship is not an option, as probability calculus dictates that the only means by which we can possibly reduce the cumulative probability of a failure, and still have a mining industry with an increasing inventory of closed sites, are: a) hope for some future technology wherein the ML/ARD issue is dealt with, either in the plant or within the impoundment, such that the need for submergence is retroactively eliminated; b) seek alternative means of providing submergence that reduce or eliminate dam safety risk; or c) continuously improve all aspects of dam safety stewardship so that the annual probability of failure of a tailings dam going forward is significantly decreased relative to experience to date.

It is neither rational nor responsible to plan now on the basis of some new, imagined, hoped-for technology of the future, although with the mining industry's record of innovation, improved solutions to ML/ARD issues are surely a matter of when, not if, and the answer may well reside not within how we construct and manage impoundments, but rather what happens in the process plant. As discussed in a companion paper (Martin, 2011a), two previously deployed alternative means of providing submergence, lake disposal and ocean disposal, are now judged such pariahs it seems impolitic to even mention them anymore, besides which they are not available as options for most sites in any case. Other means will have to be found.

For the foreseeable future, we are left with ever improving dam safety stewardship as the only means of managing and mitigating the permanent submergence versus dam safety risk bargain the industry, its regulators, and the public have collectively made. It is incumbent on all parties, but most particularly the mining industry, to ensure that the bargain does not become Faustian in nature, and this was the conclusion the writer took from Vick's sobering presentation at the 1999 CDA conference. It is by no means a new one. Industry associations such as the Mining Association of Canada (MAC), the Canadian Dam Association (CDA), the International Committee on Large Dams (ICOLD), other international organizations and, most critically, mining companies themselves, have been spearheading initiatives in this direction for years now. The MAC (1998) guidelines for the management and operation of tailings facilities, which provide a stewardship framework, appropriately emphasize one particular aspect forcefully and repeatedly: senior level management review for continual improvement. It will undoubtedly take time for such initiatives to become reflected in the safety record for mine waste impoundments, and indeed, on a global basis, a review by Davies and Martin (2009) suggests that the frequency of serious incidents, and thus the annual probability of same per tailings impoundment one would derive from that frequency, has not declined since 1968. Statistics appear then to indicate that over the course of the past decade, the status quo is the reality, however unacceptable that may be going forward. A step change improvement is needed.

As the inventory of large flooded impoundments in British Columbia increases over time, the mining industry in this province will find itself as much in the dam safety business, if not more so, as is B.C.

Hydro, for which dams constitute revenue-generating assets, not liabilities. Management of that legacy will require that the mining industry replicate a B.C. Hydro level of effort to its closed facilities on an ongoing basis, with continuous review and improvement the cornerstone of that endeavour. This will include dam safety reviews as prescribed in the CDA (2007) dam safety guidelines, a practice now mandated by the B.C. MEM. But besides taking that and the other aforementioned initiatives to heart, the mining industry would do well to make use of a well-established, well-substantiated, but much under-utilized means of improving the safety of mine waste impoundments: independent review boards or other forms of systematic third party review.

Independent Review Boards for Mine Waste Impoundments

Martin and Davies (2000) discussed a number of recent trends related to the stewardship of tailings management facilities. Amongst the noted trends was the increasing engagement of independent, third party review in the form of a review board, comprised of eminent and acknowledged experts in the various disciplines falling within the terms of reference of the board. The functions and benefits of such boards are described by Matich (1986), McKenna (1998), and more recently Morgenstern (1999, 2010), who crucially observed that, for documented case histories of tailings impoundment failures, “*in no case was there systematic third party review*”. A number of large, multi-national mining companies formally mandate systematic, independent third party review, be it in the form of review boards or other means, as a formal risk management tool at a corporate level. Apart from safety issues, such systematic and independent review is no less beneficial in the context of risk communication and acceptance for mine waste management solutions, acquiring and maintaining the trust of regulators and the public, and facilitation of regulatory review processes.

The Kemess tailings management facility greatly benefitted from the continuous involvement, since 1997, of a review board, the three members of which collectively possessed over 120 years of experience. The Review Board was indispensable in helping the owner, the designer, the operators, and the regulatory agencies grapple with the many challenging aspects of that tailings facility. The writer’s view of the benefits derived from the Review Board’s involvement are eloquently expressed by Olive (2003), who in describing the function of the review board for the design and construction of the precedent-setting in-lake dikes at the Diavik Diamond Mine in Canada’s Northwest Territories, stated “*The board gave comfort to the owners and the regulators, but just as importantly, it was a constant source of reassurance, of wisdom, of encouragement, and occasionally of cautionary advice to the engineering team. Their meetings also provided the very useful discipline of forcing us, in the midst of the chaos of activity, to stop, think, articulate, debate, and record our ideas so that we knew we were on solid ground.*”

Dam Safety in Remote Areas

None the least of the challenges for ongoing stewardship of closed flooded mine waste impoundments in B.C. is the remote nature of many of the facilities already completed, under construction, or being contemplated. Site access will not be a routine matter, and human presence for inspections will be infrequent, but already technology is providing solutions. With remote surveillance capabilities, automated data acquisition and transmission systems, satellite uplink technology, remote sensing, and other emerging technologies, the capacity for remote monitoring of closed tailings dams and impoundments is impressive already, and is quickly advancing. The instrumentation network for the Kemess tailings dam, for which closure and reclamation activities are in progress, is currently being upgraded for the closure phase, and fitted with systems to allow instrumentation and surveillance (cameras) to gather and transmit vital information to personnel responsible for monitoring. Threshold limits for nominal and alarm levels will be programmed in and automatic notifications directed to the

appropriate parties. As technology inexorably advances, so will the ability to monitor and steward modern mining's legacy.

Operational and Closure Spillways for Tailings Impoundments

It is common practice in B.C. to not have in place emergency overflow spillways for tailings impoundments during the operational life of the mine (i.e. when the dams are being raised on an annual basis), with the proviso that sufficient flood storage capacity is provided at all times. Often, only at closure is a spillway constructed. For tailings dams, there is an interesting and unintended consequence of the ability to operate these facilities without an emergency overflow spillway. Namely, the design of the closure spillway can tend to remain in a conceptual "line on a drawing" state until closure draws near, and only then does it become fully evident just how difficult and expensive the construction of the closure spillway can be. Further, many factors go into the site selection for a tailings dam, including spillway conditions, but for the vast majority of the life of a tailings facility, which is to say closure, the significance of most of the other site selection factors (most particularly, avoidance of permitting roadblocks) that were once pre-dominant have diminished to irrelevance, and it is the closure spillway, at the early project planning stages too often something of an afterthought, that is of principal importance. Finally, as miners are exceedingly adept at finding more ore and thus producing more tailings, unanticipated dam raising requirements due to increased storage capacity requirements can result in locations once designated for the closure spillway being instead occupied by a higher tailings dam, and preferred spillway alignments displaced with less favourable alignments becoming a fait accompli.

B.C.'s mountainous terrain poses a myriad of challenges to spillway design and construction, and the closure spillway currently under construction for the Kemess Mine tailings facility serves to illustrate several. The right dam abutment, despite bedrock being exposed, was unsuitable due to its steep grade and talus activity and avalanche chutes. The left abutment is free of geo-hazards, and the terrain relatively benign, but the spillway could only be located in bedrock for the first half of the 2.4 km alignment (solid line, middle frame, Figure 9). The chute section of the channel, which has slopes between 10% and 20%, was therefore lined (compacted till in some areas, geomembrane in others), with an overlying filter and transition zones sequence, and large riprap, which had to be quarried from a NPAG rock source. Because of fracturing of the rock, significant waste was produced from the quarrying operation.



Figure 8: Kemess Mine tailings dam (left) and closure spillway (right, under construction)

Because of the requirement for a wide above water tailings beach post closure in the left abutment area, a long approach channel was required. The channel was kept in bedrock for as far downstream as possible before beginning the chute section, to reduce the likelihood of a spillway failure that could in turn lead to erosion of the downstream shell of the dam. The fact that the dam has an overall downstream slope of 6.5H:1V further lengthens the spillway, which has an elevation drop from inlet to outfall of about 180 m, designed for a peak routed PMF flow of 35 m³/s.

The approach channel and inlet structure were designed to prevent the formation of frazil ice in the winter via maintaining slow flow velocities, with a v-notch in the weir, to concentrate the slightly warmer water under the winter ice cover in the approach channel and allow it to flow over the weir into the steeper downstream channel before freezing. A barrier is being constructed at the inlet to prevent the channel becoming clogged with ice and debris. A program of periodic clearing of fallen trees and floating debris from the reservoir will be required in perpetuity. Instrumentation is planned for the spillway and its reinforced concrete control structure, including thermistors, water level monitors, and cameras, with all data to be transmitted via satellite uplink, and pre-set trigger levels for various actions including notifications should anomalous conditions be indicated.

For the main Huckleberry tailings impoundment, in distinct contrast, with a bedrock saddle near one of the dam abutments, and a natural drainage course largely incised into bedrock that discharges beyond the dam's downstream toe, the closure spillway will be constructed by means of a relatively minor rock cut. Such fortuitous conditions for tailings impoundment closure spillways have proven decidedly rare in B.C. in the writer's experience.

How Long is “Long Term”?

Dam safety stewardship for the ever-expanding inventory of large mine waste impoundments in B.C. is a long term commitment, which in turn leads one to ponder if “long term” can be quantified in any graspable manner inasmuch as closed mine waste impoundments are concerned. Flooding of PAG mine waste may prevent ARD, but it also preserves the potential to generate it, presumably forever. But forever is a frame of reference that is anything but comprehensible, so we need a concrete timeframe. Some useful context in this regard might derive from a topical issue far more fashionable nowadays that the long term safety of tailings impoundments: the climate change issue. This is not altogether unrelated to mine waste closure, as those designing mine waste management solutions are frequently queried “*how have you accounted for climate change in your design?*” Given that climate has been changing more or less continuously for the last 4.5 billion years or so, with far more dramatic change even during the supposedly stable and benign Holocene than the change of recent decades which has elicited such excitement, this query is, however much an outgrowth of the clamour of the times, both valid and long overdue.

The climate change issue provides quite a useful context for pondering the nature of “long term” in a manner useful to the subject at hand. Figure 7 provides one measure, and represents temperature anomalies as recorded in Greenland ice core data reaching back 800,000 years. For roughly 90% of that timeframe, the planet in general, and British Columbia in particular, has been gripped by the Pleistocene's succession of ice ages, with ever so brief respites represented by the inter-glacial periods, which typically last no more than about 10,000 years. The current inter-glacial is the Holocene, which is already well beyond its “best before” date in juxtaposition to previous inter-glacials.

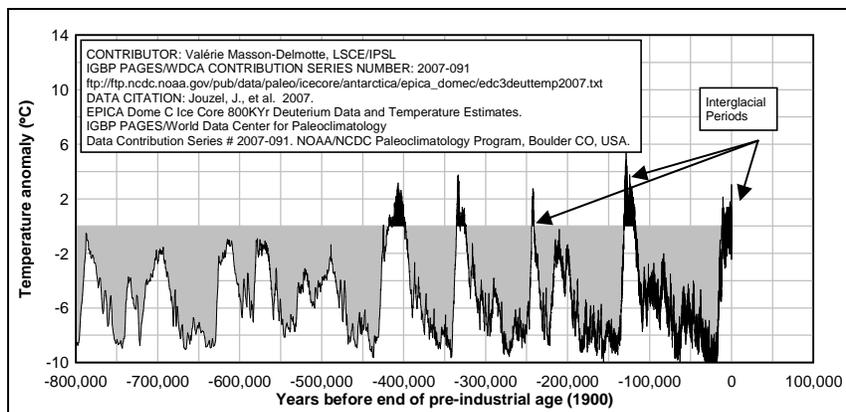


Figure 9: EPICA C ice core temperature proxy data to 800 kya

Of course, should the Holocene inter-glacial come to an end, as Figure 7 rather compellingly suggests it eventually must, humanity in general, and British Columbians in particular, will presumably have far more pressing concerns than the fate of mine waste impoundments. So, taking a more condensed perspective of what the phrase “long term” might entail, ponder the higher resolution ice core paleoclimatic data for the Holocene, plotted in Figure 8. These data indicate climate swings during the Holocene considerably more rapid, and of greater amplitude, than the warming of recent decades that has elicited widespread alarm. At the end of this plot is the modern warm period, which marks the recovery from the very recent Little Ice Age, the coldest period in the Holocene since the end of the Wisconsin glaciation. We see also in this plot post-ice age sea level rise orders of magnitude higher than the 2 to 3 mm/year currently being recorded, and that global temperatures, as represented by ice core data from Greenland and Antarctica, have been in overall decline since the warmth of the early Holocene, a trend consistent with the pattern in previous inter-glacials prior to their demise.

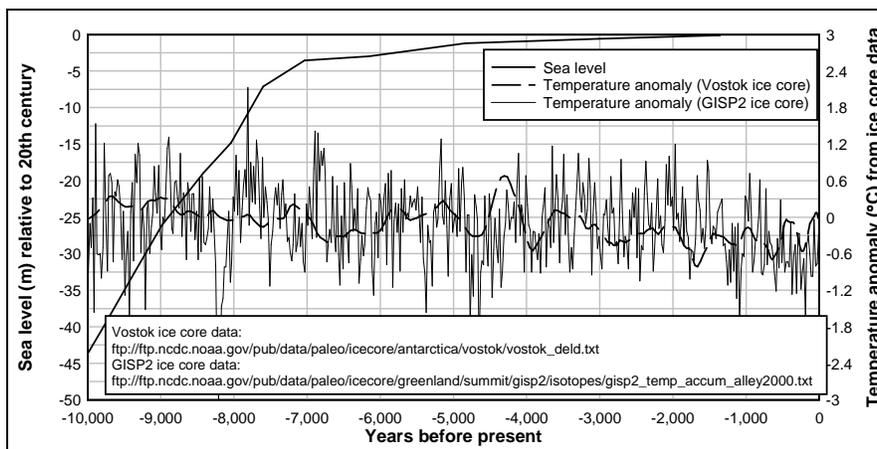


Figure 10: Ice core temperature proxy data to 10 kya

The entire progress of human civilization has taken place largely in the latter two-thirds of the Holocene. Many civilizations have risen and fallen over this timeframe, and climate change has been a significant contributor to this anthropogenic turmoil (Fagan, 2004). Given the changes that have taken place, it would seem the zenith of hubris and fantasy to imagine we can devise closure solutions valid on a millenary scale. We need to look shorter term in our quest to define “long term”.

Consider next the paleo-climatic data for the previous two millennia, in Figure 9, resolved to a scale of centuries, illustrating distinct climatic eras well-documented in recorded history. Figure 9 shows that climate can vary dramatically even over the centenary timeframes we typically attempt to ponder in

terms of mine closure designs. As an anecdotal demonstration of this, consider that in 1653 the alarmed villagers of Naterser, their village besieged by the rapidly advancing Aletsch glacier in Switzerland, arranged for Jesuit priests to deploy “the most important exorcisms” against the advancing wall of ice (Fagan, 2000). In 2007, a mere three and a half centuries later, 600 activists stripped naked to lie on that very same Aletsch glacier to protest global warming¹ and bewail the glacier’s retreat. Over a few centuries climate had changed radically; only the reliably bizarre and angst-ridden response of humanity to climate change seemed to have held steadfast and unwavering.

The foregoing would seem to address two points. Firstly, in terms of closure designs and planning, and the legacy we bequeath to our descendants, a centenary timescale is the most we can realistically even hope to comprehend and avoid accusations of mine waste divination. Secondly, it is quite clear that climate change considerations should indeed be accounted for in the design, management, closure, and long term monitoring of closed tailings impoundments. We are but two centuries removed from the end of the Little Ice Age in western Canada (Menounos et al., 2009). Bruce (2003), and the B.C. Ministry of for Land, Water and Air Protection (2002), show there have been statistically significant changes in hydrometeorology observed over the course of the 20th century, and given the size of watersheds to be accommodated or diverted for many waste management facilities in B.C., such changes can be more than statistically significant. This is particularly so in watersheds affected by glacial retreat (Moore et al., 2009), which leads to a host of geo-hazards that can affect waste impoundments over the long term.

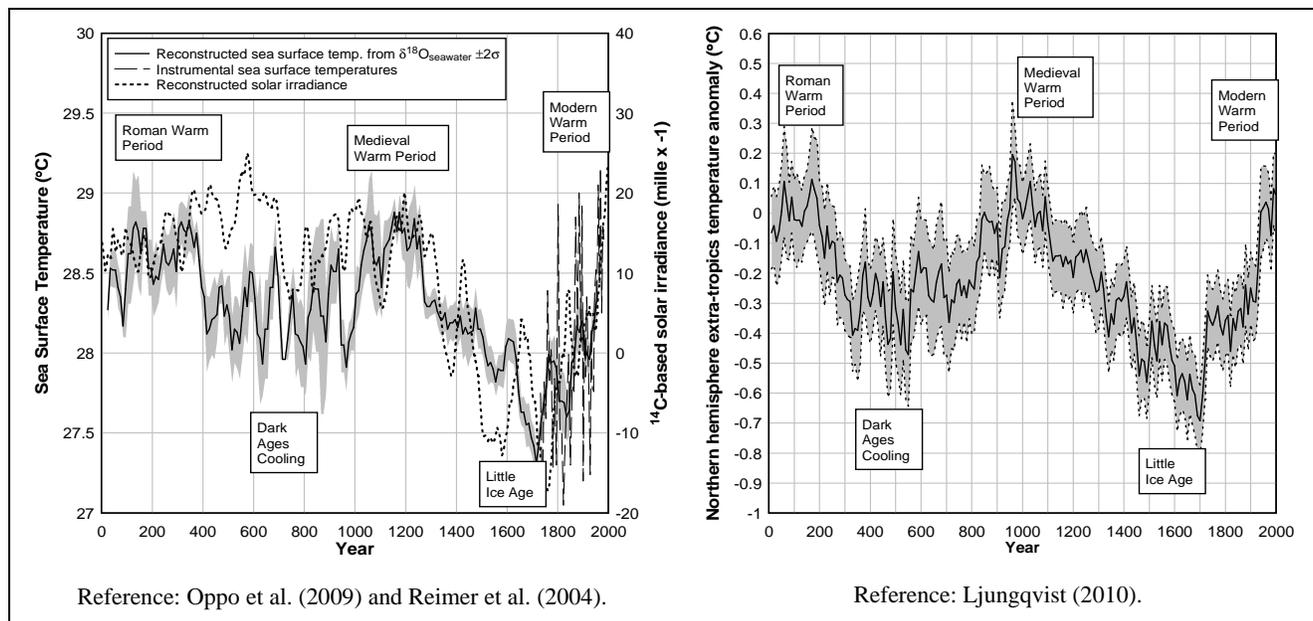


Figure 11: Proxy-based paleo-temperature reconstructions to 2 kya

But how should climate change be incorporated into designs and closure planning, or other long term considerations for that matter? The notion that this should be achieved via unidirectional projections of climate centuries from now, based on computer models that assume an anthropogenic “command and control” climate, and that have demonstrated a rather shoddy forecasting track record (e.g. Fildes and Kourentzes, 2011, Anagnostopoulos et al., 2010, and Stephens et al., 2010) on global and particularly regional scales, is imprudent. Closure designs are far better evaluated for resiliency under

¹ See <http://www.greenpeace.org/international/en/news/features/naked-glacier-tunick-08182007/>.

the range of climate change that has been observed to have occurred within the Holocene, of either sign, rather than on prophesied climate change that is anthropogenically “mandated” to occur. Our Holocene ancestors had to adapt to climate change of many varieties and signs. In the stewardship of our growing inventory of mine waste impoundments, in accounting for climate and other long term considerations, it would be fallacious to imagine we and our descendants will not have to do likewise.

A Cautious Gaze into the Future

It is inevitable that, at the conclusion of a retrospective on mine waste management practices in B.C., encapsulating one’s personal experience and the experience of others, there should be the temptation, in spite of better judgment, to indulge in prognostication as to future trends pertinent to this topic. Indulging such temptation can in a sense be excused on the grounds that mine waste management solutions are supposed to be long term, closure is to be incorporated into design from the very start, and so it is incumbent on the mining industry, the consultants it employs, and its regulators, to be thinking long term. After all, closure is for perpetuity, and perpetuity, however one chooses (or not) to quantify it, is a long time.

However, predictions tend to be based on linear thinking, and as such will more often than not be shipwrecked by the reality of a non-linear world that is chaotic, complex, random, and inherently unpredictable. We cannot possibly gaze, say, 100 years into the future with any justified confidence, and to illustrate this, one need merely ponder if any person associated with the mining industry, 100 years ago, would have predicted, or even conceived of, any of the following: 1 km deep open pits, Minesight, Whittle pits, mature fine tailings, permanent submergence of sulphidic mine waste behind engineered dams, 360 tonne haul trucks, 67 yd³ shovels, tailings and mine waste conferences, reclamation symposia, 0.3% copper as ore, filtered tailings dry stacks, paste tailings, cyanide destruct circuits, closure bonding, perpetual care and maintenance, aerial gravity surveys, ML/ARD management plans, 250 m high tailings dams, closure and reclamation bonding, remote sensing, environmental impact assessments, and so on.

Another pitfall to be considered is the added credibility typically accorded the prophesying of experts, which counter-intuitively enough is thoroughly unjustified by experience. Gardner (2010) summarizes years of research into expert predictions led by Phillip Tetlock of the University of California’s Haas School of Business. Tetlock’s team gathered 27,450 expert judgments from 284 experts about the future, and the results, in Tetlock’s words, demonstrated that the acknowledged experts, forecasting into the future over matters germane to their respective fields of expertise, would have been put to shame “*by a dart-throwing chimpanzee*”. Experts who were complex and cautious in their thinking, hedging their bets, and stressing of uncertainty, out-performed by a large margin those whose thinking was simple and confident. Ironically, it seems to be the latter type of expert to whom we gravitate, craving certainty in an uncertain world. Humility and caution are most certainly called for when making forecasts, but they are not popular amongst those seeking forecasts. As Voltaire opined, “*Doubt is not a pleasant state, but certainty is a ridiculous one*”.

These caveats and disclaimers stated and on the record, following are some prognostications cautiously offered up by the writer, who observes their worth to be no more than what the reader has paid for them.

Market Drivers

The price of copper is often considered something of a bellweather for the mining industry. Whether adjusted for inflation or not, the price of copper, save for a brief spell during the 2008 world financial debacle, has risen dramatically thus far in the 21st century. Given UN-projected trends in world

population (itself an exercise in fortune-telling), plotted along with the copper price in Figure 10, and the presumed desire on the part of peoples in developing nations to share in the sort of lifestyle enjoyed in the developed nations, it is difficult to envision demand for metals waning significantly, although the cyclical nature of the mining industry seems unlikely to change.

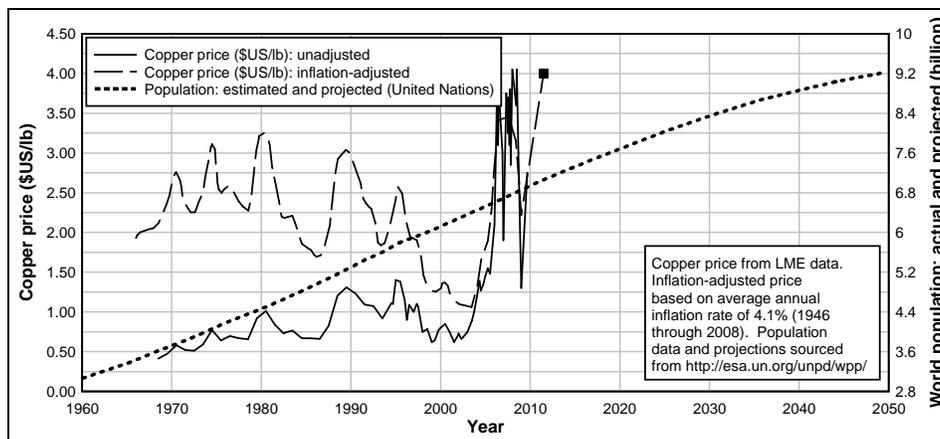


Figure 12: Historical copper prices, and projected global population

Assuming then that metal prices and thus the mining industry are likely to be robust, in historical terms, more often than not going forward, one then speculates as to what this could mean for the mining industry in general, and mine waste management issues in particular. With B.C. having been a leading and trend-setting mining jurisdiction for many years, it is unsurprising that potential clues to these trends are to be found here, and to those clues we now turn.

From Kemess North to Kemess Underground

One recent product of robust metal prices is that the Kemess North orebody is now being envisioned as an underground rather than open pit development. Despite the rejection of the Kemess North project in 2007 by a joint federal-provincial review panel, Northgate Minerals Corp. persevered in pursuit of means of unlocking the value in the orebody, including exploration drilling to define higher grade zones. These efforts proved fruitful, and Northgate (2011), in a press release, announced the results of a preliminary assessment that incorporated an underground project decidedly more modest than the originally proposed Kemess North open pit project (Klohn-Crippen, 2005), and with other advantages, as listed in Table 2.

Table 2: Kemess North (2007) vs. Kemess Underground (2011)

Aspect	Kemess North	Kemess Underground ²
Ore production rate (ktpd)	96,000	24,000
Tailings (Mtonnes)	325 (less concentrate)	136.5 (less concentrate)
Waste rock (Mtonnes)	397	Likely negligible
Waste repository	Duncan Lake	Kemess South open pit
Dams required	Three, with heights of 90 m, 35 m, 10 m	One of modest height at low end of open pit
Waste repository permitting	Rejected by review panel	Already permitted
Levels of government agencies involved in permitting	Federal and Provincial	Possibly only Provincial

The project, scaled down, will produce negligible waste rock, and the tailings are to be accommodated in the Kemess South open pit, already permitted for tailings storage. It could be that robust metal prices, in an increasingly risk averse and challenging permitting environment, will be sufficient to entice proponents to scale projects down to the point that mine waste considerations and permitting constraints drive the mine plan. To some degree this was also the case with the integration of the mine waste management plan and the mine plan at Huckleberry. But that project too has returned to the drawing board, suggesting another potential nascent trend.

Waste Today, Ore Tomorrow

As discussed previously, the mine plan for the Huckleberry Mine was governed in part by the ML/ARD management plan, and called for the Main Zone pit to be mined out at an early stage, so that it could be backfilled with PAG waste rock and tailings. The East Dam was constructed between the Main Zone Pit, being backfilled, and the active East Zone pit. Eventually the Main Zone pit and the TMF-2 impoundments merged to form a single large impoundment. The progression of site development is illustrated on Figure 11.

However, a very robust mine waste management plan, fully integrated with the mine plan, may as a result of high metal prices be sent back to the drawing board. Huckleberry is currently contemplating the removal of the backfilled waste rock and tailings, and additional mining of the Main Zone ore body. Should this project proceed, it would require construction of a third tailings impoundment in order to accommodate the additional process tailings and additional PAG waste rock, along with the rehandled tailings and waste rock currently occupying the backfilled pit. Recovery of the additional ore is entirely consistent with the principles of sustainability, but so too was the decision, taken in the planning of the project nearly 20 years ago, to backfill the Main Zone Pit, a more secure and economical means of storing and flooding mine waste one could hardly imagine. Backfilling of the Main Zone Pit made even more sense when backfilling commenced in 2002, at which time copper prices were about US \$0.75/lb. It would hardly have been rational to avoid backfilling of the pit in the hopes that copper prices would, within a decade, reach US \$4/lb.

² http://www.northgateminerals.com/Theme/Northgate/files/pdf/Releases/2011/08-02-11-Kemess%20UG%20PEA_f.pdf



2001, looking southwest, Main Zone Pit being mined, tailings impoundment in background.



2003, looking south, tailings and waste rock co-disposal into the Main Zone Pit in progress, reclaim barge within the pit.



2005, looking west. East Zone Pit being mined, Main Zone Pit largely backfilled with tailings and waste rock.



2007, tailings to the main impoundment, and beginning of PAG waste rock backfilling of East Zone Pit, mining of Main Zone Expansion pit (see arrow) commencing.



2008, looking east, main impoundment being progressively drained, mining of Main Zone Expansion continuing, and tailings and waste rock to East Zone Pit.



2010, main tailings impoundment fully drained, Main Zone Expansion pit mining continues, tailings and waste rock to East Zone Pit. Approximate outline of proposed Main Zone Optimization pit indicated. ©Google-Imagery©Cnes/Spot Image, Digital Globe, Geoeye

Figure 13: Huckleberry Mine site progression 2001 – 2010

But the world is a complex system (Mitchell, 2009), one in which the elements of the system interact amongst themselves such that any perturbation to the system will produce results inherently unpredictable. Looking to the future, with the Huckleberry experience representing a possible precursor, it seems probable that certain of the waste rock dumps, tailings impoundments, and abandoned pits of today and yesteryear could become the orebodies of tomorrow. The inexorable progress of technology can only facilitate such a trend.

Technology and Future Paradigm Shifts in Mine Waste Management

There has been much increased interest in alternative tailings management technologies in recent decades, spanning the range of thickened tailings, paste tailings, and filtered tailings, the “tailings dewatering continuum” as described by Davies et al. (2010). Similarly, as demonstrated by Kemess and Huckleberry and numerous other projects, mill processes are being used to separate NPAG from PAG tailings, to facilitate strategic management of those process streams; increasingly, tailings management is beginning within the process plant. It would hardly constitute prescience to presume that these technologies and practices will continue, evolve, and become more widespread.

The real question is what will be the next great paradigm shift in terms of mine waste management? Whatever advances lie ahead in terms of the handling of mine waste rock and tailings, the writer anticipates that the next great paradigm shift will take place within the process plant itself. Eventually, one hopes, within the confines of the process plant, besides extraction of the valuable minerals, the tailings stream will be treated in such a manner such that a geotechnically and geochemically stable and innocuous product exits the process plant, posing much reduced challenges for handling, storage and long term stability. In the oilsands, tremendous effort has been expended in this direction already, and that effort is only accelerating and broadening in scope.

Whatever shape future technology takes, those developing and deploying it will still be faced with the question of what additional problems, both foreseen and unforeseen, that new technology might pose for their contemporaries and descendants, for however mine waste management practices may change in the future, those practices will still take place in a world governed by complex systems. An inescapable aspect of such systems is that when we interact with them, we may provoke downstream consequences that emerge over a wide range of timescales. In short, we solve one problem but potentially create another. Vigilance and adaptation to delayed and untoward consequences is always required, regardless of the state of technology, and regardless of the time.

Conclusion

We are inclined to view ourselves, one decade into the 21st century, as vastly superior in our stewardship of mine waste relative to our predecessors of 100 years ago, when mine waste management constituted little more than finding the most convenient tipping point, or discharging tailings out the back door of the mill. Indeed we have come a long way, even over the course of a few decades. But what matters more than where we have come from is where we are going, and how we will be judged by those savouring the splendour of B.C.’s mountains several generations hence. This is a matter the writer contemplates often, and leads into one final prediction, offered in the form of a response to the question of how our mine waste management solutions and legacies will come to be viewed by our descendants in 100 years time. Those descendants will judge us in part through the lens of technology that we can no more foresee today than someone 100 years ago could have foreseen nuclear power, laptop computers, iPhones, or the internet. Nonetheless, the writer expects, or perhaps hopes, our descendants will concede that the contemporary mining industry, its regulators, and the public, notwithstanding shortcomings and some decisions and priorities that were curious, and others that seemed more dogmatic than pragmatic in hindsight, collectively did their very best and generally succeeded, within the zeitgeist of their era, in managing the risks associated with mine waste management, minimizing impacts on the environment and on future generations, and preserving the beauty and splendour of this province.

Surely, that is all our descendants could possibly ask of us. And in the here and now, and most particularly here in British Columbia, truly the “*Best Place on Earth*”, it is the very least that we should demand of ourselves. But in so doing, we must take the long view and be mindful of the advice

of a great British thinker and writer of the 18th century, Samuel Johnson, who astutely admonished “*Let’s not be befuddled, by the clamour of the times*”.

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