FROM ENVIRONMENTAL BURDEN TO NATURAL RESOURCE: NEW REAGENTS FOR COST-EFFECTIVE TREATMENT OF, AND METAL RECOVERY FROM, ACID ROCK DRAINAGE

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Abstract

Acid rock drainage remains the greatest environmental issue faced by the mining sector and as the new millennium approaches, low capital/operating cost treatments remain elusive. Therefore as part of an ongoing process to develop a leading edge, innovative and cost-effective approach, pilot trials were conducted by KEECO in collaboration with the New Bunker Hill Mining Company on a substantial and problematic metal-contaminated acid flow, emanating from underground workings at the Bunker Hill Mine, Idaho.

The aims of the work were fourfold. First to assess the capacity of KEECO's unique Silica Micro Encapsulation (SME) reagents and associated dosing systems to cost-effectively decontaminate the acid flow to stringent standards set by the U.S. Environmental Protection Agency (USEPA), where alternative and standard technologies had failed. Second, to demonstrate that treatment using a compact system suitable for underground installation. Third, to demonstrate that the treatment sludge had enhanced chemical stability in absolute terms and relative to standard approaches. Fourth, to examine the potential for resource recovery via sequential precipitation. Although the focus to date has been the development of a cost-effective treatment technology, the latter aim was considered essential in light of the growing pressure on all industrial sectors to develop tools for environmentally sustainable economic growth and the growing demands of stakeholders for improved resource usage and recycling.

Two phases of work were undertaken: a laboratory-based scoping exercise followed by installation within the mine workings of a compact reagent delivery/shear mixing unit capable of treating the full flow of 31 L s^{-1}. At a dose rate of 2.0 g L^{-1} (equivalent to a final treated water pH range of 7-9), the SME reagent KB-1 reduced metal concentrations to levels approaching the U.S. Drinking Water Standards, which no other treatment piloted at the site had achieved. Based on the USEPA's Toxicity Characteristic Leaching Procedure, the sludge arising from the treatment was classified as non-hazardous. Operating costs compared favourably with those of lime use, while estimated capital costs were considerably lower due to the compact nature of the reagent delivery system and the rapid settling characteristics of the treatment sediment.

Resource recovery was attempted using a two-stage selective precipitation approach. The first stage involved pH adjustment to 5.5 (by addition of 1.5 g L^{-1} of KB-1) to produce a sludge enriched in aluminium, iron and manganese, with lesser amounts of arsenic, nickel, lead and zinc. Further KB-1 addition to a total of 2.1 g L^{-1} generated sludge enriched in zinc (33% by dry weight), demonstrating that resource recovery is theoretically feasible. Further work on downstream processing is required, although it is considered that the most likely route for zinc metal recovery will be high temperature/pressure due to the chemically inert nature of the zinc-rich sediment.

Key Words

Silica Micro Encapsulation, KB-1, acid rock drainage, TCLP, resource recovery, K250, Bunker Hill.

Mining and Waste Disposal

Metals and other mineral resources are rarely found in a sufficiently pure state to be sold in an "as-mined" form. Metals are often found in chemical combination with oxygen (as oxides), sulphur (as sulphides) or other elements (e.g. chlorides, carbonates, arsenates, phosphates, etc) and physically mixed with less valuable or valueless minerals phases (e.g. silicates). Non-metal mineral resources (e.g. coal, industrial minerals) also normally contain physically or chemically entrained impurities in their undisturbed state. Valueless or sub-economic minerals associated with the target or economic mineral(s) are generally known as gangue. Inputs from mining (extraction) to mineral processing/extractive metallurgy invariably contain varying levels of gangue and low-value minerals which exit the process or processes in a number of forms (e.g. as contaminants in the primary product, as separate saleable by-products, solid wastes, dissolved species, gases, fumes, suspended particulates). During the extraction and processing of the ore, mass is conserved. However, the physical and chemical characteristics of the input phases may be modified by interactions with process chemicals and/or the process itself. For example, depending on the point at which it is rejected from the process, gangue may be disposed of in an as-mined state (e.g. waste rock), as tailings (e.g. following mineral processing), as slags (e.g. after smelting) or as other waste products (e.g. dusts, sludges from water treatment, spent ore from leaching etc). These various wastes may also contain significant quantities of the target mineral or metal due to inefficient processing, technological limitations or mineralogical factors. Therefore, the disposal of solid and liquid wastes in the mining industry is a major issue, and one that is likely to remain so in the foreseeable future.

Deliberate and controlled modification of the physical and chemical characteristics of waste outputs represents a potentially powerful tool to complement and enhance current waste management strategies. There are a number of potential routes towards generating environmentally harmless or inert wastes. Some may involve modification of the processing pathway to generate metal or mineral contaminated wastes in a form that is proof against leaching (e.g. the formation of low solubility glassy slags during smelting). Others may involve end-of-pipe treatment to improve the characteristics of a waste after it has been generated, where the formation of the waste itself can not be controlled or modified. It is this latter scenario that is the focus of this paper, which addresses the innovative treatment of acid rock drainage (ARD), one of the most intractable problems faced by the non-ferrous metal and coal mining sectors, and one that can often only be dealt with by end-of-pipe treatments.

Acid Rock Drainage

ARD is certainly considered one of the most serious environmental impacts caused by mining and the industry's greatest environment-related technical challenge. The global depletion of non-acid generating oxide ore deposits and the increasing dominance of sulphide ores means that the potential for ARD incidents will continue to increase. Once initiated, the cycle of chemically and biologically mediated and catalysed reactions leading to ARD generation is difficult to stop. While there is evidence to suggest that the degree of contamination of ARD will decrease rapidly within a relatively short timeframe,[1] experience in historic mining regions of the world indicates that the problem may persist for centuries at certain sites.

Current best practice in dealing with ARD puts the emphasis on prediction and prevention, planned from the outset of the operation and integrated with each phase of the mine site life cycle. The elements that constitute best practice are becoming more clearly defined and as this process of clarification continues industry will undoubtedly accelerate the process of best practice implementation, overcoming at last the image of mining as a great despoiler of land, an image largely based on past, rather than current practices. However, it is equally clear that despite the best efforts of industry and regulators, many sites will continue to generate ARD during operation and following closure - in many cases, the legacy of ARD arises from operational and strategic decisions made decades ago, before the risks and impacts of the self-sustaining cycle of ARD generation were properly understood. Add to this ARD generation from poorly managed operations and from historic and abandoned sites, and it becomes clear that the treatment of ARD will be required for the foreseeable future to protect water quality, and ecosystem and human health.

Lime and the treatment of ARD - an end to the monopoly?

Despite these recent advances in predictive and preventative measures, treatment technologies have been stuck in something of a rut for several years, and remain dominated by the application of lime in a number of basic and more sophisticated guises. Although the drawbacks and deficiencies of lime-based systems are well known, the absence of cost-effective alternatives has ensured that it remains the treatment of choice at the majority of sites. Although the negative aspects of lime-based systems vary according to the nature of particular sites, it is possible to draw up a generic list, which includes:

- Relatively high capital cost.
- Chemical instability of treatment sludges leading to possible classification as hazardous wastes requiring high-cost disposal at designated sites.
- Poor handling characteristics of treatment sludges, which may require extensive land for dewatering or expensive mechanical dewatering.
- High pH required to remove metals such as manganese may in turn cause other metals (e.g. zinc and aluminium) to resolubilise, necessitating a multi-stage treatment to reduce all metals to acceptable concentrations.
- Limited potential for resource recovery - treatment sludges normally have no commercial value, and reprocessing to extract the metal content is uneconomic with existing technologies due to the large excesses of lime that are often used during treatment to ensure complete metal precipitation.
- Long-term liability associated with sludge disposal sites as a result of the potential for contaminant redissolution.

In broader terms there are also a number of other "drivers" of change – these are a more generic list of societal and other pressures that continue to promote new and innovative approaches to environmental issues:

- "Voice of Society".
- International codes of conduct and Agenda 21.
- Pressure groups and NGOs.
- Financial drivers.
- Peer pressures.
- Internal pressures from shareholders and employees.
- Competitive incentives.
- Regulatory drivers.

While lime is widely accepted by the mining industry at present on the basis of operational costs and a proven capacity to treat ARD, it is becoming increasingly clear that these drawbacks will continue to undermine its monopolistic position in the next century and contribute to the overturning of industry hesitance in taking up alternative innovative techniques.

KEECO's Silica Micro Encapsulation - a technology for the new millennium

KEECO has been aware of the drawbacks of lime-based treatments systems for a number of years. In response the company has been developing a cost-effective and high-performance reagent and associated delivery technology that has all the positive characteristics of liming systems (e.g. capacity to respond to variations in flow and degree of contamination, capacity to treat highly acidic waters, and performance that is independent of temperature), but none of the drawbacks. That reagent is KB-1™, a unique proprietary calcium/silica-based formulation, manufactured as a powder and applied in dry or slurried form.

KB-1 contains three major components. The first is a pH adjuster that initiates the precipitation of heavy metals from the water. The second component undergoes condensation polymerisation, chemisorbing the metals into a three-dimensional structure, or matrix, composed primarily of silica (the process of Silica Micro Encapsulation or SME). These microscopic matrices contain no fissures or fractures, completely surround the metal precipitates and continue to strengthen with time. The bound metal precipitates are in the form of a fast-settling, sand-like product, which is environmentally benign and resistant to degradation under naturally occurring environmental conditions. Due to the coarse size and high density of the particles (relative to precipitates resulting from liming), no flocculent is required to induce settling, which occurs naturally at a high rate. The third component of KB-1 acts as a support structure for the pH adjuster and polymeriser components, increasing the available surface area and maximising reactivity.

KEECO believes that KB-1 and its associated reagent delivery systems represents the first serious alternative to lime that delivers reliable performance, a high level of environmental protection and a waste management tool that meets the wider requirements of sustainable development at low capital and operating cost. Its application as a dry powder or as a slurry means that there is no need for major reinvestment in terms of plant for those sites already using lime, removing one very significant obstacle often seen in the uptake of innovative technologies. Its position as a serious contender with lime is being confirmed by an upsurge in the last twelve months in field trials and commercial contracts, of which one of the first was the treatment of an acid stream emanating from the Kellogg Tunnel of the Bunker Hill Mine in Kellogg, Idaho. This site is of particular interest as the low land availability led to the development of a unique low-cost, compact and high-throughput reagent delivery system - the K250 shear-mixing unit - that could be located inside the mine itself.

Implementation of the SME process at Bunker Hill Mine

Dynamic mining companies are in the midst of a series of major transformations because of external stimuli or drivers relating to environmental and social performance as measured or perceived by a broad range of stakeholders. Naturally, to be a useful tool in the quest for a sustainable society, benefits must also accrue to the company from the implementation of innovative technologies through either incremental improvements or quantum advances. In more general terms, the development and/or acquisition of innovative technologies could be especially attractive where they hold the promise of reducing environmental damage costs while at the same time maintaining the social and economic benefits of mining (e.g. jobs, taxes, foreign exchange earnings, skill and technology transfer, royalty payments).

The Bunker Hill mine was one of the largest lead and zinc mines in the United States and has been in virtually continuous operation for over 100 years. With 31 levels, over 150 miles of drifts, 6 miles of major inclined shafts and a total volume of disturbed ground reaching approximately 5 cubic miles of disturbed ground,[2, 3] the mine is an archetypal example of the long-term consequences of failing to manage and plan for the prevention and control of ARD from the outset, and also of the difficulties of retrospectively implementing preventative measures in underground workings once the process of acid generation is under way. Preventative measures have also been hindered by the infiltration and percolation of incipient rainfall through several thousand feet of sulphide-bearing rock overlying the mine workings.

The sulphidic mineralogy of the mine is complex and gives rise to a broad range of metals and metalloids in the acid discharge, including lead, zinc, iron, copper, manganese, arsenic and antimony. In a wider context, the mine is part of the Bunker Hill Mining and Metallurgical Complex, which covers 21 square miles in Idaho. Soil and water contamination are major issues within this area.

The main entrance to the mine is at Level 9 (the Kellogg Tunnel), a 2 mile drift that terminates in the heart of the mountain under which the mine lies. The Tunnel is the main haulage route into, and out of, the mine and is the level at which water percolating downwards through overlying sulphide-bearing strata is collected with water pumped from lower levels and discharged.

Until relatively recently the mine was under a care-and-maintenance regime and its discharge was treated in a lime-based system that dealt centrally with effluents from the Complex area. Much of the remedial work in the area has been funded through the Superfund and therefore it is not surprising that after its purchase in 1991 by the current owners, the New Bunker Hill Mining Company, liability for the mine's acid discharge was transferred to the company. Therefore, at the time of the field trials, the owner of the mine was under heavy pressure from the U.S. Environmental Protection Agency to improve the quality of water being discharged from the mine and thereby reduce the load on the central treatment facility. Standard treatment processes had proved unsuccessful or uneconomic (including the use of lime-based systems) (Bob Hopper, personal communication) and subsequently KEECO was invited to undertake trials at the mine. At the time of KEECO's trials an acid stream of approximately 500 gallons per minute at a pH of 1.96 was emanating from a large underground working known as the Stanley Stope.

Laboratory Studies

Several gallons of mine water were subjected to laboratory treatment with KB-1. Analysis of the treated water samples was undertaken using ICP-AES analysis. The water samples were taken from the Stanley Stope at a distance of approximately 2.0 miles distance from the portal of the Kellogg Tunnel. The raw Stanley Stope water was deep red in colour due to dissolved ferric iron, and had a pH of 1.96 and calculated hardness of 2536 parts per million.

To determine the order in which the metal ions were removed and to establish a rough estimate of KB-1 consumption, a stepwise titration was performed with a 1L aliquot of water and KB-1 applied as a dry powder. The titration consisted of the addition of KB-1 into the mechanically stirred water. KB-1 addition began at 2.0 g and proceeded in increments of 0.5 g. Samples of 25 mL were extracted using a plastic syringe and filtered at 0.45 µm, then acidified to an equivalent of 2% HNO_3. Sample analysis was undertaken using an ICP-AES with a Perkin Elmer Optima 3000 dual view spectrometer, allowing the simultaneous analysis of up to 35 elements. Averaged data from the tests are shown in Table 1.

Table 1. Data from laboratory treatment of Bunker Hill mine water samples (elemental values are shown in µg/L)

	IDL	Control Sample (Filtered)	Control Sample (Unfiltered)	Step #1	Step #2	Step #3	Step #4	Step #5	Step #6	Step #7
KB-1 (g/l)		0.00	0.00	2.00	2.50	3.00	3.50	4.00	4.50	5.00
pH		2.59	2.59	4.38	6.22	7.20	8.71	10.12	11.44	11.81
Al	12.8	10457.6	13512.6	4700.0	<IDL	<IDL	<IDL	21.2	449.4	663.8
As	1.4	409.3	539.9	5.2	4.3	4.1	4.0	1.7	<IDL	6.8
B	2.7	1120.0	1405.9	42.1	17.5	17.0	14.9	18.6	16.5	41.2
Ba	1.0	<IDL	<IDL	23.7	17.1	23.7	16.3	14.3	17.3	51.7
Be	2.0	<IDL	<IDL	2.5	<IDL	<IDL	<IDL	<IDL	<IDL	<IDL
Bi	2.0	<IDL	<IDL	<IDL	<IDL	<IDL	7.9	11.9	15.9	18.7
Ca	2.9	60289.5	73561.0	492744.2	620906.6	662924.4	754004.1	971313.8	888253.8	947680.5
Co	1.0	220.3	264.9	192.4	141.8	115.8	2.4	<IDL	<IDL	<IDL
Cr	1.1	<IDL	<IDL	<IDL	<IDL	<IDL	<IDL	<IDL	<IDL	<IDL
Cu	1.3	524.3	720.3	394.9	7.7	3.5	<IDL	3.1	<IDL	1.5
Fe	1.4	465984.1	545234.1	3261.1	37.6	<IDL	<IDL	<IDL	<IDL	4.3
K	15.2	<IDL	<IDL	1641.1	1862.6	1890.2	1783.7	2380.7	1580.1	2611.7
Li	2.0	51.2	62.4	58.0	57.7	60.9	56.0	74.6	51.9	54.5
Mg	6.5	112236.8	139024.3	134105.2	118148.9	117094.7	83995.5	43310.9	1178.6	97.5
Mn	1.4	101418.4	115450.6	91393.2	86448.3	69762.5	20717.1	216.3	<IDL	10.8
Mo	1.1	<IDL	<IDL	<IDL	<IDL	<IDL	<IDL	2.9	2.2	3.7
Na	112.1	40105.5	39621.1	40555.6	21010.7	12110.1	1174.2	977.7	1143.4	1681.7
Ni	1.7	217.5	258.8	358.0	235.9	209.6	5.3	<IDL	<IDL	<IDL
P	2.0	153.8	206.8	<IDL	<IDL	<IDL	<IDL	20.2	10.7	19.5
Pb	1.3	704.5	869.1	66.5	12.6	11.4	8.8	2.5	8.0	10.3
S	5.0	865687.2	1065878.2	695750.7	670298.4	693288.1	673953.3	753773.9	615490.9	657217.9
Se	2.0	<IDL	<IDL	33.5	22.9	22.2	6.2	<IDL	<IDL	<IDL
Si	8.3	6247.5	6879.9	4926.7	2007.8	1084.2	132.8	81.6	67.6	96.8
Sr	NA	34.8	44.3	280.7	289.9	335.2	364.8	483.9	385.9	428.9
Ti	1.7	<IDL	25.1	2.5	4.0	3.9	4.2	4.2	3.8	5.7
Tl	2.0	<IDL	<IDL	<IDL	<IDL	<IDL	<IDL	<IDL	<IDL	<IDL
V	1.7	30.7	<IDL	<IDL	<IDL	<IDL	<IDL	<IDL	4.2	8.8
Zn	0.8	371933.7	413769.5	245186.5	168671.4	99286.3	29.4	<IDL	144.4	1649.7
Zr	2.0	<IDL	33.6	3.1	<IDL	<IDL	4.1	4.6	11.3	<IDL

<IDL = less than the instrument's detection limit

Analysis of the data contained in Table 1 indicates that the metal contamination from the Bunker Hill Stanley Stope is controlled in laboratory processes with the application of 3-4 g L^{-1} KB-1.[a] Major contaminants such as aluminium, arsenic, iron, manganese, lead and zinc were reduced to acceptable concentrations in the pH range 7-9.

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[a] Field application requires significantly less KB-1 per litre to achieve control of the metals due to the high shear mixing and injection provided by the K250 unit, as discussed later in this paper.

Field Trials

To accommodate underground treatment of the Bunker Hill Mine waste stream KEECO developed the K250 shear-mixing unit. This machine utilises a system that blends KB-1powder with a bleed stream from the main acid flow. Efficient mixing is accomplished through the blending action of a high shear mixer to homogenise the KB-1 slurry and the use of compressed air to assist with injection of the slurry into the main waste stream. The sheared KB-1 slurry is extremely reactive and is dispersed through a chemically resistant, ventilated plastic manifold to facilitate rapid dispersion of the reagent throughout the stream. This process results in rapid reaction between dissolved metals and the KB-1. As the unit is designed to inject slurry directly into the water stream, it is capable of treating very high flows. For example, in previous field trials, a single K250 treated a flow of 2,000 gallons per minute. This significantly reduces the capital outlay that is often associated with systems that must respond to seasonal or production-related changes in flow. The compact nature of the K250 is demonstrated in Figure 1, which shows *two* K250 units located at the treatment point on Level 9, two miles inside the mine. The only additional space required beyond that shown is for the reagent feed hopper and reagent storage (relative to lime the latter is lower per tonne due to the higher bulk density of KB-1

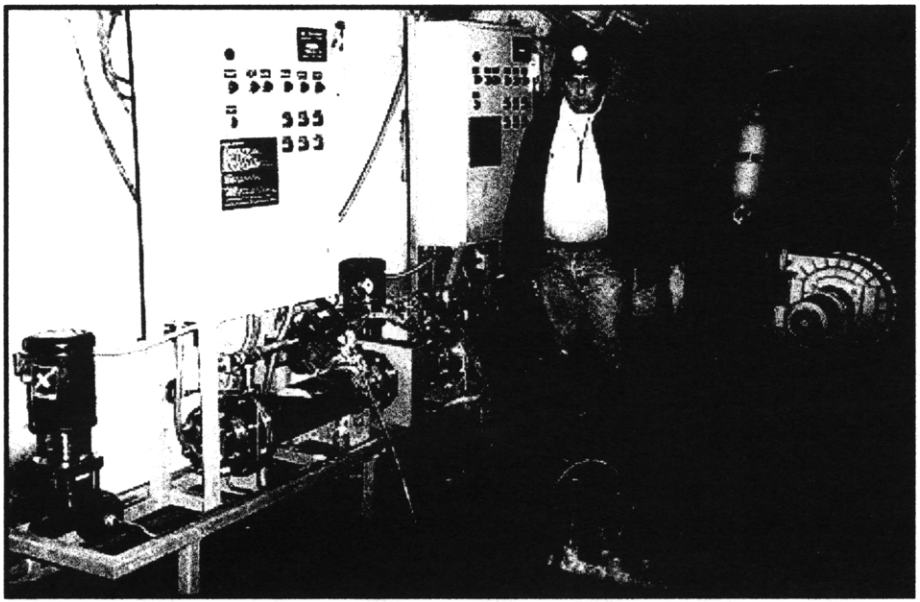

Figure 1. Two K250 units in place at the treatment point, 2 miles from portal at Level 9

The sheared KB-1 slurry was injected into a drainage ditch receiving approximately 500 gallons per minute of acidic water from Stanley Stope. Following injection, the treatment sediment was transported along the 1.5- 2.0° down-slope gradient of the drainage ditch to the portal 2 miles distant. Future treatment plans call for the capture of the sediment within the upper and lower sand galleries for underground disposal into worked-out stopes.

Water quality samples were taken at various points along the drainage ditch:

- Upstream - located 150 feet from the mixing station to sample the water quality of the untreated Stanley Stope water.
- Switch #1 - located 300 feet downstream from the mixing station, utilised to monitor the pH and quality of the treated water shortly after the application of KB-1 (flow rate approximately 500 gallons per minute).
- Drift #3 - located several thousand feet downstream from the mixing station where a secondary water flow of between 350 and 400 gallons per minute pumped from lower levels of the mine emerges at on Level 9.
- Passing track - located approximately 1 mile from the portal where the untreated stream from Drift #3 and the treated Stanley Stope water merge.
- Portal - located at the drainage exit at the Kellogg Tunnel portal (flow rate up to 1,000 gallons per minute).

Water quality data are shown in Table 2.

Table 2. Water quality, Level 9, Bunker Hill Mine (elemental values shown in $\mu g\ L^{-1}$)

Location	Stanley Stope water	Treated water at Switch #1	Untreated Drift #3 water	Treated water mix at Drift #3	Passing track	Portal
pH	2.0	9.0	5.0	7.5	7.5	8.0
Al	13778.11	202.00	2085.92	287.29	225.93	0.00
As	584.68	97.01	38.10	32.91	31.07	1.40
B	927.77	286.68	513.22	400.58	311.88	487.21
Ba	32.28	109.68	48.03	135.38	93.68	126.01
Be	12.64	<IDL	<IDL	3.60	<IDL	<IDL
Bi	18.23	13.31	<IDL	13.03	<IDL	<IDL
Ca	58776.81	810683.42	422028.01	907090.43	691948.76	545990.07
Co	240.72	<IDL	447.54	<IDL	20.77	87.09
Cr	<IDL	<IDL	<IDL	<IDL	<IDL	<IDL
Cu	573.98	<IDL	<IDL	<IDL	<IDL	<IDL
Fe	506027.43	0.00	190745.78	296.74	23.40	0.00
K	646.34	841.33	16669.34	3857.65	1345.24	2163.16
Li	14.09	33.22	90.59	16.28	52.45	36.08
Mg	125334.75	64171.24	566684.37	21436.89	117416.68	122641.61
Mn	119308.04	16793.86	471346.23	809.74	81233.33	101824.69
Mo	<IDL	<IDL	<IDL	14.90	<IDL	<IDL
Ni	217.03	<IDL	376.98	<IDL	<IDL	35.11
P	150.22	32.74	<IDL	283.63	<IDL	<IDL
Pb	880.17	73.03	327.54	95.88	14.81	23.21
S	975467.27	750571.08	1566452.65	763351.14	771325.53	675978.07
Se	55.63	1.78	119.13	45.09	96.91	<IDL
Si	6692.69	229.75	11235.62	330.14	838.99	1407.98
Sr	702.62	742.98	682.48	1074.99	570.79	1011.30
Ti	34.75	<IDL	<IDL	<IDL	<IDL	<IDL
Tl	<IDL	<IDL	<IDL	39.46	46.10	<IDL
V	81.54	76.67	<IDL	17.81	148.61	<IDL
Zn	438668.93	297.07	71995.99	140.87	6136.82	57029.55
Zr	27.70	<IDL	<IDL	<IDL	<IDL	<IDL
Hardness	2536.09	2321.64	4709.69	2358.59	2370.60	2142.40

<IDL = less than the instrument's detection limit

Sampling of treated water at Switch #1 indicated that the treated Stanley stope waters approached U.S. Drinking Water Standards when a pH of between 7.5 and 8.5 was maintained (see Table 3).

Table 3. U.S. Drinking water standards (metals in $\mu g\ L^{-1}$)

Parameter	**U.S. Drinking Water Standard**
pH	6.5 – 8.5
As	50
Cd	5
Cu	150
Fe	-
Pb	15
Zn	5000

It is interesting to note that the analysis of the treated water/untreated water mixture immediately downstream from Drift #3 suggested that dilution and reaction with the sediment (that may contain unreacted KB-1) resulted in the reduction of dissolved aluminium, arsenic, cobalt, iron, manganese, nickel, lead and zinc in the combined flow. This suggests that the addition of 2 g L^{-1} of KB-1 is sufficient to treat the 500 gallon per minute flow from Stanley Stope, and to substantially reduce metal concentrations in the water pumped from lower levels emerging on Level 9 (at a flow rate of 350-400 gallons per minute). Consequently, the actual consumption of KB-1 may be as low as 1.1 g L^{-1} taking into account the total flow. However, it is also important to note that there are clearly other sources of water inputs to the drainage ditch on Level 9 (up to 100 gallons per minute from seeps and springs), which may affect the water quality of water issuing from the portal. For example, the zinc concentration of water was clearly increased between the point at which treated Stanley Stope water and untreated waters from lower levels merged, and the portal. With the exception of iron, zinc is the major heavy metal contaminant, and the additional capacity of the treated sediment to removed dissolved contaminants was clearly exceeded by fresh inflows of water from seeps and springs as the drainage ditch approaches the portal.

Toxicity Characteristic Leaching Procedure (TCLP) Analysis

The sediment generated by KB-1 treatment of the Stanley Stope water (2.0 g L^{-1}) were shown to pass a modified version of the EPA Method 1311 TCLP protocol. Typical analyses are shown in Table 4.

Table 4. TCLP analysis of sediment arising from KB-1 treatment (all values in $\mu g\ L^{-1}$)

Element	Extracted concentration	EPA TCLP Action Limits
Ag	<10ppb	5000
Al	250.6	-
As	<10ppb	5000
Ba	201.4	100000
Ca	104795.8	-
Co	772.7	-
Cr	<10ppb	5000
Cu	<10ppb	-
Fe	<10ppb	-
Hg	<10ppb	200
K	2250.2	-
Li	<10ppb	-
Mg	511721.1	-
Mn	24803.7	-
Na	61020.7	-
Ni	703.1	-
P	<10ppb	-
Pb	<10ppb	5000
S	188197.3	-
Se	<10ppb	1000
Si	15378.6	-
Sr	3804.8	-
Zn	682015.5	-
Zr	<10ppb	-

Resource Recovery

KEECO and the owner of Bunker Hill have been working together to explore the possibility of recovering a zinc product from the contaminated water as an integral part of the treatment process. Preliminary tests have been very promising. Using a primary treatment step with the addition of 1.5 g KB-1 L^{-1} to raise the pH to 5.5, and a secondary step where a further 0.5 g L^{-1} is added to bring the pH to 8.5, zinc-depleted and zinc-rich sediments can be separated. Typical analysis of the primary and secondary stage sediments is shown in Table 5. The primary stage sediment passed the TCLP, while the secondary stage sediment was comprised of approximately one-third zinc, with the other major components being calcium, iron and manganese. KEECO is now exploring processing options for the economic recovery of the zinc – based on the chemical stability of the sediment; it is likely that a pyrometallurgical process will be the most appropriate route. While this approach would not be suitable for every operation, given the fact that no additional KB-1 is required, it has tremendous potential at certain sites to generate additional revenue to offset the cost of treatment.

Table 5. Sediment analysis by SEM-EDS

Element	**Stage 1 (wt%)**	**Stage 2 (wt%)**
Al	2.48	2.09
Ca	9.10	6.16
Fe	31.07	3.60
Mg	1.40	3.68
Mn	1.36	7.72
O	37.98	32.47
S	4.80	6.58
Si	3.94	4.38
Zn	*7.44*	*33.05*
Total	99.56	99.72

Conclusions

Results of the trials were very promising. The K250 plant was set up and running within hours of its arrival at the mine site. Previous laboratory tests had indicated that a dose rate of 3-4 g KB-1 L^{-1} would be required to reduce metal concentrations to acceptable levels. However, the high efficiency of the K250 reduced this to 2.0 g L^{-1} under field conditions, at a cost of under half a cent per gallon. At this dose rate the treated waters achieved discharge criteria and in fact were sufficiently clean to satisfy the U.S. drinking water criteria for arsenic, cadmium, chromium, lead and zinc. The silica-encapsulated sediments also passed the U.S. Environmental Protection Agency's Toxicity Characteristic Leaching Procedure (TCLP), confirming the non-hazardous nature of the waste and eliminating the expense of hazardous waste disposal. Ultimately, it is planned that the encapsulated sediments will be returned to worked-out areas of the mine, removing the need for a surface disposal site. Following liquid-solid separation, the supernatant water pH returned to approximately 7, allowing direct discharge without further treatment.

In ending, it is certainly worthy of note that the mine owner has stated that the KEECO process represents a substantial reduction in the capital expenditure required for water treatment to a magnitude unmatched by anything to his knowledge, while still providing the desired water quality results. The ability to implement a consistent treatment programme that can adequately address any requirements for both present and future regulatory criteria was the primary reason for the mine owner's decision to implement the KEECO process. Understandably, the mining industry is relatively conservative when investing its funds in new technologies or approaches. This reflects in part the low profit margin of many companies. However, new technology must be incorporated into mine design and closure plans as it becomes available. Thus far, it appears that the project at the Bunker Hill mine is a success, and a substantive stepping-stone on the way to the increased implementation of the Silica Micro Encapsulation process, and the next generation of environmental technologies for water and waste treatment in the mining industry.

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