APPENDIX A

TECHNICAL MEMORANDUM FOR SULFATE SOURCE CONTROL EVALUATION SIERRITA TAILING IMPOUNDMENT

Prepared for:

FREEPORT-MCMORAN SIERRITA INC.
6200 West Duval Mine Road
Green Valley, Arizona

TECHNICAL MEMORANDUM FOR SULFATE SOURCE CONTROL EVALUATION SIERRITA TAILING IMPOUNDMENT

October 2008

Prepared by:

MWH
1475 Pine Grove Road, Suite 109
P.O. Box 774018
Steamboat Springs, CO 80487
(970) 879-6260

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1.0 INTRODUCTION

1.1 OVERVIEW OF FEASIBILITY STUDY

This Technical Memorandum identifies and evaluates potential mitigation response actions, control technologies, process options, and alternatives for source control at the Sierrita Tailing Impoundment (STI) located south of Tucson, Arizona (see Figures 1 and 2). The source control alternatives evaluated in this Technical Memorandum could supplement existing source control provided by the existing interceptor wellfield and Focused Feasibility Study (FFS) wellfield proposed for installation east of the STI to improve seepage capture downgradient of the northern portion of the interceptor wellfield (M&A, 2007). Potential source control technologies/process options were screened relative to their effectiveness, implementability and cost and were assembled into potential supplemental source control alternatives for additional analysis. The screening of source control technologies/process options and development of supplemental source control alternatives is reported in this Technical Memorandum along with a feasibility-study level analysis of the proposed alternatives.

This Technical Memorandum has been developed as an appendix to the Feasibility Study (FS). The FS evaluates potential mitigation response actions for source control, plume management, and drinking water supply mitigation, pursuant to Mitigation Order on Consent Docket No. P-50-06. The scope of this Technical Memorandum is limited to source control upstream and at the STI.

The development and evaluation of potential supplemental source control alternatives was a three-step process. First; potentially applicable mitigation response actions, technologies, and process options capable of reducing sulfate mass loading from the STI to regional groundwater were identified and screened qualitatively for effectiveness, implementability, and cost (Section 2). Second; mitigation response actions, technologies, and process options retained during the screening step were combined into source control alternatives for which conceptual designs were developed (Section 3). Third; the source control alternatives were evaluated quantitatively based on their implementability, effectiveness and cost (Section 4).

The development of potential source control alternatives was based on site-specific data including tailing mineralogy and pore-water chemistry, groundwater chemistry, hydrogeologic conditions in the interceptor wellfield area, Freeport-McMoRan Sierrita Inc. (Sierrita) infrastructure and mineral processing technology, and discussions with Sierrita personnel and consultants. Cost and engineering-feasibility data were provided by Sierrita personnel and consultants based on vendor quotes and actual costs for similar work at other sites.

1.2 SITE BACKGROUND

The STI is approximately 25 miles south of Tucson and 0.5 to 1.5 miles west of Green Valley in Pima County, Arizona (see Figures 1 and 2 in main document). The STI covers approximately 3,600 acres east of the Sierrita Mine site and west of Green Valley.

The STI began operations in 1970 (M&A, 2007). In the mid 1970s, results of monitor well installation and groundwater sampling indicated that sulfate was present along the east edge of the STI. In 1978, Duval Corporation initiated installation of extraction wells to control eastward movement of seepage from the STI. Collectively, these wells are known as the "interceptor wellfield." Operation and expansion of the interceptor wellfield have continued to date, with 23 interceptor wells currently being operated by Sierrita. Water pumped from the interceptor wellfield is used at the mine. The development and operation of the STI and the interceptor wellfield is described in detail by Montgomery & Associates (2007).

1.3 SIERRITA - MINERAL PROCESSING TECHNOLOGY

Crushed ore from the Sierrita open pit is transferred to the milling/grinding circuit via the mill feed belt system. A primary flotation system uses a mixture of reagents to recover copper and molybdenum concentrates from the milled ore. The residual fraction (known as tailing) is conveyed as a slurry and deposited on the surface of the STI.

A secondary floatation circuit is used to recover molybdenum disulfide (MoS_2) from the copper concentrate. The molybdenum disulfide still contains some copper and lead sulfide residuals that are oxidized by a hydrometallurgical process involving a hot ferric chloride ($FeCl_3$) leach producing moly trioxide. Following the hydrometallurgical process, the liquid is separated from the solids followed by recovery of the dissolved copper as cement copper and regeneration of the leach liquor through chlorination. The resulting molybdenum concentrate is then sent through an on-site roaster.

Ore that is too low in copper concentration or of the wrong chemical composition to be sent through the milling process is hauled out of the pit and deposited on the leach stockpiles in order to be processed in the solution extraction/electrowinning (SX/EW) process. Leaching operations involve applying a dilute sulfuric acid solution to the leach ore stockpiles. As the solution percolates downward through the stockpile, copper and other metals are leached out of the rock. The copper laden solution is called pregnant leach solution (PLS) and is recovered at one of the headwalls and sent to the SX Plant. At the SX Plant copper in solution is extracted and concentrated into an electrolyte solution that is pumped to the EW tankhouse for processing.

1.4 SIERRITA - TAILING IMPOUNDMENT OPERATION

This section describes the STI operation including dam construction methods, dust control methods, tailing mineralogy and pore water chemistry.

1.4.1 STI Operations

Discharge of tailing slurry to the STI began in March 1970 and continues to the present day based on the current mill production rate of 112,000 tons per day. The STI is an approximately 300-foot high, 3,600-acre tailing impoundment that retains the tailing material. The side slopes of the impoundment are comprised of the coarse fraction of the tailing and have been constructed at an approximate slope of 3:1. The current volume of tailing in the STI is estimated to be 1.7 billion tons.

The STI is constructed using a "wet-dam" construction method to minimize fugitive dust emissions from the tailing impoundment. A 42-inch tailing-delivery line delivers the tailing slurry to the STI at about 52% solids by weight. The tailing slurry gravity flows from the thickeners at about 25,000 gallons per minute (gpm). The tailing-delivery line feeds into header lines located along the north and south perimeter of the impoundment. Approximately 20 spigots are operated over a length of approximately 1,600 feet of header line. The spigots are spaced to fill the impoundment evenly (URS, 2007).

The tailing solids are a mixture of sand, silt and clay size particles. As tailing flows out of the spigots, the coarse sand settles first followed by the slime (defined as 50% passing No. 200 sieve size) as the tailing migrates to the back of the impoundment. The spigotting of the tailing is controlled such that the beach aggrades to a uniform slope. The intent is to maximize the hydraulic sorting of the whole tailing so that a uniform and relatively free-draining shell of tailing is created (URS, 2007).

As the slurry is deposited onto the sloped STI surface, the solids settle out allowing the decanted water to flow away from the crest of the impoundment and toward the reclaim pond. The reclaim pond is maintained approximately 5,000 feet from the crest of the impoundment. Water from the reclaim pond is pumped back to the Sierrita mill for reuse in mineral processing. The moisture that does not decant is contained in the pore spaces of the tailing material. Structural stability of the dam is greatly reduced if a significant volume of pore-space water is not allowed to drain from the impoundment. However, this allows for some tailing water to infiltrate deeper into the tailing impoundment and eventually discharge to groundwater beneath the impoundment (URS 2007).

1.4.2 Dust Control

A wet surface is maintained on the tailing to help control fugitive dust emissions from the impoundment. The spigot construction method is designed to promote classification of the particle sizes during deposition and drainage of the exterior shell to enhance stability. In addition to exploiting the spigot method of deposition for dust suppression, algae and bacteria are added into the tailing disposal line at 30 gpm to mix with the tailing slurry before it is deposited. The algae and bacteria bind together creating a stable surface (i.e, crust) on the tailing impoundment that reduces fugitive dust emissions. Magnesium chloride ($MgCl_2$) is sprayed on the roads around the impoundment and on the impoundment surface to aid in binding of the tailing material further reducing fugitive dust emissions.

1.4.3 Tailing Mineralogy and Pore Water Chemistry

The mineralogy of the tailing based on the average of eight samples collected in 2006 (Phelps Dodge, 2006) is shown in Table 1.

TABLE 1
AVERAGE MINERALOGICAL ANALYSIS OF TAILINGS

Mineral Sample	Average Wt.% based on sample dried at 40^{o}C
Plagioclase	31.33
K-Feldspar	28.04
Quartz	23.81
Muscovite	3.63
Swelling Clay	3.24
Biotite	2.96
Calcite	1.44
Pyroxene	1.43
Chlorite	1.21
Gypsum	1.14
Pyrite	0.94
Kaolinite	0.56
Magnetite	0.15
Amphibole	0.13

Pore-water chemistry of water within the STI was estimated based on the data shown in Table 2 using the ten samples collected from the reclaim pond.

TABLE 2
WATER QUALITY DATA MEASURED FROM SIERRITA TAILING IMPOUNDMENT DECANT WATER

No.	Sample ID	Sampled Date	Alkalinity	Ba	Ca	Cl	F	K	Mg	Na	NO_2 & NO_3 as N	pH	SO_4	Temp
1	RECLAIM	8/15/03	96	0.044	476	103	0.5	23	56.7	156	1.56	7.4	1670	NA
2	RECLAIM	12/21/04	60	0.033	354	131	1.2	30.3	9.4	166	1.22	9.1	1180	13
3	RECLAIM	12/13/05	118	0.041	392	129	0.2	9.4	78.2	131	1.36	7.8	1370	24.9
4	RECLAIM	11/17/06	101	0.048	489	133	1	21.7	78	178	1.34	7.8	1540	23.6
5	Reclaim Pond	9/30/97	24	NA	645	172	NA	62.2	3.3	358	NA	6.8	2100	NA
6	Reclaim Pond	12/30/97	36	NA	581	175	1	36	4.6	220	NA	9.4	1640	NA
7	Reclaim Pond	3/31/98	28	NA	587	240	NA	28.1	4.2	266	NA	9.2	1550	NA
8	Reclaim Pond	6/30/98	90	0.052	645	320	1.3	59.3	0.5	276	NA	10.4	1820	28.6
9	Reclaim Pond	10/14/99	34	0.03	503	180	1.3	53	0.6	278	1.96	8.9	2140	NA
10	Reclaim Pond	11/17/06	33	0.056	625	210	2.9	45.4	51	247	1.66	7.5	1900	16

Notes:
1. Alkalinity, chloride and sulfate represent total concentrations. Measurement units are mg/L.
2. The pH was measured in the laboratory.
3. Temperature was measured in °C.
4. NA is equal to not analyzed
5. Water quality data were provided by Sierrita.
6. "Reclaim Pond" is the name for water sampled from the surface of the Reclaim Pond on the STI.
7. "RECLAIM" is the name for water sampled from the Reclaim Water Booster Station that returns solutions to the mill for reuse. "RECLAIM" water contains solutions from the Reclaim Pond and the interceptor well system (interceptor wells IW-1 through IW-24).

1.5 SULFATE MASS BALANCE AND GEOCHEMICAL MODELING

This section presents the sulfate mass balance for the STI and the geochemical modeling of pore waters within the STI.

1.5.1 Sulfate Mass Balance

All known sources of sulfate to the STI have been included and considered in a sulfate mass balance to help develop and screen sulfate source control technologies. Data provided by Freeport-McMoRan Copper & Gold Inc. were used to construct the sulfate mass balance (Table 3). Current sources of sulfate to the STI include pit dewatering water added to the mill stream, water derived from the Canoa Ranch wellfield, the copper flotation circuit, the molybdenum processing circuit, sulfate contained in the tailing solids, and stormwater runoff diverted from the leach field/Amargosa Pond and transported to the STI via the Duval Canal.

The estimated yearly sulfate loading to the STI during 2007 is summarized in Table 3 and Figure 4. Only the mass of sulfate from ore and processing contributions were considered in this estimate. As part of the copper extraction process, sodium hydrosulfide (NaHS) is added to suppress chalcopyrite flotation. In order to construct the sulfate mass balance, the resultant solution was conservatively assumed to oxidize to sulfate. As part of the molybdenum ore extraction process, molybdenum disulfide is sent through an on-site roaster. As the concentrate is roasted, the sulfide is oxidized to sulfur dioxide, which is then captured with a lime slurry. This results in a gypsum slurry that reports to the STI. Water from the reclaim pond and interceptor wellfield were not included in the sulfate mass balance since these sources are re-circulated into the mill stream. Approximately 80% of the sulfate can be attributed to sulfate contained in the ore. The other sources of sulfate include processing of molybdenum (8%) and copper (4%) ores, followed by water dewatered from the pit (5%) and stormwater runoff (2%) (Figure 4). Groundwater extracted from the Canoa Ranch wellfield for mine and potable-water use adds a negligible amount of sulfate to the system (<1%). Stormwater diverted to the Duval Canal is neutralized with lime before it reaches the STI, so a portion of the sulfate is expected to be present as gypsum ($CaSO_4 \cdot 2H_2O$).

The sulfate mass balance excludes the large reservoir of sulfate already present in the STI. The inventory of sulfate and sulfur within the STI was estimated from chemical analyses of composite tailing samples obtained during drilling. The average sulfate-sulfur concentration of the tailings was 0.34%, which amounts to 17,340,000 tons (short, US) of sulfate, or approximately 1.02% of the total mass of tailings in the impoundment. The average sulfide-sulfur concentration of the tails was 0.89%, which amounts to 15,130,000 tons of sulfide. Under some scenarios (e.g. reduced concentrations of gypsum in the tailing system), it is conceivable that gypsum could dissolve and provide a source of sulfate to STI seepage water; this scenario is evaluated below in Section 1.5.1. In addition, pyrite contained in the tailing could oxidize to produce sulfate, but this process is believed to be negligible at this time based on the neutral pH of the seepage and the lack of evidence of oxidation at depth in samples collected from drill cores.

Figure 4. Estimated yearly loading of the mass of sulfate from ore and processing contributions to the STI during 2007.

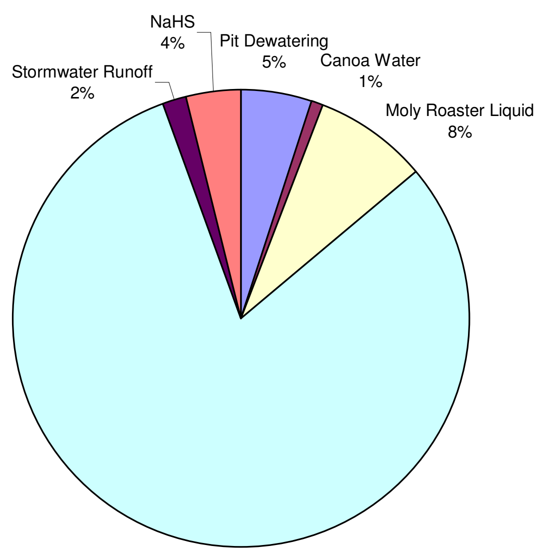


TABLE 3
ESTIMATED YEARLY LOADING OF SULFATE TO THE STI DURING 2007

Sulfate Source	Sulfate Concentration (mg/L)	Sulfur as Sulfate (%)	Estimated Average Water Flow (gpm)	Sulfate mass (tons)	Sulfate mass (% of total)
Pit Dewatering	8,400	100	636	11,700	5
Canoa Ranch Wellfield	90	100	11,150	2,200	1
Moly Roaster Slurry	-	100	-	18,800	8
Stormwater Runoff from Leach System	31,200	100	58	3,930	2
Ore from mill (tailing)	4,810	100	106,874 (tpd)	188,000	80
Copper Flotation (NaHS)	-	0	-	9,330	4
TOTAL	**-**	**-**	**-**	**233,960**	**100**

Notes:
1. Data supplied by FCX.
2. Tons are reported as short, US.
3. Moly roaster sulfate assumes that 98% of the sulfur reports to the tailing and is based on the mass of MoS_2 roasted.
4. NaHS, the calculated mass of sulfate assumes all sulfur is oxidized, and is based on the mass of NaHS consumed by the mill
4. Values of stormwater runoff were reported from water flow from the Amargosa pond to the STI.

1.5.2 Geochemical Modeling of STI Water

Water quality data collected from the Sierrita reclaim pond were examined to determine probable geochemical processes affecting the chemical composition of pore water within the STI. The geochemical-computer code PHREEQC 2.13.2 (Parkhurst and Appelo, 1999) with the wateq4f.dat thermodynamic database was used to calculate the saturation status of sulfate-bearing phases (e.g. gypsum). This information was used to evaluate whether chemical transformations (mineral precipitation and dissolution) could be controlling sulfate concentrations within the STI. The saturation status was quantified by predicting the saturation index, which is a function of the solution composition and the solubility constant. A saturation index of zero indicates that the mineral is in equilibrium with the solution, a positive saturation index indicates that the mineral would precipitate while a negative saturation index indicates that the mineral would dissolve.

Geochemical-equilibrium modeling was conducted using ten water-quality samples collected from the reclaim pond and tailings-decant water between 1997 and 2006 (see Table 2). A water temperature of 25°C was assumed for the calculations when field measurements were missing. Water samples labeled as "Reclaim Pond" and "Reclaim" both represent water collected from the STI, but were labeled differently in the database. These waters come from the same source. Based on the saturation-index calculations for each water sample, the average saturation index for gypsum was -0.07, which suggests that the water collected from the STI is in equilibrium with gypsum.

The saturation-index calculations, coupled with the presence of gypsum (1.14%) in the tailing (see Table 1) suggest that gypsum is controlling sulfate concentrations in the STI. These calculations indicate that decreasing sulfate concentrations in the tailings-discharge stream could result in the dissolution of gypsum (solid) into the aqueous phase in order to maintain equilibrium conditions. This would occur until the mass of gypsum (solid) in the tailing was consumed (approximately 17.3 million tons). This gypsum dissolution process would maintain sulfate concentrations at values currently occurring in the STI and in seepage waters until the gypsum was consumed.

1.6 WATER BALANCE FOR STI

A water balance for the STI was developed to determine annual seepage and sulfate mass flux rates from the impoundment (M&A, 2007). Conceptually, water balance calculations consist of treating the domain as a closed system, in which the volume of water flowing into (inflow) and out of (outflow) the system during a time period are summed. If the volume of water stored in the system is changing with respect to time, a change-of-storage term is also included in the calculations.

For the STI, the *inflow* components are:

1. Water in the tailing slurry delivered to the impoundment
2. Precipitation directly onto the impoundment
3. Surface water discharge from upgradient areas, much of which is captured and delivered via Duval Canal.

The STI *outflow* components are:

1. Evaporation
2. Water recovered via pumping from the STI reclaim pond
3. Seepage through the impoundment

The change-of-storage term represents water retained in the deposited tailing. Values were determined on a calendar year basis and based on measured and/or available data and appropriate assumptions for all the water balance components except seepage (M&A, 2007). Assuming conservation of volume, estimates of seepage were calculated as a residual of the water balance model.

The results of the water balance model prepared by M&A (2007) are summarized in Figure 5 (a) and (b). For the inflow components as represented by 2006 (M&A, 2007, Figure 6), approximately 85% of the inflow or 26,323 acre-feet can be attributed to water delivered with tailing, the next largest contributor is precipitation (14%) followed by surface water discharge (1%). For the 2006 outflow components (M&A, 2007, Figure 6), approximately 46% of the outflow can be attributed to evaporative losses, the next largest contributor is seepage (29%) followed by pumping water from the reclaim pond (25%).

The results of the water balance model suggest that alterations to the design of the reclaim pond (e.g., a smaller and deeper configuration or separate lined facility) would not significantly conserve water losses from the STI. However, seepage could be significantly reduced if the volume of water were reduced.

Figure 5 (a) estimated inflows for 2006

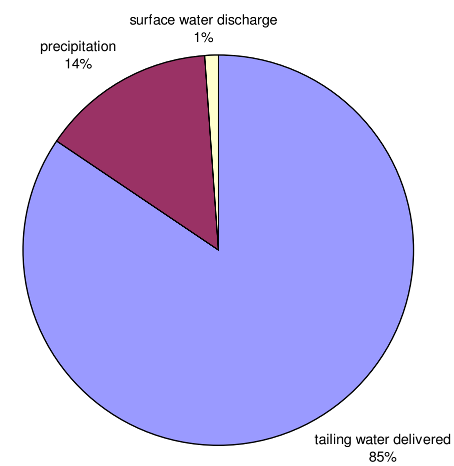
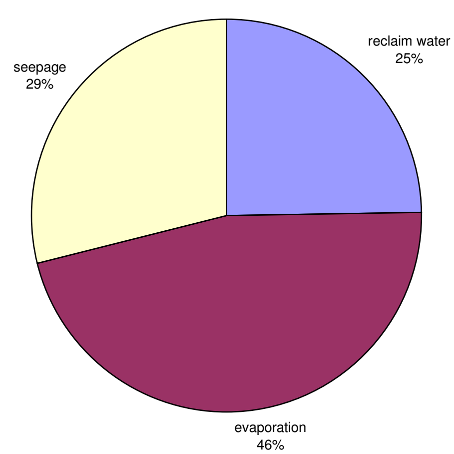


Figure 5 (b) estimated water outflows for 2006



2.0 IDENTIFICATION AND SCREENING OF POTENTIALLY APPLICABLE SOURCE CONTROL RESPONSE ACTIONS AND MITIGATION TECHNOLOGIES/PROCESS OPTIONS

This section discusses the source control mitigation action objective and presents a screening analysis of mitigation response actions, control technologies, and process options screened to control sulfate-impacted water upstream and within the STI. Generally speaking, source control response actions are generic categories of steps that can be taken to accomplish the response action objective. These actions can be composed of more than one technology, and each technology can consist of one or more process options.

Potentially applicable mitigation response actions were identified and qualitatively screened for effectiveness, implementability and cost. Effectiveness refers to the ability and reliability of the technology or process option to meet the mitigation objectives, consideration of impacts during construction, and whether the technology is proven and reliable. Implementability is defined for the screening process as the ability of the technology or process option to be permitted, constructed and operated at the site, given general site conditions and administrative constraints, and whether the technology is technically feasible to implement. Effectiveness and implementability were the primary screening criteria. Cost was evaluated qualitatively as a secondary screening criterion to discriminate between control technologies and process options with equivalent effectiveness and implementability.

2.1 SOURCE CONTROL MITIGATION ACTION OBJECTIVE

A mitigation action objective is a qualitative and quantitative statement of the mitigation goals. In this technical memorandum, response actions were considered for reducing sulfate mass loading from the STI to the regional aquifer.

2.2 MITIGATION RESPONSE ACTIONS

Mitigation response actions considered as part of the screening process included:

- No action
- Sulfate source control for the tailing discharge and stormwater discharge (to the tailing impoundment)
- Water source control
- Seepage source control for reclaim pond
- Containment
- In-situ tailing treatment
- Tailing discharge source control

Sulfate source control includes technologies that could potentially reduce the amount of sulfate in the tailing discharge to the STI (e.g., process technologies within the mine) and in stormwater discharges to the STI. Water source control includes technologies that could potentially reduce the amount of water discharged with the tailing. Seepage source control includes technologies that control seepage from the STI. Containment source control involves reducing infiltration into the STI following closure. In-situ tailing treatment would attempt to reduce sulfate mobility and leaching through the STI. Discharge source control includes potentially eliminating tailing discharge to the STI through using the tailing to produce a marketable product.

2.3 IDENTIFICATION AND SCREENING OF MITIGATION RESPONSE ACTIONS AND CONTROL TECHNOLOGIES/PROCESS OPTIONS

Specific control technologies/process options considered for each of the seven mitigation response actions are listed in Table 4. Table 4 also provides a summary of the screening outcome for each potential technology and process option. In the following sections, technologies and process options are discussed in more detail for screening purposes along with rationale for eliminating them from further consideration, when appropriate.

2.3.1 Sulfate Source Control Options for Tailing and Stormwater Discharges

The objective of this general response action is to reduce the mass sulfate in the tailing or stormwater discharges to the STI. The following sulfate source control options were considered.

Tailing discharge source control options

1. Removal of NaHS from concentrator discharge
2. Removal of $CaSO_4$ from molybdenum roaster scrubber discharge
3. Remove pyrite from tailing
4. Reduce pyrite reactivity
5. Stormwater discharge source control options

Option 1: Sodium hydrosulfide (NaHS) is added during the copper extraction process to suppress chalcopyrite flotation. Removal of NaHS from the concentrator discharge would involve substitution of cyanide for NaHS in the milling process. The cyanide substitution option was eliminated from further consideration due to environmental risk (implementability) and because NaHS has been quantified as a relatively small contributor of sulfate load to the STI (sees Section 1.5). Also, removal of NaHS and roaster scrubber discharge from the process could also reduce the formation of the tailing crust, which serves to control fugitive dust emissions.

Option 2: Removal of $CaSO_4$ from moly roaster scrubber discharge was retained for further screening because it is implementable, and may produce a product that can be used by the mine (sulfuric acid). It is also the largest source of sulfate other than the ore. An important factor requiring further evaluation is the potential for decreases in sulfate in the tailing discharge to be offset by dissolution of sulfate in existing tailing within the STI, which could result in no net reduction in sulfate concentrations in seepage water. This scenario is evaluated in greater detail in Section 4.

Option 3: Removal of pyrite from the tailing prior to deposition would require construction of an additional flotation plant (approximate cost in excess of $20 million) and would not effectively alter the current sulfate loading due to the limited amount of pyrite oxidation occurring in the existing tailing. Therefore, this process was eliminated from further consideration. There was no visible pyrite oxidation in auger samples of tailing material taken in 2007. In addition, the sulfide-sulfur assay of the tailing material indicated a sulfide-sulfur concentration of 0.89%, which corresponds well to the estimated 2% pyrite in the original tails.

TABLE 4
SUMMARY OF SCREENING OF SULFATE SOURCE CONTROL OPTIONS

Operable Unit	Mitigation Response Action	Control Technology	Process Option	Description	Screening Comments
Sierrita Tailing Impoundment (STI)	No Action			No Action	Retained for further screening as baseline condition.
	Sulfate Source Control for Tailing and Stormwater Discharge	Reduce amount of sulfate in tailing discharge	Remove NaHS from concentrator discharge	Substitute cyanide for NaHS in milling process	Potential future reductions due to process changes are not significant relative to existing mass of sulfate in tailing. Cyanide option removed from additional screening due to environmental risk.
			Remove $CaSO_4$ from moly roaster scrubber discharge	Install an acid plant or pressure leach vessel (PLV)	Test work ongoing at Bagdad. Retain for further screening (Note: May not be available in time frame required and will not address existing sulfate mass).
		Remove pyrite from tailing	Modify milling circuit and reactive mineral passivation	Add gravity separation or flotation process to milling circuit and install treatment process for passivation of reactive minerals	Retain for further screening (Note: Flotation is approx. $20M, plus need to treat/dispose of product. Sulfate production from pyrite oxidation is assumed to be relatively low).
		Reduce pyrite reactivity	Control oxygen flux to tailing	Maintain high water saturation to reduce oxygen flux to reactive sulfide	Water saturation is a function of operational water balance and climatic conditions. Saturation of tailing also affects dam stability. Increasing saturation in tailing would reduce water available for mine operations, stress other water sources and negatively affect dam stability. It would also increase seepage to interceptor wells. Do not retain for further screening.
		Reduce Amargosa Pond overflows Reduce Duval Canal discharges	Expand leach system storage Divert Duval Canal to lined stormwater pond	Expand lined leach system storage ponds Construct lined pond near STI	Retain for further screening (Note: This will happen in 2008).
	Water Source Control for STI Tailing Discharge	Tailing filtering process		Reduce water from tailing discharged to STI	Retain for further screening, but does not address existing mass and not proven at scale required.
		Tailing paste process		Reduce water content of tailing discharged to STI	Retain for further screening, but does not address existing mass and not proven at scale required.
	Seepage Control for Reclaim Pond	Extraction	Infiltration gallery/caisson	Construct infiltration gallery beneath pond to reduce seepage	Pond pumping is much more effective than capturing seepage through tailing (permeability controlled). Do not retain for further screening.
			Wicking system	Install wicks in tailing to reduce seepage	Not likely to be effective due to uniform nature of tailing and depth to water table. Do not retain for further screening.
		Containment	Low permeability liner	Line bottom of reclaim pond to limit infiltration	Not implementable. Do not retain for further screening.
		Operational	Control pond location	Maintain pond location in area with lowest permeability to reduce seepage	Best operational practice. Retain for further screening.
			Reclaim pond pumping	Operate existing pumps to maximize recovery from pond	Best operational practice. Retain for further screening.
	Containment	Cover	Earthen Cover	Close STI and construct soil cover to limit infiltration	Will occur at final reclamation and closure. Retain for further screening.
			Stormwater controls	Construct stormwater controls to convey stormwater away from STI	Best operational practice. Retain for further screening.
	In-Situ Tailing Treatment	Physical/chemical treatment	In-situ stabilization	Inject or mix stabilizing agent to reduce sulfate mobility	Not proven or implementable at scale required. Could mobilize other constituents. Do not retain for further screening.
			In-situ vitrification	Use electrical current to melt tailings and reduce sulfate mobility	Not proven technology. Electricity limited. Do not retain for further screening.
			In-situ passivation of reactive materials	Inject or mix passivation agent to reduce mineral reactivity	Not proven technology. Do not retain for further screening.
	Tailing Discharge Source Control	Formed products	Bricks	Manufacture bricks from tailing	There is currently no local manufacturing facility capable of manufacturing formed products from tailing. Manufacture of formed products would not address source control issue because it will not address the existing tailing sulfate mass. Do not retain for further screening.

Option 4: The mitigation option of reducing pyrite reactivity within the existing tailing in the STI was not retained for further screening. Pyrite reactivity is controlled by the availability of oxygen to react at the pyrite mineral surface. For this option to be effective, high water saturation would need to be maintained in the tailing to reduce the flux of oxygen to reactive sulfide. Water saturation is a function of the operational water balance and climatic conditions. Tailing saturation also affects dam stability. Increasing saturation would increase water needed for mine operations and negatively affect dam stability. It would also increase seepage to interceptor wells. Therefore, this option was not retained for further screening.

Option 5: Stormwater discharge source control options retained for further analysis included reducing Amargosa Pond overflows and reduction of Duval Canal discharges (approximately 2% of the sulfate balance). These are described in greater detail in Section 3.1.1

2.3.2 Water Source Control Technologies for STI Discharge

Water source control includes technologies that could potentially reduce the amount of water discharged with the tailing. The objective of this potential alternative is to reduce the amount of water discharged to the STI with the tailing stream. Two potential process options were included in the screening:

1. Paste tailing (thickened tailing)
2. Filtered tailing (dry-stack tailing)

Both of these processes would reduce the amount of water being discharged to the STI. Three papers with additional background on filtered and paste tailing methods are provided in Attachment 1.

<u>Option 1: Paste tailing disposal</u>

In this method of tailing disposal, the tailing slurry is dewatered in specialized paste thickeners to achieve a mixture with low water content (approximately 30 to 40% by weight; 35% by weight = 42% by volume), but the slurry can still be pumped (moisture content data from Scola and Landriault, 2007). Typically, positive displacement pumps are used to transport the slurry to the tailing impoundment. To facilitate the thick tailing flow, the tailing materials must contain a minimum of 15% particles less than 20 micron. The deposited tailing materials do not segregate during transportation and placement, and form a relatively steep beach; ranging from 4% to 10% as compared to 0.5% to 2% in conventional wet deposition. The amount of water released after deposition is small and a reclaim pond typically does not form. Depending on the climate of the area, provisions have to be made for collecting runoff.

Currently the most common use of paste tailing is for underground backfill and commonly includes an additive such as cement. Paste tailing is being implemented at surface mines for tailing management and offers the benefits of limited seepage, reduced water use and reduced reclamation and closure costs.

Paste tailing was retained for further screening.

<u>Option 2: Filtered tailing disposal</u>

In filtered tailing disposal, the tailing materials are "dried" using filter presses, filter belts or vacuum belt filtration. Vacuum belt filtration is perhaps the most practicable for larger scale operations (Davies, M.P. and S. Rice 2001). The resulting material generally has a moisture content of 24 to 15% by weight or 29% to 18% by volume (moisture content data from Scola and Landriault, 2007).

Filtered tailing is not pumpable and is transported using trucks or conveyors. The material is stacked in lifts of selected thickness and usually compacted to a specified density. Minor amounts of water are released during consolidation or compaction of the tailing. Although a reclaim pond is not formed, provision may be required for collecting runoff or infiltrated water. Closure of the facility can be concurrent with construction as access for vehicles is available immediately after deposition. Water losses are minor and filtered tailing requires significantly smaller area compared to other disposal methods because side slopes of the deposit can be steeper during construction (they may need to be reduced during reclamation and closure). The main limitations of this method are; potential fugitive dust, the cost and capacity of the currently available filter presses and belt filters, and transportation costs.

The physical stability of a dry-stacked tailing pile greatly reduces the possibility of an embankment breach. Embankments and berms can be smaller, which reduces capital costs in construction.

Filtered tailing was also retained for further screening.

2.3.3 Seepage Source Control for Reclaim Pond

Seepage source control includes options that could potentially reduce the amount of seepage from the STI reclaim pond during operation. Three general categories of seepage source control were screened: extraction, containment and operational practices. These general categories are summarized below:

Extraction

1. Infiltration gallery
2. Wicking system

Reclaim Pond Containment

3. Low permeability liner

Operational

4. Control pond location
5. Reclaim pond pumping

Option 1: Infiltration galleries are generally used to intercept runoff of subsurface flow and promote water percolation and collection through a geologic material. An infiltration gallery would consist of horizontal screens or slotted pipes placed near or below the reclaim pond to promote subsurface flow and collection. An infiltration gallery would intercept flow through the means of a slotted pipe surrounded by permeable sand to provide an opportunity for removal of water through pumping. Infiltration galleries within the STI would be difficult to construct and maintain due to the dynamic nature of tailing deposition and water production would be limited by the low permeability of the fine tailing.

Option 2: Wicking systems generally use evaporative forces to remove water and have been used to promote tailing consolidation, but remove much smaller volumes of water than an infiltration gallery. A wicking system would also be difficult to maintain on the active STI and would produce relatively low volumes of water. Both wicking and infiltration gallery systems, if they were effective, could draw water away from the pond and reverse gradients within the STI. Extraction options using wicks or infiltrations galleries would be much less effective and more energy intensive than removing the water through pumping in the pond. Therefore, these options were not retained for further screening.

Option 3: Containment of the reclaim pond with a low permeability liner is not implementable due to the operational constraints of the system (i.e. the dynamic nature of deposition). In addition, the pond would need to be relined as tailing deposition occurs and the height of the STI increases. A low permeability liner could potentially be floated if significant upward hydraulic heads exist in the vicinity of the liner. Therefore, this option was not retained for further screening.

Options 4 & 5: Operational controls include maintaining the pond in an area with the lowest permeability to reduce seepage and operating the reclaim pond pumps to maximize recovery from the pond. These two options are considered best operational practice and were retained for further screening as part of the base alternative.

2.3.4 Containment Source Control

Containment source control involves limiting infiltration into the STI after closure to minimize infiltration of precipitation and enhance the rate of drain down.

Two options were considered as shown below:

1. Soil cover
2. Stormwater controls

Options 1 & 2: A soil cover would be designed to store infiltration from precipitation events and discharge this water during dry periods through evapotranspiration (ET). ET covers have been shown to be highly effective in semi-arid areas. Design and construction of an ET cover will occur during final reclamation and this option was retained. Stormwater controls to prevent run-on and infiltration are considered best operational practice and were also retained.

2.3.5 In-Situ Tailing Treatment

The objective of in-situ tailing treatment would be to reduce sulfate mobility within the tailing. Both physical and chemical methods of in-situ treatment were evaluated as show below:

1. In-situ stabilization
2. In-situ vitrification
3. In-situ passivation of reactive minerals (sulfide)

Option 1: In-situ stabilization would attempt to inject or mix a stabilization agent into the tailing to reduce sulfate mobility. This option was not retained for further analysis because it is not proven or implementable at the scale required within the STI.

Option 2: In-situ vitrification is not considered a proven technology at the scale required and would require massive amounts of electricity. Therefore, it was eliminated from further consideration.

Option 3: Injection or mixing of a passivation compound into the tailing to reduce sulfide reactivity was also eliminated for two reasons; 1) it is not a proven technology and 2) reducing or eliminating sulfide activity (e.g. pyrite oxidation) would not effectively alter the current sulfate loading due to the limited amount of pyrite oxidation occurring in the existing tailing as determined with sampling and analysis performed in 2007.

2.3.6 Tailing Discharge Source Control

The objective of discharge source control would be to eliminate discharge to the STI. One option was considered for this alternative as shown below:

- Formed Product Manufacturing

Formed product manufacturing (i.e. forming brick from tailing) cannot be implemented due to the lack of an existing, local, commercial manufacturing facility that can manufacture formed product from tailing. Therefore, this option was not retained for further analysis.

2.4 SUMMARY OF ALTERNATIVES RETAINED FOR FURTHER ANALYSIS

The following process options were retained for further analysis based on the screening conducted in this section:

- Remove $CaSO_4$ from moly roaster scrubber discharge
- Tailing thickening process (paste tailing)
- Filtered tailing
- Reduce Amargosa Pond overflows
- Reduce Duval Canal discharges
- Control pond location
- Reclaim pond pumping
- Soil cover
- Stormwater controls

3.0 DEVELOPMENT OF SOURCE CONTROL ALTERNATIVES

This section describes alternatives for sulfate source control upstream and at the STI based on the process options retained by the previous screening evaluation (Section 2.4). These alternatives would supplement the existing interceptor wellfield and proposed FFS wellfield. The performance and cost of the supplemental source control alternatives are described in Section 4, as part of the detailed analysis of alternatives.

3.1 DEVELOPMENT OF SOURCE CONTROL ALTERNATIVES

Source control alternatives were developed to meet the mitigation objective of reducing sulfate mass loading for the STI to regional groundwater. Alternatives retained through the screening process include the following:

- Alternative 1 – Reduction of Amargosa Pond and Duval Canal Discharges, Control Reclaim Pond Location and Pumping, Soil Cover at Final Reclamation and Stormwater Controls
- Alternative 2 – Limit $CaSO_4$ from Moly Roaster Scrubber Discharge
- Alternative 3 – Filtered Tailing Process
- Alternative 4 – Paste Tailing Process

It should be noted that the options contained in Alternative 1 represent currently planned activities at the site and would be implemented in conjunction with any alternative.

3.1.1 Alternative 1 - Reduction of Amargosa Pond and Duval Canal Discharges, Control Pond Location and Pumping, and Final Reclamation and Closure

This alternative consists of reduction of Amargosa Pond and Duval Canal discharges to the STI; controlling the reclaim pond depth and optimizing pumping operation; and reclamation and closure through the installation of a soil cover and stormwater controls.

<u>Current Condition of the Reclaim Pond</u>

The Reclaim Pond forms as the tailing slurry is deposited from the tailing delivery line through spigots onto the surface of the active area of the impoundment. Some of the water separates from the solids as the energy dissipates and tailing material settles out. Due to the depositional slope of the tailing, the reclaim pond forms near the center of the STI (Figure 2). The pond has three barge pumps which are accessed by air boats.

<u>Planned Upgrade to Operation of the Reclaim Pond</u>

The alternative includes maximizing the recovery of Reclaim Pond water through optimization of the barge pump operation. Water turbidity is the limiting factor controlling operation of the barge pumps. The pond has to be maintained deep enough to allow the pumps to draw clean water free of suspended solids. The alternative may also include increasing the depth of the Reclaim Pond. The feasibility of deepening the pond, however, is limited by the geometry of the STI and ability of the tailings to flow.

<u>Current Condition of Amargosa Pond</u>

Amargosa Pond provides containment for stormwater runoff and upset conditions along Amargosa Wash. The facility serves as an overflow for Headwall No. 1, Bailey Lake, Raffinate Pond No. 2, and

Drain Pond No. 2. The facility is a single-lined (80-mil HDPE) pond capable of containing a 100-year, 24-hour storm event and is located approximately 1,000 feet downgradient of Bailey Lake and approximately 1,500 feet upgradient of B-Pond. Amargosa Pond is approximately 400 feet wide by 450 feet long and has a capacity of 49-acre feet (Dames & Moore, 1995). Fluids collected in Amargosa Pond are pumped back to Raffinate Pond No. 2 for reapplication to the leach areas. Overflow from Amargosa Pond discharges through the spillway and is carried to Duval Canal by the Amargosa Spillway (a concrete and HDPE lined conveyance channel). These features are shown on Figure 2.

Planned Upgrade to Amargosa Pond

Amargosa Pond upgrades will include one or two additional solution containment ponds totaling approximately 100 acre-feet of additional storage capacity to contain excess solutions. The construction of additional solution containment pond(s) will minimize the need for overflow to report to Duval Canal, and therefore, will reduce the volume of sulfate-rich solution reporting to the STI.

Current Condition of Duval Canal

Duval Canal is a lined conveyance channel that collects stormwater runoff and directs it via gravity flow to the STI. Duval Canal extends from the Mill to the STI. Contributing flows to the Duval Canal include runoff from the mill site, overflow from B Pond, overflow from Amargosa Pond and seepage collected and pumped from B and C Sumps. However, as the STI crest is raised, Duval Canal will no longer be able to gravity feed runoff to the STI.

Planned Upgrade to Duval Canal

Sierrita is in the process of finalizing the construction a 200 acre-foot–capacity, lined solution containment pond named the "Duval Canal Impoundment" that will contain the runoff from Duval Canal. In order to maintain an elevation that allows gravity flow along the length of Duval Canal. The Duval Canal Impoundment will be located at the boundary between the southwest corner of the Esperanza Tailing Impoundment and the western-most section of the STI.

3.1.2 Alternative 2 – Limit $CaSO_4$ from Moly Roaster Scrubber Discharge

Alternative 2 would include implementation of a technology to remove $CaSO_4$ from the moly roaster discharge, along with the source control options included in Alternative 1.

There are two potential technologies for removing $CaSO_4$ from the moly roaster discharge:

- Development of a pressure leach system
- Development of an acid plant for off-gas

Due to the limited amount of site-specific information available for the first technology, it was not retained for further analysis. This technology could be reconsidered in the future as new information becomes available.

Development of an acid plant for the off-gas has been evaluated by Sierrita and the Freeport Technology Group. In this process, the off-gas from the roaster is cleaned and converted into high-grade sulfuric acid with commercial value. Wet gas Sulfuric Acid (WSA) technology is one way to convert off-gas to sulfuric acid. The WSA technology is evaluated for cost, effectiveness and implementability in Section 4.

3.1.3 Alternative 3 – Filtered Tailing Process

Alternative 3 would include implementation of a filtered tailing process, along with the source control options included in Alternative 1.

Filtered tailing is tailing material that has been de-watered. The material is not "dry" but its moisture content has been reduced to near 20% by volume. The mechanical process of dewatering tailing involves pressure or vacuum force (M.P. Davies and S. Rice 2001). This force can be applied by a filter press, filter belt, or vacuum belt filtration. Due to the low moisture content of filtered tailing, deposition is achieved via truck or conveyor. The tailing is usually deposited from a high-point and is stacked in a conical pile. This generally is achieved by stacking towers or a ramp. Any water that remains in the tailing after the filtering process reports to the toe of the pile as will any runoff. The flow rate of any remaining pore water and runoff will be of a significantly less volume than that of a conventional impoundment, therefore a reclaim pond will not form as it does in the conventional wet-dam method of deposition.

The stacked, conical pile can be re-graded following deposition to allow for further compaction and consolidation, as well as making room for more tailing. Consolidation occurs at a much higher rate than conventional wet deposition impoundments. The filtered tailing process is evaluated for cost, effectiveness and implementability in Section 4.

3.1.4 Alternative 4 – Paste Tailing Process

Alternative 4 would include implementation of a paste tailing process, along with the source control options included in Alternative 1.

Paste tailing is tailing material that has been thickened so that moisture content has been reduced to near 30% to 40% by volume. The mechanical process of thickening tailing involves thickeners such as a deep cone thickener that is designed to optimize solid concentration. Due to the low moisture content of paste (thickened) tailing, conveyance and deposition are achieved via positive displacement pumps. The tailing delivery line could be connected to perforated pipe that deposits the tailing into shallow cones to later be graded. Some of the water that remains in the tailing after the thickening process reports to the toe of the pile as runoff or drains from the base of the pile. Some water is retained within the deposited material. In some cases, an additive such as cement is incorporated into the tailing (e.g. when it is used for backfill).

The shallow conical piles can be graded following deposition to allow for further compaction and consolidation, as well as making room for more tailing deposition. Consolidation occurs at a much higher rate than conventional wet deposition impoundments. The paste tailing process is evaluated for cost, effectiveness and implementability in Section 4.

4.0 DETAILED ANALYSIS

4.1 ALTERNATIVE 1 – DISCHARGE REDUCTION TO STI, RECLAIM POND MANAGEMENT, AND FINAL RECLAMATION AND CLOSURE

Alternative 1 includes elimination of Amargosa Pond and Duval Canal discharges to the STI; control of Reclaim Pond operation and evaporation; and reclamation and closure through the installation of a cover system and stormwater controls.

Effectiveness

The planned upgrades to the Amargosa Pond and Duval Canal will reduce sulfate reporting to the STI by 2%. Therefore, the effectiveness of this alternative is considered low.

Implementability

The time to implement Alternative 1 is considered to be high. The Duval Canal upgrades will occur in 2008 while the Amargosa Pond upgrades will be completed by 2010. Control of the Reclaim Pond surface area (evaporation) and optimization of pumping is an on-going process. Installation of an ET cover and stormwater controls will occur during final reclamation and closure of the STI.

Reclaim Pond Operational Changes

The alternative includes maximizing the recovery of reclaim pond water through optimization of the barge pump operation. In addition, the alternative may include operational changes to increase the depth of the pond thereby decreasing the surface area. This decrease in surface area will lead to a reduction in evaporation of decanted tailing water and allow Sierrita to reclaim more water from the STI. The implementation of decreasing the surface area of the pond and increasing the pumping capacity will allow for additional savings in water usage. Although there is no known feasible method of achieving a deeper reclaim pond at this time, Sierrita is currently researching this opportunity.

Duval Canal Impoundment

The Duval Canal Impoundment will be located near the boundary between the southwest corner of the Esperanza Tailing Impoundment and the western edge of the STI. The elevation of the pond will allow for continued gravity flow from Duval Canal. The pond is designed to have approximately 200 acre-feet in storage capacity and will be lined with high density polyethylene (HDPE).

The construction of this new facility has been completed. A modification to include this new facility in their Aquifer Protection Permit has been submitted to ADEQ. ADEQ approval is expected to be completed in 2008 at which time the pond will be put in use.

Amargosa Pond

The design, permitting and construction of the new pond(s) are currently underway. Sierrita has identified the need for an additional 200 acre-feet of storage capacity. If one location cannot be identified that is large enough to facilitate a 200 acre-feet pond, then multiple smaller ponds will be constructed.

Cost

The estimated cost for the construction of the Duval Canal Impoundment is $3.6 million.

The estimated cost for the construction of additional storage to augment Amargosa pond storage is $20 million. Thus, the total cost for Alternative 1 is $23.6 million.

4.2 ALTERNATIVE 2 – LIMIT $CASO_4$ FROM MOLY ROASTER SCRUBBER DISCHARGE

Alternative 2 would include implementation of an acid plant to remove $CaSO_4$ from the moly roaster discharge, along with the source control options included in Alternative 1.

Effectiveness

The effectiveness of this alternative is considered low. Although the moly roaster scrubber represents 8% of the sulfate load to the STI, the reduced loading would likely not result in a commensurate reduction in sulfate loading to groundwater. This is because reducing the gypsum load would cause the gypsum in the tailing to dissolve, which could release sulfate thus maintaining sulfate concentrations in seepage water at current levels until all gypsum within the tailing is consumed. The mass of sulfate within existing tailing is far greater than the mass of sulfate in the seepage and would provide a long-term source. Dissolution of gypsum in the tailing would mask any upstream reduction of sulfate loading. The large amount of sulfate in the ore reduces the effectiveness of this option as well.

Acid production from the oxidation of sulfide was estimated by performing a theoretical mass balance for a WSA plant for Sierrita by Haldor Topsoe in their cost estimate dated January 18, 2008. The daily production of sulfuric acid is estimated to be 140.2 tons, all of which could be utilized by Sierrita.

The WSA plant could increase molybdenum ore throughput and recovery creating cost savings and/or increased profit from molybdenum production. Further cost savings could be realized from the cessation of having to purchase sulfuric acid for use in the SX/EW process. A summary of potential benefits from the WSA include:

- Increased roaster throughput due to elimination of scrubber cleaning
- Acid production of up to 200 tons per day depending on sizing of preheater
- Increased rhenium recovery due to West Electrostatic Precipitators in new plant cleaning circuit

Implementability

The implementability of this option is considered high. The time to implement a new WSA Plant is approximately one to three years.

This technology is applied at more than 60 locations world-wide. The first application of this technology was in the early 1980's and has since been further refined to be more efficient and effective in removing sulfur (Laursen, J.K of Haldor Topsoe, 2007).

Laursen, J.K, and Jensen, F.E. of Haldor Topsoe (2007) has identified that the WSA technology has been proven to:

- Recover more than 99% of total sulfur
- Produce clean, concentrated commercial grade sulfuric acid
- Consume very little cooling water
- Produce little to no waste effluent

Haldor Topsoe (reference 19??) identified the following needs for construction of a WSA plant at Sierrita:

- The plant will have a footprint of approximately 13,000 ft^2,
- 40-60 Normal[1] cubic meters per hour (m^3/hr) of natural gas will be required for support in the process,
- 1600 m^3/hr of cooling water will be required, and
- Construction project of between 14-18 months.

<u>Cost</u>

The cost associated with constructing a WSA plant is separated into *Capital Cost*, *Cost Offset,* and *Additional Operating Cost.*

Capital Cost

Haldor Topsoe estimated the design and construction costs at $22,000,000. However, Sierrita estimated the cost of acid storage, offloading equipment and off-gas cleaning equipment to be an additional $13,000,000 bringing the cost estimate to $35,000,000 in addition to the costs of Alternative 1 ($23,600,000) that will be completed in conjunction with the chosen Alternative therefore, the total Capital Cost for this alternative would be $58,600,000.

Cost Offset

The estimated production rate of sulfuric acid is 140.2 tons per day and the commercial cost of sulfuric acid is currently $100 to $300 per ton depending on the source. Sierrita could consume all 140.2 tons per day of sulfuric acid, therefore, Sierrita could save $10,000,000 a year from having to purchase sulfuric acid (assumed $200 per ton at a rate of 51,000 tons per year consumed).

Additional Operating Cost

For a WSA plant to fuel the process autothermically, the SO_2 input needs to be greater than 6-7%. Below that, a plant will need support fuel (Arne Kristiansen, 2005). According to the Quick Mass Balance (Haldor Topsoe, 2008), the input volume of SO_2 is estimated at 1.6%. Operational costs will need to include support fuel in the form of natural gas. The estimated volume of natural gas needed is 1,413 to 2,119 ft^3 for every hour of plant operation. According to the Energy Information Administrations webpage (www.eia.doe.gov), the current cost of natural gas in Arizona for industrial usage is $9.68 per thousand ft^3. Using this price for natural gas as support fuel and the maximum operational volume of support fuel estimated, the operational cost for support fuel could be as high as $20.52 per hour or $493 per 24 hours ($180,000 per year).

[1] Normal conditions are defined as 1 atmosphere of pressure at 20 degrees Celsius.

Final Cost

Capital Cost = $58,600,000
Cost offset = $10,000,000
Additional Operating Cost = $180,000 per year
Total Capital Cost= $48,600,000

4.3 ALTERNATIVE 3 – FILTERED TAILING PROCESS

Alternative 3 would include implementation of a filtered tailing process, along with the source control options included in Alternative 1. Several sources were referenced for this section and residual moisture content following filtering and costs varied widely between sources.

Effectiveness

The effectiveness of filtered tailing is considered high due to the environmental benefits of reducing the amount of water discharged to the STI and beginning drain down of existing pore water. This would result in reduced operation time of the interceptor well system.

The amount of water conserved is also a significant benefit to filtered tailing. Conservation of water occurs during recovery through the filtering process and there is also reduced evaporative losses from facilities used to store and transport water including the reclaim pond, decant ponds and the tailing disposal line.

Assuming current moisture content of 58% (by volume) for the wet tailing and a range of possible moisture contents for filtered tailing of 29% to 18% (by volume), results in a savings of from 50% to 69% of the water used with the tailing. This would result in the savings of approximately 13,000 to 18,000 acre-feet of water per year, based on the water balance estimate of 26,323 acre-feet of water used with tailing on an annual basis.

It should be noted however, even in the arid climate of the Southwest, filtered tailing could still have a minor amount of seepage that will report to the toe of the pile. After draindown of existing pore water within the STI, the potential for infiltration to groundwater would be limited and could potentially occur through infiltration of rain water although at drastically lower rates. This risk can be reduced with progressive reclamation of the pile including grading and capping the exterior slopes of the dry-stack tailing material immediately following deposition.

Fugitive dust emissions from the top surface of the dry-stacked tailing are also a concern that would need to be addressed.

From a sulfate source control perspective, filtered tailing is considered to have a high effectiveness due to its affect on the water balance and reducing water (and sulfate discharges) from the STI.

Implementability

The time to implement is considered medium (3-10 years) which considers the length of time it would take to procure the necessary equipment and construct all ancillary facilities.

The implementation of filtered tailing process requires a good understanding of the filtering and geomechanical characteristics of the tailing including strength, hydraulic conductivity, moisture retention and clay mineral content (Davies and Rice, 2001). Stormwater controls would need to be implemented to convey runoff away from the stacked tailing. A contingency plan should be created that stipulates what protocol to follow should the filtering process be temporarily disabled. The geotechnical aspects of depositing filtered tailing on top of the existing impoundment would require significant study and are not well known at this time.

Once a good understanding of the material characteristics is established, the next step in implementing filtration process is to select a specific method of filtration, then engineer, procure and construct the filtration system. The filtered tailing process is known to work well for small-scale operations (i.e. less than 20,000 tons per day). Vacuum filtration is recommended for larger-scale operations. Currently, the largest filtered tailing operation is in Zambia at 50,000 tons per day.

The main limitation to implementing a filtered tailing operation at Sierrita involves the need to truck or convey the material to the STI. Large trucks cannot be driven on the STI, which would be required to grade and reclaim the material. In addition, fugitive dust problems could occur due to the dry nature of the material and arid/windy conditions at the site, which would require concurrent reclamation. Based on these issues, the implementability of filtered tailing at the STI is considered low.

Cost

The capital cost of the filters and ancillary equipment needed to process in excess of 100,000 tpd would be significant, perhaps on the order of $450 to $650 million, depending on the method of filtration. The operating cost does not include the cost of concurrent reclamation. The cost associated with filtered tailing is detailed below.

Cost Savings

- Reduced pumping costs due to reduction in tailing water

Additional Costs

- Capital cost of filter plant (see capital costs below)
- Operating costs – filtering, transportation, placement and compaction

Filter equipment is detailed below.

- **Filter Presses**. Filter presses are used for chemical and concentrate filtration. The filter cycle requires that the pressure chambers are filled and emptied. This means that time spent in filtration is a percentage of the total cycle. These filters have a relatively low capacity.

- **Vacuum Belt Filters**. This filter uses a horizontal belt driven by a head pulley. Vacuum is drawn through holes in the belt. Maximum filtration rates of 225 to 360 tons per hour (t/h), based on filtration area, filtered material and elevation can be achieved. This equipment has generally been accepted as the most economical for the filtration of tailing materials.

An average operating cost of approximately $2 per ton was assumed for filtered tailing based on current operating dry stack operations. However, actual costs can vary widely due to the range of operating conditions at any given site. Currently costs for disposal are $0.108 per ton plus $0.032 per ton for thickener operation. At the current production rate of 112,000 ton per day, this results in a differential of $76,036,800 per year (based on $2 per ton).

Total capital cost could be from $450,000,000 to $650,000,000 in addition to the costs of Alternative 1 ($23,600,000) that will be completed in conjunction with the chosen Alternative. Based upon this estimate, the costs for a filtered tailing operation at Sierrita are considered very high.

4.4 ALTERNATIVE 4 – PASTE TAILING PROCESS

Alternative 4 would include implementation of a paste tailing process, along with the source control options included in Alternative 1. Several sources were referenced for this section and residual moisture content following the filtering and costs varied widely between sources.

Effectiveness

The effectiveness of paste tailing results from the environmental benefits of reducing the amount of water discharged to the STI and the reduced seepage from the tailing impoundment. Conservation of water occurs during the thickening process and there are also reduced evaporative losses from facilities used to store and transport water including the reclaim pond, decant ponds, and the tailing disposal line. In addition, paste tailing has a relatively low permeability, which would limit percolation of sulfate-rich pore water, and thereby, reduce sulfate loading into the groundwater beneath the STI.

Even in arid climates, paste tailing will still have a minor amount of seepage reporting from the toe and base of the pile. After drain down of existing pore water within the STI, the potential for infiltration to groundwater would be limited and could potentially occur through infiltration of rain water although a drastically lower rates. This risk can be reduced with progressive reclamation of the pile including grading and capping the exterior slopes of the dry-stack tailing material immediately following deposition.

Fugitive dust emissions from the top surface of the tailing are also a concern that would need to be addressed.

Assuming current moisture content of 58% (by volume) for the wet tailing and a possible moisture content for paste tailing of 42% (by volume), results in a savings of 27% of the water used with the tailing. This would result in the savings of approximately 7,000 acre-feet of water per year, based on the water balance estimate of 26,323 acre-feet of water used with tailing on an annual basis.

From a sulfate source control perspective, paste tailing is considered to have a high effectiveness due to its effect on the water balance and reducing water (and sulfate discharges) to the STI, which would initiate drain down of the current STI. This would limit the time needed to operate the interceptor wellfield system. However, its effectiveness would not be as great as the filtered tailing option due to paste tailing's lower reduction in water use relative to filtered tailing.

Implementability

The time to implement is considered medium (3-10 years) due to the time it would take to procure the necessary equipment and construct the ancillary facilities to support this process.

The implementation of paste tailing process requires a good understanding of the geotechnical characteristics of the material in the tailing including strength, hydraulic conductivity, moisture retention and clay mineral content (Davies and Rice, 2001). The Duval Canal upgrade, which will be constructed in 2008, addresses the need to convey runoff away from the stacked tailing. A contingency plan should be created that stipulates what protocol to follow should the thickening process be temporarily disabled. The geotechnical aspects of depositing paste tailing on top of the existing impoundment would require significant study and are not well known at this time.

Once a good understanding of the material characteristics is established, the next step in implementing a thickening process is to calculate the proper density that reduces as much water as possible while maintaining an adequate balance of moisture to enable pumping of the thickened tailing by reducing friction loss.

Due to the high capital costs associated with thickening tailing, it so far has only been implemented on a small scale that makes it more reasonable to implement. The paste tailing process is known to work well for small-scale operations (i.e. less than 20,000 ton per day). Fugitive dust is a concern with paste tailing due to the dewatered nature of the material. Based on these issues, the implementability of paste tailing at the STI is considered low.

Cost

Capital Costs

The potential capital costs for constructing a paste thickening system could be as high as $250 million. This cost was adjusted from a study that was developed for two scenarios in Latin America (Scolia, Landriault, 2007) at mines whose production rates could be as high as 225,000 tons per day and whose capital costs are elevated due to make-up water costs. Therefore, this cost was considered as an upper limit.

The capital cost of the paste thickeners and ancillary equipment needed to process in excess of 100,000 tpd would be significant, perhaps on the order of $250 million. The current wet tailing disposal method operating unit cost is $0.14 per ton. At the current production rate of 112,000 tons per day, this results in a differential of $169,120 per day or $61,728,800 per year based on the unit operating cost of $1.65 per ton for paste. The Capital Costs of this alternative combined with the costs of Alternative 1 ($23,600,000) that will be done in conjunction with the chosen Alternative would raise the total capital cost for this alternative to as high as $273,600,000.

Operating costs

An average operating cost of approximately $1.65 per ton was assumed for paste tailing based on a recent study of costs to switch from conventional wet deposition to paste thickened tailing deposition (Scolia, Landriault, 2007). However, actual costs can vary widely due to the range of operating conditions at any given site. The range of cost can be from $1 to $10 per ton depending on how the process is managed. This range of cost includes thickening, transport, and placement of tailing. Currently costs for disposal are $0.018 per ton plus $0.032 per ton for thickener operation. At the current production rate of 112,000 ton per day, this results in a differential of $169,120 per day or $61,728,800 per year (based on $1.65 per ton) for paste versus the current wet tailing disposal method.

This combined with order of magnitude capital cost of $250 million indicates that the costs for a paste tailing operation at Sierrita are considered very high.

4.5 COMPARATIVE ANALYSIS OF ALTERNATIVES

A summary of effectiveness, implementability and cost for the proposed alternatives is show below in Table 5, *Summary of Alternatives*.

TABLE 5
SUMMARY OF ALTERNATIVES

Alternative	Effectiveness	Implementability	Cost
STI discharge control, Reclaim Pond management, and final reclamation and closure	Low	High	Low
Remove $CaSO_4$ from moly roaster scrubber discharge	Low	High	Medium
Filtered tailing	High	Low	Very High
Paste tailing	High	Low	Very High

4.5.1 STI Discharge Control, Reclaim Pond Management, and Final Reclamation and Closure

The effectiveness of this alternative is considered low because even though it would reduce seepage from the reclaim pond to the maximum extent feasible and eliminate two sources of sulfate to the STI, it would only have a minor impact on reducing sulfate loading to groundwater. The implementability of this alternative is considered high based on the proven nature of the technologies and the ability to construct these projects. This alternative has a low cost relative to the costs for the other alternatives.

4.5.2 Limit $CaCO_4$ from Moly Roaster Scrubber Discharge

The implementability of this alternative is considered high. The effectiveness of this alternative is considered low because even though it would eliminate a significant source of sulfate to the STI, it would not substantively reduce sulfate loading to groundwater. The cost of this alternative is considered medium. The high implementability is due to the proven nature of the technology and operational benefits (e.g. creating sulfuric acid), which will reduce the operational costs for SX/EW.

4.5.3 Filtered Tailing

Filtered tailing has a high effectiveness based on the recovery of water from the tailing prior to deposition. Filtered tailing would effectively reduce sulfate loading to groundwater by recovering process water from the tailing. Implementability of filtered tailing is considered low due to the need to truck or convey the tailing to the existing STI, the inability to drive trucks on the existing STI, and potential fugitive dust problems. The cost of the filtered tailing alternative is considered very high.

4.5.4 Paste Tailing

Paste tailing has a high effectiveness based on the recovery of water from the tailing prior to deposition, although not as high as the filtered tailing due to higher residual moisture contents. Paste tailing would effectively reduce sulfate loading to groundwater by recovering process water from the tailing. Implementability of paste tailing is considered low due to potential fugitive dust problems and the scale of the operation. The cost of the paste tailing alternative is considered very high.

4.5.5 Recommended Supplemental Source Control Alternative

As was discussed in Section 1.1, the purpose of this evaluation was to identify a source control alternative that could be implemented to supplement source control provided by the existing interceptor wellfield and potential FFS wellfield. Based on the detailed alternative evaluation and comparative analysis presented above, Alternative 1 is the preferred supplemental source control alternative. Although Alternative 1 would only have a minor impact on reducing sulfate loading to regional groundwater, it would eliminate two sources of sulfate to the STI. Alternative 1 is easily implementable in a short period of time and its cost is lower than the cost of the other alternatives.

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ATTACHMENT 1

Paste and Filtered Tailing Technology Papers (3)

An alternative to conventional tailing management – "dry stack" filtered tailings

Michael P. Davies and Stephen Rice
AMEC Earth & Environmental, Vancouver, Canada

ABSTRACT: Development of large capacity vacuum and pressure belt filter technology presents the opportunity for storing tailings in a dewatered state, rather than as conventional slurry and/or in the "paste like" consistency associated with thickened tailings. Filtered tailings are dewatered to moisture contents that are no longer pumpable and need to be transported by conveyor or truck. Filtered tailings are placed, spread and compacted to form an unsaturated, dense and stable tailings stack (termed a "dry stack") requiring no dam for water or slurried tailings retention. This paper presents the basics of dry stack tailings management including design criteria and site selection considerations. Examples of several operations using dry stack technology are presented. Approximate operating costs for dry stack facilities are also included. Dry stack tailings are not a panacea for tailings management but present, under certain circumstances, an option to the tailings planner.

1 INTRODUCTION

Tailings management for the past several decades has largely involved the design, construction and stewardship of tailings impoundments. These impoundments are developed to store tailings slurry that typically arrives at the impoundment with solids contents of about 25% to 40%. The management of the traditional tailings impoundment is therefore a combination of maintenance of structural integrity and managing immense quantities of water.

The basic segregating slurry that has been used for conventional tailings management is only part of a continuum of products available to the modern tailings designer. Development of large capacity vacuum and pressure filter technology has presented the opportunity for storing tailings in a dewatered state, rather than as conventional slurry and/or in the "paste like" consistency associated with thickened tailings. Tailings are dewatered to moisture contents that are no longer pumpable. The filtered tailings are transported by conveyor or truck, and placed, spread and compacted to form an unsaturated, dense and stable tailings stack (a "dry stack") requiring no dam for retention. While the technology is currently (considerably) more expensive per tonne of tailings stored than conventional slurry systems, it has particular advantages in:

a) arid regions, where water conservation is an important issue
b) situations where economic recovery is enhanced by tailings filtration
c) where very high seismicity contraindicates some forms of conventional tailings impoundments
d) cold regions, where water handling is very difficult in winter

Moreover, "dry-stacks" have regulatory attraction, require a smaller footprint for tailings storage (much lower bulking factor), are easier to reclaim, and have much lower long-term liability in terms of structural integrity and potential environmental impact.

This paper will utilize the most common terminology in the industry. This includes:

- slurry tailings – the typically segregating mass of tailings that are in a fluidized state for transport by conventional distribution systems

• thickened tailings –partially dewatered but still a slurry that has a higher solids content by weight than the basic tailings slurry but is still pumpable. Chemical additives are often used to enhance slurry tailings thickening

• paste tailings – thickened tailings with some form of chemical additive (typically a hydrating agent such as Portland cement)

• wet cake tailings – a non-pumpable tailings material that is at, or near, saturation

• dry cake tailings – an unsaturated (e.g. not truly dry) tailings product that cannot be pumped.

The terms "dry stacked" or "dry stack" tailings have been adopted by many regulators and designers for filtered tailings. As long as the designers, owners and regulators understand that the tailings are not truly dry but have a moisture content several percent below saturation, there is nothing wrong with continuing the use of this terminology.

2 CONTINUUM OF TAILINGS

Figure 1 shows the continuum of water contents available for tailings management today and includes the standard industry nomenclature.

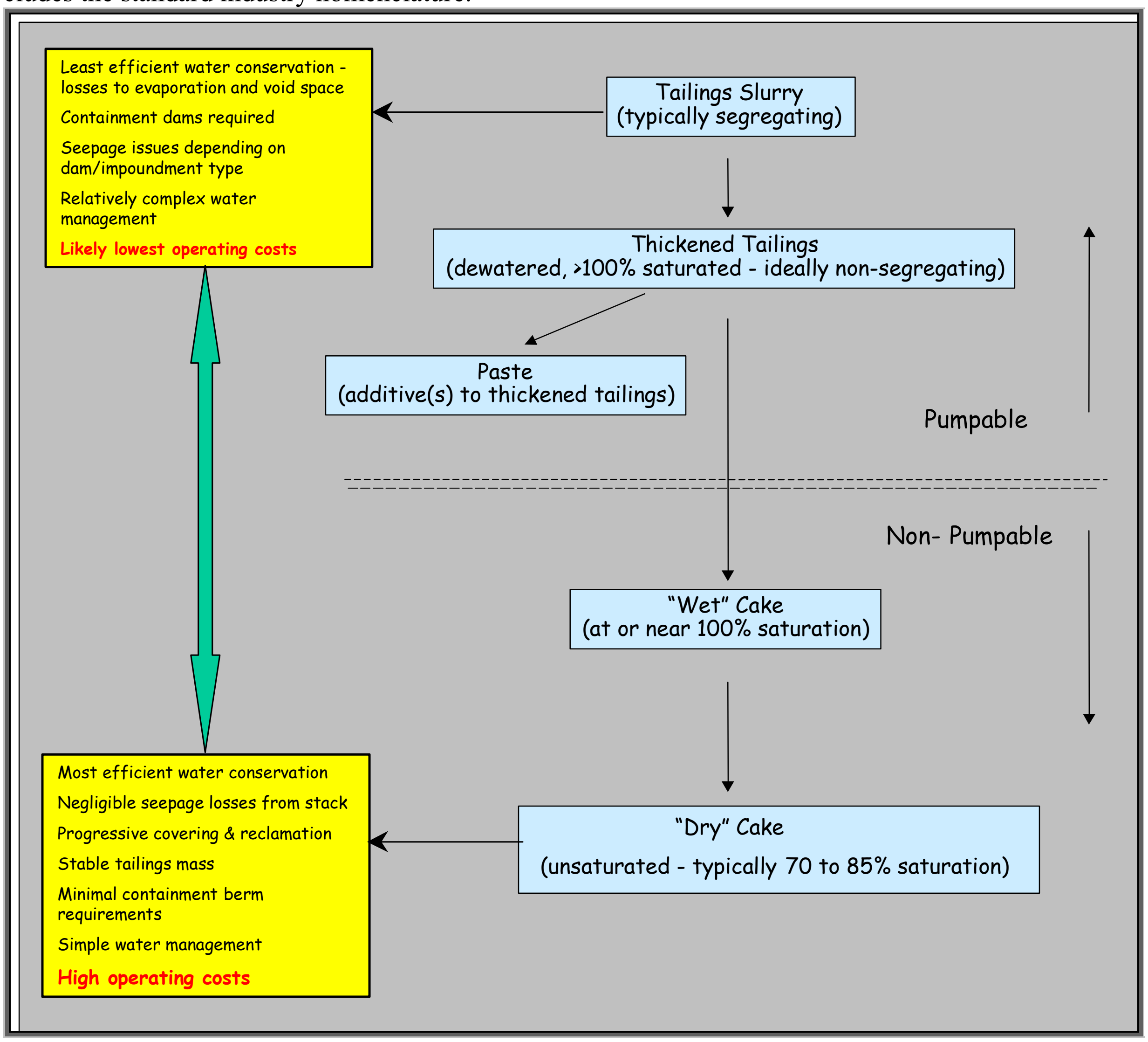

Figure 1. Tailings Continuum

Filtered tailings are typically taken to be the dry cake material shown in Figure 1. This material has enough moisture to allow the majority of pore spaces to be water filled but not so much as to preclude optimal compaction of the material.

Filtering can take place using pressure or vacuum force. Drums, horizontally or vertically stacked plates and horizontal belts are the most common filtration plant configurations. Figure 2 shows a typical filter press. Pressure filtration can be carried out on a much wider spectrum of materials though vacuum belt filtration is probably the most logical for larger scale operations.

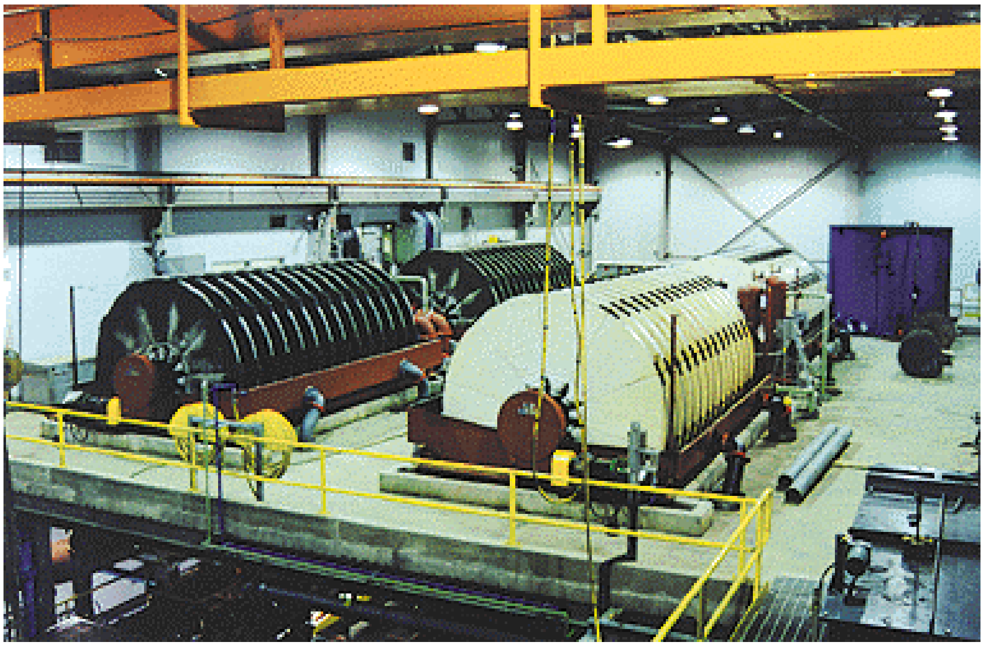

Figure 2. Example of a Filter Plant

The nature of the tailings material is important when considering filtration. Not only is the gradation of the tailings important, but the mineralogy is as well. In particular, high percentages of <74 μm clay minerals (i.e.. not just clay-sized but also with clay mineralogy) tend to contra-indicate effective filtration. Furthermore, substances such as residual bitumen (e.g. oil sands tailings) can create special difficulties for a filtration plant.

3 CONSIDERATIONS FOR FILTERED TAILINGS

As for any other form of tailings management, there are a number of issues that require careful consideration prior to selecting filtered tailings for a given project. Ultimately, these considerations are all about economics (capital, operating and closure liability) but require individual attention during the prefeasibility and feasibility stages of the project.

3.1 *General*

Whether filtered tailings are a candidate for a given project depends on the motivation to consider alternatives to a conventional slurried tailings impoundment. The motivation could include a more favourable, or timely, regulatory process or perhaps one of several technical issues presented by the site.

As noted in the introduction, filtered tailings could have application to meet technically challenging sites in:

a) arid regions

b) mines where dissolved metal recovery is enhanced by tailings filtration
c) high seismicity regions
d) cold regions
e) mine sites where space is limited as filtered tailings result in a lesser footprint than for slurried tailings.

In addition, site legacy issues are also part of the selection criteria as dry stacked tailings facilities are substantially easier to reclaim for mine closure, in most circumstances, when compared to conventional impoundments. Following is some elaboration on key issues to be considered.

3.2 *Water Management*

Where water is relatively scarce, either year round or seasonally due to extreme cold, sending immense quantities of water to quasi-permanent storage in the voids of a conventional impoundment can severely hamper project feasibility. By reclaiming the bulk of the process water in or near the mill, far more efficient recycle is achieved. Moreover, the amount of water "stored" in a dry stack facility will be typically >25% less than that in a conventional slurried impoundment even if 100% pond reclaim efficiency is achieved with the impoundment.

3.3 *Commodity Extraction*

Many mines, particularly those dealing with precious metals, can improve the bottom line by maximizing the amount of tailings water that can be reclaimed. Both the economic commodity (e.g. dissolved gold) and process chemicals (e.g. cyanide) can be recovered from the filtration water and one or more rinse cycles.

3.4 *Storage Availability*

Filtered tailings can be placed in a relatively dense state meaning that more solids per unit volume can be achieved. Furthermore, more aggressive use of available land (e.g. valley slopes) can be used with filtered tailings. As discussed in 3.5, lesser foundation conditions can also be considered in comparison to conventional impoundments.

3.5 *Geotechnical Issues*

The questionable manner in how some conventional impoundments are designed and/or operated provides support to considering the geotechnical advantages of filtered tailings. By objectively reviewing an instability database for conventional slurry tailings impoundments, over the past 30 years there have been approximately 2 to 5 "major" tailings dam failure incidents per year (Davies and Martin, 2000). There have been at least two events each year (1970-1999, inclusive). If one assumes a worldwide inventory of 3500 conventional tailings impoundments (a tenuous extrapolation at best), then 2 to 5 failures per year equates to an annual probability of between 1 in 700 to 1 in 1750. This rate of failure does not offer a favorable comparison with the 1 in 10,000 figure that appears representative for conventional water dams. The comparison is even more unfavorable if less "spectacular" tailings impoundment failures are considered. These impoundment failures, often equally economically damaging, are not just of older facilities constructed without formal designs, but include facilities designed and commissioned in the past 5 to 20 years - supposedly the "modern age" of tailings dam engineering.

The most common failure modes for slurry tailings impoundments are physical instability (including static and dynamic liquefaction) and water mismanagement issues (including lack of freeboard and seepage phenomena like piping). Filtered tailings placed in dry stacks are essentially immune to catastrophic geotechnical "failure" and can be readily designed to withstand static and seismic forces. A case can also be made for a reduction in the seismic design criteria based on failure consequence. This can significantly reduce operating costs. The unsaturated tailings mass is extremely resistant to saturation and seepage is governed by unsaturated hydraulic conductivities. Moreover, far less is required of foundation conditions as the unsaturated, largely dilatant tailings within a dry stack are not susceptible to static liquefaction or catastrophic breaching by an impounded pond should the foundation move creating substantive shear strains in the tailings mass.

3.6 *Reclamation/Closure Issues*

Dry stack facilities can be developed to consist of, or closely approximate, their desired closure configuration. Some form of assured surface runoff management plan is required. The tailings can be progressively reclaimed in many instances. In all cases, a closure cover material is required to resist runoff erosion, prevent dusting and to create an appropriate growth media for project reclamation.

The lack of a tailings pond, very low (if any) appreciable seepage from the unsaturated tailings mass and general high degree of structural integrity allows dry stacks to present the owner/operator with a comparably straight forward and predictable facility closure in comparison with most conventional impoundments.

3.7 *Environmental Stewardship*

Issues related to the environmental impacts from tailings dams were first seriously introduced in the 1970's in relation to uranium tailings. However, environmental issues related to mining have received attention for centuries. For example, public concerns about the effects of acid rock drainage (ARD) has existed for roughly 1,000 years in Norway. Today, environmental issues are growing in importance as attention has largely turned from mine economics and physical stability of tailings dam to their potential chemical effects and contaminant transport mechanisms. Recent physical failures such as Merriespruit, South Africa in 1994 and Omai, Guyana in 1995 and Los Frailes in Spain in 1998 illustrates this issue with most of the media reports highlighting the real or perceived environmental impacts of the failures.

Dry stacked tailings facilities have some tremendous potential environmental advantages over impounded slurried tailings largely because the catastrophic physical failures that define tailings management to non-supporters of the industry cannot occur. Moreover, leachate development is extremely limited due to the very low seepage rates possible. Oxidation processes are possible though the very slow rates for such, coupled with the limited seepage potential, limits or eliminates the concern of significant metallic drainage. Clearly, industry/regulatory standards of testing for potential operating and long-term impacts are essential. However, if the stack is operated to maintain its unsaturated character, any potential impacts should be predicted as acceptable except under unusual conditions.

Fugitive dusting, both during operation and upon closure, is a very real concern with dry stacks; particularly in arid environments. Progressive reclamation is the only effective method to address this concern.

3.8 *Regulatory Environment*

The regulatory environment worldwide is generally becoming less tolerant of one of humanities essential industries. Mining cannot exist without the creation of some form of tailings so the availability of a management strategy that is viewed (and correctly so) as both less invasive and less difficult to decommission as well as one that does not conjure up "massive" failure scenarios is a positive to the industry. As discussed elsewhere in this paper, the challenge is to get this regulatory friendly tailings management system to become cost-effective for those operations that would benefit (eg. in terms of the permitting process) from its consideration.

4 DESIGN CRITERIA

4.1 *General*

There are four main design criteria for filtered tailings:

1. filtering characteristics
2. geomechanical characteristics
3. tailings management
4. water management

In addition, the design must be compatible with an optimal closure condition (designing for closure). Implicit to the overall design criteria is project economics.

4.2 *Filtering Characteristics*

Determine the most cost-effective manner to obtain a dewatered product consistent with the other three design criteria (geomechanics, placement management and water management). Filter suppliers are both knowledgeable and helpful in this regard but some form of pilot test(s) is essential as every tailings product will exhibit its own unique filtering character. It is important to anticipate mineralogical and grind changes that could occur over the life of the project. The candidate filtering system(s) must be able to readily expand/contract with future changes at the mine with the least economical impact.

4.3 *Geomechanical Characteristics*

The strength, moisture retention and hydraulic conductivity characteristics of the tailings need to be established. The saturated tailings should be determined to "anchor" the results and tests as variable moisture contents are required to demonstrate the impact of the inevitable range of operating products. The other important geomechanical characteristic to determine is the moisture-density nature of the tailings. The unsaturated moisture-density relationship indicates in-situ density expectation as well as the sensitivity of the available degree of compaction for a given moisture content. From a compaction perspective, the filtered tailings should neither be too moist nor too dry. The optimal degree of saturation is usually between 60 and 80%.

4.4 *Tailings Management*

The design needs to be compatible with how the stack can be practically constructed using conventional haulage and placement equipment. Other than the capital and operating costs of the filtering process, the economics of dry stack management is the most important component of filtered tailings viability. Haul distance, placement strategy and compactive effort and additional works for closure and reclamation can make a larger incremental difference to the unit cost of a dry stack facility in comparison with a slurried impoundment.

The design should also clearly identify what contingency(s) will be in place if the filtering process experiences short-term disruptions. A temporary storage area or vessel is sound strategy. It is, however, the authors' experience that the filters should become part of the process plant under the management of the mill superintendent. The tailings processing then becomes integrated with the metal recovery functions and consequently down time is minimized because operation of the tailings system becomes critical to the overall mill performance.

4.5 *Water Management*

Surface water, particularly concentrated runoff, should not be permitted to be routed towards a dry stack. As important, the catchment and routing of precipitation (and any snow melt in colder climates) on the stack itself must be appropriately designed for. For the surface runoff within the overall catchment containing the dry stack, one (or more) of perimeter ditches, binds or under-stack flow through drains designed for an appropriate hydrological event(s) should be included in the design. For on stack water management, routing of flows to armoured channels and limiting slope lengths/gradients to keep erosion potential at a minimum are the best design criteria.

5 CONSTRUCTION AND OPERATIONAL CONSIDERATIONS

5.1 *General*

There are a number of construction and operational considerations that need to be accounted for in the design and planning of a dry stack. These considerations are very different from the construction and operational considerations normally associated with slurry tailings facilities. The main considerations are usually:

1. Site development
2. tailings transport and placement
3. water conservation and supply
4. reclamation and closure

In addition, there are often other considerations that need to be addressed on a site-specific basis for example co-disposal of waste rock in a combined mine waste management facility, storage of water treatment plant sludges etc.

5.2 *Site Development*

Site development for a dry stack normally consists of the construction of surface and groundwater control systems. There are normally two systems:

1. A collection and diversion system for non-contact water (i.e. natural surface water and groundwater from the surrounding catchment area that has not yet come into contact with the tailings). This system usually consists of ditches to divert surface runoff around the site and if necessary a groundwater cut-off and drainage system usually combined with surface water diversion. The cut-off system can range from simple ditches to sophisticated cut-off walls depending upon site conditions.
2. An interception and collection system for contact surface water, impacted groundwater, and seepage from the dry stack. This system usually consists of an underdrainage system of finger drains, toe drains, drainage blankets and french drains; collection sumps and ponds. Water collected in the ponds and sumps is usually used in process or pumped to a water treatment plant depending upon the site water balance. Liners for the facilities can also be components of the interception and collection system depending upon predicted impacts and regulatory requirements.

5.3 *Tailings Transport and Placement*

There are two methods in common use for transport of the filtered tailings to the tailings storage facility. These are conveyors or trucks and the equipment selection is a function of cost. Placement in the facility can be by a conveyor radial stacker system or trucks depending upon the application and the design criteria. Conveyor transport of tailings to the disposal site can be combined with placement by truck, so conveyor transport does not automatically result in placement by radial stacker.

The main issue associated with the placement of the filtered tailings by truck is usually trafficability. The filtered tailings are generally produced at or slightly above the optimum moisture content for compaction as determined in laboratory compaction tests (Proctor Tests). This means that a construction/operating plan is required to avoid trafficability problems. This is especially true in wetter environments since trafficability drops as moisture content rises and if the tailings surface is not managed effectively it can quickly become un-trafficable resulting in significant placement problems and increased operating costs. In addition, in high seismic areas there is often a design requirement to compact the tailings to a higher density in at least the perimeter “structural” component of the facility. This requirement increases the need for construction quality control. It is the authors’ experience that the degree of compaction required for assured and efficient trafficability is often higher than the compaction required to achieve design densities.

Dry stack designs often incorporate placement zones for “summer/good weather” placement (dry, non-freezing conditions) and “winter/bad weather” placement (wet, or freezing conditions) with summer placement being focused on the structural zones. Again, this is especially true for facilities planned for wetter or colder climates were seasonal fluctuations are significant and predictable.

The key is to consider the environment and the design criteria and develop a flexible operating plan to achieve them.

5.4 *Water Conservation*

Often one of the main reasons to select dry stacked filtered tailings as a management option is the recovery of water for process water supply. This is particularly important in arid environments were water is an extremely valuable resource and the water supply is regulated (e.g. Northern Chile and Mexico). Filtering the tailings removes the most water from the tailings for recycle when compared with other tailings technologies as discussed earlier. This recovery of water has a cost benefit to the project, which offsets the capital and operating cost of the tailings system. It should be noted, that water surcharge storage needs to be factored in to the design of a filtered tailings system. Depending upon the application this can be a small water supply reservoir or tank.

5.5 *Reclamation and Closure*

One of the main advantages of dry stack tailings is the ease of progressive reclamation and closure of the facility. The facility can often be developed to start reclamation very early in the project life cycle. This can have many advantages in the control of fugitive dust, in the use of reclamation materials as they become available, and in the short and long term environmental impacts of the project. Progressive reclamation often includes the construction of at least temporary covers and re-vegetation of the tailings slopes and surface as part of the annual operating cycle.

6 ECONOMICS

6.1 *General*

It is hard to compare the economics of dry stack filtered tailings with other tailings options particularly conventional slurry tailings. This is mainly because of the difficulty of estimating the cost of closure and the potential costs associated with the long-term risk environmental liability associated with mine waste facilities. Therefore, the following discussion on economics is very subjective with a focus on perception.

6.2 *Capital Cost*

The capital costs are clearly a function of the size of the operation. Dry stack, filtered tailings currently appears to be limited to operations of 15000 tpd or less depending upon financial credits e.g. water recovery for use in process. Capital costs normally shift from the construction of engineered tailings containment structures to the dewatering (filter) plant. The capital costs may be further mitigated if the application is considered for small tonnage (less than say 4000 tpd) where the mine plan calls for paste backfill underground. Paste backfill requires a tailings processing plant with dewatering so incremental dewatering to produce filtered tailings make the economics more attractive. The capital cost appears to be much more attractive for operations under approximately 2000 tpd.

Other costs that should be factored into the equation are reduced costs associated with the smaller footprint, site development costs, and regulatory acceptance associated with dry stack tailings. These costs are often difficult to estimate accurately.

6.3 *Operating Cost*

The operating costs associated with the transport and placement of dry stack, filtered tailings are higher when compared with conventional slurry tailings, transported hydraulically and deposited in a tailings pond. The operating costs for a dry stack are difficult to summarize as every operation accounts for the costs differently. For example, if a mine uses a surface crew who do both tailings stack development as well as other duties, the cost/tonne will be much lower than a dedicated dry stack work force. Under the range of conditions for the presently operating dry stacks, the cost per tonne ranges from \$1 to \$10 but the average is more like \$1.50 to \$3. All costs are \$US and include filtering, transport, placement and compaction in the facility.

6.4 *Reclamation and Closure*

Reclamation and closure costs are significantly reduced for dry stack tailings when compared with conventional tailings. This cost reduction is due to a reduced footprint and constructability. Other issues that need to be somehow factored into the "cost" of closure are the reduction in long-term risk and liability associated with dry stacks.

7 EXAMPLES

There are a growing number of dry stack facilities. At the same time, it would be fair to say that there is likely not any one of those operations who can point to an overall operating economic advantage to the practice. However, for at least three of the operating dry stack projects, the increased operating cost was sufficiently negated by other factors including regulatory issues and closure/liability costs.

The majority of the dry stacks are either in colder climates (e.g. Greens Creek, Alaska, Raglan, Quebec) or in arid environments (e.g. La Coipa, Chile). The La Coipa facility, developing at more than 15,000 tons/day, is one of the largest operating dry stacks. The La Coipa facility is located in a high seismic region with designed, and confirmed, structural integrity. Figure 3 shows the La Coipa facility a few years ago.

Figure 3. Dry-Stack Tailings Facility - Chile

8 SUMMARY AND CONCLUSIONS

There are several candidate scenarios where dewatered tailings systems would be of advantage to the mining operation. However, dewatered tailings systems may have less application for larger operations for which tailings ponds must serve dual roles as water storage reservoirs, particularly where water balances must be managed to store annual snowmelt runoff to provide water for year round operation.

Filtered tailings, a form of dewatered tailings, are not a panacea for the mining industry for its management of tailings materials. Purely economic considerations rarely indicate a preference for dry stacked tailings facilities over conventional slurry impoundments. However, under a growing number of site and regulatory conditions, filtered tailings offer a real alternative for tailings management that is consistent with the expectations of the mining industry, its regulators and the public in general.

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Paste 2007 — A.B. Fourie and R.J. Jewell (eds)
©2007 Australian Centre for Geomechanics, Perth, ISBN 0-9756756-7-2

An Evaluation of Highly Dewatered Tailings Disposal Applications in Large Scale Mining Operations in Chile's Atacama Desert

J.C. Scola *Golder Associates SA, Chile*

D. Landriault *Golder Paste Technology Ltd, Canada*

ABSTRACT

Golder has recently completed studies on highly dewatered tailings disposal methods for a number of large scale mining operations/projects in northern Chile. The lessons learned have been incorporated into the two case studies presented in this paper. The case studies show that there are important potential cost savings to motivate existing operations to change from conventional slurry tailings disposal systems to alternative highly dewatered tailings disposal systems.

1 INTRODUCTION

The two case studies covered in this paper are related to large scale mining operations located in the Atacama Desert of northern Chile, where precipitation is very low at 5 mm/year and evaporation is very high at 10 mm/day. Make up water for mining operations in the area has historically been sourced from surface streams and groundwater deposits mainly located in the high Andes mountains in environmentally sensitive areas. The majority of such water sources are currently considered to be exploited to their limits, whilst some are nearing depletion or will have to be closed down to limit environmental damage. Mining companies operating in the area are now turning their attention to the Pacific Ocean as the water source for their future water needs.

This paper demonstrates that extracting water from the tailings has the potential to be a better option than sourcing make up water from the sea. The tailings dewatering methods considered in these case studies range from high compression thickening, to paste thickening, to vacuum filtration, to pressure filtration; each method producing a higher degree of tailings dewatering over the previous one.

2 CASE STUDY 1

The first case study is based on an existing large copper mine processing 225000 t per day and currently depositing conventional slurry tailings at 50 wt% solids. Water recovery from the deposited tailings is very low, mainly because of the high evaporation rate in the area. This operation has a 20 year mine life ahead. Some of its make up water sources have short lives and will have to be replaced in the near future. The capital and operating costs of the potential new water sources will be high. To be able to continue depositing conventional slurry tailings, the owners will have to invest a large capital sum in the tailings management facility (TMF).

The main economic and/or environmental drivers for a mine of this size and location to consider converting to a paste/thickened tailings/filter cake deposition system are:

- Potential depletion and/or stability of long-term source of make up water offset by a major increase in water recovery from the tailings.
- Off set or eliminate high capital/operation costs for new water sources (sea water desalinisation) to maintain and/or increase production.
- Substantial capital/operation cost reduction in the TMF as compared to conventional slurry tailings disposal.

In this case study three different scenarios are considered as the base case:

- Scenario 1 is the most favorable: for the continuing disposal of conventional slurry tailings over 20 years, a total of US$ 300 million in capital is needed at the TMF for containment construction, tailings distribution pipelines upgrades and water return system upgrades. No capital cost will be required for new make up water sources. Any additional make up water is to be sourced from 3rd parties at US$ 1.40/m^3.
- Scenario 2 is the intermediate: in addition to the US$ 300 million in capital needed for the TMF facilities, an extra US$ 270 million in capital is required for one new make up water source capable of delivering 575 L/s.
- Scenario 3 is the least favorable: in addition to the US$ 300 million in capital needed for the TMF an extra US$ 700 million in capital is required for one new make up water source capable of delivering 1500 L/s.

The table below outlines the capital and operating costs associated with the three base case scenarios described above. As shown in the table, the combined tailings placement and make up water Net Present Cost (NPC) for the different scenarios range from US$ 1.033 to US$ 1.733 billon dollars over the 20 year mine life. This equates to an NPC of US$ 0.62 to US$ 1.05 (inclusive of make up water supply) per tonne of tailings placed in the TMF.

Table 1 **Base case scenarios – economical evaluation**

	Base Case		
	Scenario 1 lower CAPEX	Scenario 2 intermediate CAPEX	Scenario 3 higher CAPEX
1 — Tailings disposal			
CAPEX, million US$	300	300	300
OPEX, million US$ per year	5	5	5
Return water LoM[1], million m^3	189	189	189
Tailings disposal, US$/t	0.24	0.24	0.24
2 — Make up water supply			
CAPEX, million US$	0	270	700
Make up water flowrate, l/s	2324	2324	2324
Make up water[2], m^3/t	0.89	0.89	0.89
Make up water costs[3], US$/t	1.24	1.24	1.24
Total (1+2)			
Unit cost (tailings + make up water), US$/t	1.48	1.64	1.90
Net present cost[4], million US$	1033	1303	1733
Net present cost[4], US$/t	0.62	0.79	1.05

[1] LoM: Life of Mine

[2] cubic meters of make up water per t of tailings placed in the TMF

[3] at US$ 1.40/m^3

[4] at a discount rate of 10%

The alternative tailings deposition system options evaluated in this case study are listed in Table 2. The options are listed in increasing tailings dewatering capability from high compression thickening up to pressure filtration. With the increasing water removal from the tailings the volume of water recovered obviously increases which results in an increasing deposition placement angle.

Table 2 Tailings dewatering process system options

Option	Dewatering Method	Transportation	wt % Solids	Deposition Placement Angle (%)
1	High compression thickening	Centrifugal slurry pumps	60.0	4.5
2	Paste thickening	Positive displacement pumps	65.0	9.0
3	Vacuum filtration	Belt conveyors	76.0	12.5
4	Pressure filtration	Belt conveyors	85.0	17.5

2.1 Description of Alternatives

Option 1: Tailings dewatering will be achieved using high compression thickeners. Twelve thickening units are considered (55 m diameter, 11 operating/1 standby). Thickener underflow will be transported by centrifugal slurry pumps to the deposition locations in the TMF.

Option 2: Tailings dewatering will be achieved using paste thickeners. Eighteen thickening units are considered (45 m diameter, 17 operating/1 standby). Thickener underflow will be transported by piston diaphragm positive displacement pumps to the deposition locations in the TMF.

Option 3: Tailings dewatering will be achieved using horizontal belt vacuum filters. Ninety-six filtration units are considered (162 m^2, 69 operating/27 standby). Filter cake will be conveyed to the TMF and stacked using a belt conveyor system. Filtrate will be clarified prior to being returned to the mill.

Option 4: Tailings dewatering will be achieved using vertical plate membrane pressure filters. Two hundred and forty filtration units are considered (576 m^2, 174 operating/66 standby). Filter cake will be conveyed to the TMF and stacked using a belt conveyor system. Filtrate will be clarified prior to being returned to the mill.

Unfortunately, the increased water recovery levels associated with each option come with increased capital and operating costs as presented in Tables 3 and 4. To fully evaluate the economic viability of each of the dewatering systems, the potential cost savings in make up water supply must be taken into account in the calculation of the NPC per tonne of tailings placed over the life of the mine. This evaluation is presented in Table 5. These results must then be compared to the base case operation scenarios over the same time period. This comparison is presented in the discussion section.

Table 3 **Capital cost estimate (±35%) for the different dewatering options**

	Capital Cost (million US$)			
	Option 1 High compression thickening	**Option 2** Paste thickening	**Option 3** Vacuum filtration	**Option 4** Pressure filtration
Process equipment	36.1	76.2	298.0	487.1
Main "overland" pipelines	38.3	38.7	32.7	34.5
Installation costs	58.3	90.3	131.3	160.2
Total direct costs	132.7	205.1	462.0	681.9
Indirect costs	25.7	41.2	96.6	143.5
Owner costs	4.8	7.4	16.8	24.8
Contingency	32.6	50.7	115.1	170.0
Total CAPEX	195.9	304.4	690.4	1020.1

Table 4 **Operating cost estimate (± 35%) for the different dewatering options**

	Operating Cost (million US$ per year)			
	Option 1 High compression thickening	**Option 2** Paste thickening	**Option 3** Vacuum filtration	**Option 4** Pressure filtration
Power	9.8	16.2	32.8	24.4
Flocculant	4.9	4.9	4.9	0.0
Labor	0.6	0.6	0.9	1.0
Maintenance	1.5	3.0	11.9	19.5
Other	0.5	0.5	1.0	1.0
Earthmoving equipment	1.2	1.2	1.2	1.2
Total OPEX	18.5	26.5	52.8	47.0

Table 5 Economic evaluation of the different dewatering options

	Proposed Cases			
	Option 1 High compression thickening	**Option 2** Paste thickening	**Option 3** Vacuum filtration	**Option 4** Pressure filtration
1 — Tailings dewatering and disposal				
CAPEX, million US$	196	304	690	1020
OPEX, million US$ per year	19	27	53	47
Return water LoM, million m^3	552	764	1,132	1363
Tailings dewatering and disposal, US$/t	0.34	0.50	1.06	1.18
2 — Make up water supply				
Make up water flow rate, l/s	1749	1413	829	463
Make up water, m^3/t	0.67	0.54	0.32	0.18
Make up water costs @ US$ 1.40/m^3, US$/t	0.93	0.75	0.44	0.25
Total (1+2)				
Unit Cost (tailings + make up water) US$/t	1.28	1.26	1.50	1.43
Net Present Cost*, million US$	880	955	1389	1560
Net Present Cost*, US$/t	0.53	0.58	0.84	0.94

*discount rate 10%

2.2 Discussion

The change in technology, associated with any of the proposed options, would allow the placement of the life of mine tailings without the need to invest the US$ 300 million for the upgrade of the TMF as required by the base case. The lower make up water requirements, associated with the proposed options, would account for significant cost savings over the life of the operation.

Tables 6 and 7 show that options 1 and 2 are business cases for base case scenarios 1 and 2. Options 1 and 2 are not viable technical solutions for base case scenario 3, given the associated deficit in the make up water supply.

Table 8 shows that options 3 and 4 are business cases only for base case scenario 3. The "challenge" associated with the filter cake option is to organise the unprecedented manufacturing effort associated with the procurement of such amount of filters.

Table 6 **Base case scenario 1**

	Base Case Scenario 1	Option 1 High compression thickening	Option 2 Paste thickening	Option 3 Vacuum filtration	Option 4 Pressure filtration
Net present cost* million US$	1033	880	955	1389	1560
Net savings* million US$		153	78	-356	-527
Net present cost* US$/t	0.62	0.53	0.58	0.84	0.94

*discount rate 10%

Table 7 **Base case scenario 2**

	Base Case Scenario 2	Option 1 High compression thickening	Option 2 Paste thickening	Option 3 Vacuum filtration	Option 4 Pressure filtration
Net present cost* million US$	1,303	880	955	1389	1560
Net savings* million US$		423	348	-86	-257
Net present cost* US$/t	0.79	0.53	0.58	0.84	0.94

*discount rate 10%

Table 8 **Base case scenario 3**

	Base Case Scenario 3	Option 1 High compression thickening	Option 2 Paste thickening	Option 3 Vacuum filtration	Option 4 Pressure filtration
Balanced make up water supply	Yes	No	No	Yes	Yes
Net present cost* million US$	1733	880	955	1389	1560
Net savings* million US$		853	778	344	173
Net present cost* US$/t	1.05	0.53	0.58	0.84	0.94

*discount rate 10%

The economic evaluation demonstrates that the implementation of the highly dewatered tailings disposal options assessed have great potential for cost savings for different scenarios of the base case.

3 CASE STUDY 2

The second case study is based on another existing large copper mine also processing 225000 t per day and currently depositing conventional slurry tailings at 57 wt% solids. Water recovery from the deposited tailings is reasonably good, in spite of the high evaporation rate in the area, mainly because of the cell deposition strategy implemented in the TMF at a high operating cost. The current TMF has a very short life and will have to be replaced in the near future. This mining operation has a 20 year life ahead. The operation make up water supply is assured from large surface and groundwater sources at a relatively low operating cost of US$ 0.60/m^3.

The main economic and/or environmental drivers for a mine of this size and location to consider converting to a thickened tailings deposition system are:

- The operation requires a new TMF for future conventional tailings disposal.
- The topography of the existing TMF is suitable for non-conventional tailings disposal on top of the conventional tailings and for that it will not require the construction of additional containment structures.
- It is a Brownfield project with potential to change to a "new" tailings management technology.

3.1 Description of Alternatives

Base case: A large rock dam is required at the new TMF site for conventional tailings disposal. The associated CAPEX is US$350 million. Conventional TMF operating costs are high at US$ 25.2 million per year (includes high rate thickening to 57 wt% solids, impoundment compartmentalisation and water return).

The option screening criterion is to obtain a "non-segregating slurry" with a placement property to allow a 2% deposition slope to be obtained.

Option 1: Mill tailings dewatering will be achieved using high compression thickeners. Three 75 m diameter thickening units will be strategically located on higher ground around the perimeter of the TMF. Thickener underflow will be transported by centrifugal slurry pumps to the deposition locations in the TMF.

Option 2: Mill tailings dewatering will be achieved using high compression thickeners. Four 62 m diameter thickening units will be strategically located on higher ground around the perimeter of the TMF. Thickener underflow will be transported by centrifugal slurry pumps to the deposition locations in the TMF.

Option 3: Mill tailings dewatering will be achieved using high compression thickeners. Six 50 m diameter thickening units will be strategically located on higher ground around the perimeter of the TMF. Thickener underflow will be transported by centrifugal slurry pumps to the deposition locations in the TMF.

Some details related to the base case and options are presented in Table 9. The capital cost estimates are presented in Table 10. The operating cost estimates are presented in Table 10.

Table 9 Tailings dewatering process system options

Option	Dewatering Method	Transportation	wt % Solids	Deposition Slope %
Base case	High rate thickening	Open launder	57	0.5
1	High compression thickening (3 x 75 m dia.)	Centrifugal slurry pumps	67*	2.0
2	High compression thickening (4 x 62 m dia.)	Centrifugal slurry pumps	68*	2.0
3	High compression thickening (6 x 50 m dia.)	Centrifugal slurry pumps	69*	2.0

*In this case study smaller diameter thickeners have the capacity to discharge higher wt % solids underflow because they have a higher Nm/m^2 factor (higher available torque to thickener surface area ratio) which allows them to move thicker muds to the discharge outlet.

Table 10 Capital cost estimate (±35%) for the different dewatering options

	Capital Cost (million US $)			
	Base Case High rate thickening	**Option 1** High compression thickening 3 x 75 m	**Option 2** High compression thickening 4 x 62 m	**Option 3** High compression thickening 6 x 50 m
Process equipment		22.8	27.2	23.0
Main "overland" pipelines		64.1	63.8	64.3
TMF – start up facilities	350	-	-	-
Installation costs		22.5	25.2	26.0
Total direct costs		109.4	116.2	113.3
Indirect costs		18.9	20.4	19.7
Owner costs		3.8	4.1	4.0
Contingency		26.4	28.1	27.4
Total CAPEX	350	158.6	168.9	164.5

Table 11 Operating cost estimate (±35%) for the different dewatering options

	Operating Cost (million US$ per year)			
	Base Case High rate thickening	**Option 1** High compression thickening 3 x 75 m	**Option 2** High compression thickening 4 x 62 m	**Option 3** High compression thickening 6 x 50 m
Power	5.9	3.7	3.8	4.0
Flocculant		4.5	4.5	4.5
Labor		0.7	0.7	0.7
Maintenance		0.9	1.1	1.1
TMF	19.3	0.5	0.5	0.5
Earthmoving equipment		1.2	1.2	1.2
Total OPEX	25.2	11.5	11.8	11.9

An economic evaluation is presented in Table 12.

Table 12 Economical evaluation of the different dewatering options

	Base Case High rate thickening	Option 1 High compression thickening 3 x 75 m	Option 2 High compression thickening 4 x 62 m	Option 3 High compression thickening 6 x 50 m
1 — Tailings Dewatering and Disposal				
CAPEX, million US$	350	159	169	164
OPEX, million US$ per year	25.2	11.5	11.8	11.9
Tailings dewatering and Disposal, US$/t	0.51	0.23	0.24	0.24
2 — Make up Water Supply				
Make up water flowrate, L/s	1391	1311	1253	1196
Make up water, m^3/t	0.52	0.49	0.47	0.45
Make up water costs @ US$ 0.60/m^3, US$/t	0.31	0.30	0.28	0.27
Total (1+2)				
Unit cost (tailings + make up water), US$/t	0.82	0.53	0.52	0.51
Net present cost*, million US$	676	313	320	311
Net present cost*, US$/t	0.40	0.19	0.19	0.19
Net savings, million US$		363	356	365

*discount rate 10%

3.2 Discussion

All three options are business cases and show very similar bottom lines. The change of technology to thickened tailings would allow extending the life of the current TMF eliminating the need to build a new one. The change to thickened tailings would increase the life of the existing TMF site up to 80 years through the stacking of the tailings at 2% placement angle. The implementation of any of the three highly dewatered tailings disposal options proposed has the potential to save an estimated US$ 350 million.

This assessment is based on the "thicken twice" concept. Also assessed was the option of discontinuing the "thickening at the mill" unit operation and doing "thickening only once" at the TMF area. Results showed it to be more expensive. The savings from the discontinued thickening step are more than offset by larger CAPEX and OPEX needed to handle the larger flowrates.

4 CONCLUSIONS

These two case studies demonstrate that highly dewatered tailings disposal methods have great potential for overall life of mine cost reductions when compared to "Conventional Slurry Tailings Disposal Methods" as applied in large scale mining operations in northern Chile. A good part of the net savings is related to reduced costs for make up water supply.

However, each case must be evaluated considering its own drivers and site specific conditions and is very much dependent on the material properties (dewatering, transportation and placement properties) which are all related to the mineral and chemical composition of the tailings.

Paste – The Future of Tailings Disposal?

Phil Newman[1], Roger White[1], Alistair Cadden[1]

[1]Golder Associates (UK) Ltd., England

Abstract

In the last decade paste technology has progressed from a research based backfill idea to a widely accepted, cost effective backfill method with the potential to radically change the way tailings are disposed of on surface. Paste is simply dewatered tailings with little or no water bleed that are non-segregating in nature. It can be 'stacked' on surface and the risks associated with dam failure significantly reduces since there is no liquid containment and therefore no mechanism for the tailings to travel for tens of kilometres downstream in the event of a containment failure. The operating costs for the preparation and transportation of paste may be higher but life-of-mine cost analysis shows comparable costs to conventional disposal with significant environmental benefits. In addition, the eco-political impact of non water-retaining tailings dams could reduce permitting time considerably.

Introduction

The acceptance of paste backfill plants, especially in bulk mining, has been extensive in the seven years since the first modern plants were constructed in Canada. Extensive research work by INCO in the early 1990s resulted in advances in the preparation and transportation of paste. Since that time, over 30 plants have been built or are under construction. The advantages of paste backfill over hydraulic fill include reduced binder consumption, slimes handling, stope preparation and surface disposal together with productivity improvements associated with an increased mining cycle.

The increased utilisation of paste technology has improved the reliability and reduced the cost of preparation and transportation systems. This has led to the possibility of using paste for surface disposal. The final prize of such an endeavour is the introduction of virtually water-free surface tailings storage. This can eliminate the need for large water-retaining dams and remove the associated liability such structures pose to the environment. Such a step appears logical, as regulatory pressures become more demanding in Europe after recent high profile dam failures, increasing the permitting requirements for conventional tailings disposal.

The Bulyanhulu Mine in Tanzania, successfully commissioned in March 2001, is the first mine in the world to adopt a total paste solution for all its tailings. A portion will be used underground as backfill and the remainder will be 'stacked' on surface as paste. The advantages cited by Barrick Gold in their decision to develop the system include:

- Reduced capital cost (no large starter dam required)
- Water conservation (traditional disposal may have led to water scarcity and the need for a dedicated water pipeline from Lake Victoria, ~100 km)
- Decreased footprint of tailings disposal site

This paper discusses the future of paste technology as a surface disposal method and presents a case study for a fictitious mine producing non-acid generating tailings. Conventional slurry disposal is compared with paste and an NPC (Net Present Cost) analysis is completed.

In addition this paper will present a definition of paste and discuss the current areas of research into paste for surface disposal including tailings dewatering and transportation, current and future regulatory constraints on tailings disposal and the likelihood of successfully applying the technology to acid generating tailings.

Paste Definition

The definition of paste can become a very scientific and, sometimes, emotive, issue. Golder Associates, who have been working with paste technology since its infancy, has adopted a more empirical definition based on our experience in backfill and, more recently, surface disposal.

A paste can simply be defined as a mixture of solids and water that has little or no bleed water when idle. It must also, however, possess some yield stress such that when tested using a conventional concrete testing slump cone, it does exhibit slump. Figure 1 shows two slump tests, one measuring 175 mm of slump and a second, measuring 250 mm of slump, (note: the slump is measured from the top of the cone).

Figure 1 – Paste Slump – 175 mm (left) and 250 mm (right)

Paste *backfill* is always placed cemented and the optimum slump that minimises transportation pressure losses and maximises strength gain is often found between 150 and 200 mm. Pumping of paste for backfill is rare but for surface disposal, where cement is not routinely added, pumping makes up a very important part of the paste system. As a result, the optimum slump is higher, between 200 and 275 mm of slump. This reduces the friction losses and allows the paste to be transported 2 to 3 km with one large pump.

The difference between 'backfill' paste and 'surface disposal' paste is subtle but impacts significantly on the preparation method and hence the cost of plant construction. At present, it is not possible to consistently manufacture a 'backfill' paste (i.e. a slump of <200 mm) without the use of mechanical dewatering (filtration). Improvements in dewatering technology have enabled the production of higher slump pastes to become possible for some tailings and this has opened up the possibility of low cost paste production, thus bringing environmentally beneficial paste disposal one step closer.

Paste Advantages

The environmental benefits associated with paste surface disposal can be divided into two main categories - the physical characteristics of the paste itself and the operational advantages associated with its placement.

The primary advantage is that there is very little free water available to generate leachate. In addition, the relatively low permeability of the poorly sorted full plant tailings limits infiltration, resulting in reduced seepage volume present in the deposited paste. Hydraulic conductvity values are not easy to determine for an uncemented paste but values have been determined for weakly cemented samples. These range between 10^{-7} and 10^{-8} m/s.

The preparation of paste can allow for the material to be 'engineered' with the use of additives that can enhance the beneficial properties of the paste. Although not widely used at present, probably due to cost fears, additives hold significant potential for further improving the behaviour of disposed tailings.

The most commonly used additive for paste backfill is a pozzolanic binder such as cement, slag, flyash etc. These provide significant strength underground at addition levels of 3 – 6% by weight. For surface disposal, the cost makes them unattractive although tests have shown that 1 wt% cement addition can increase the neutralizing potential by an order of magnitude. It also raises the pH, which can lead to immobilisation of some metals through mineral precipitation.

Other additives that require investigation include speciality chemicals, resins and surfactants that could enhance the adsorption of metals; organic carbon and bacteria to aid biofixation and the addition of organic material (topsoil, seed and fertiliser) to assist rehabilitation work.

The solids concentration (by mass) at which tailings exhibit paste properties can vary significantly and are a property of the fines content and the colloidal chemistry associated with such fines. For example, high clay content tailings such as aluminium tailings (red mud) can exhibit paste properties at ~45 wt% solids, (wt. Solids / (wt. Solids + wt. Water)). Base metal tailings, especially when combined with sand or waste rock can develop solids contents as high as 85 wt% solids and still be easily transported as a paste. Chemically altered tailings, e.g. from Uranium and Soda Ash processing, are pastes at very low solids content, 20-40 wt% solids.

Co-Disposal

One of the most exciting opportunities for paste disposal is the wide range of co-disposal options that are available. The primary example is that of acid generating waste rock (a common occurrence for many mines) being sent to the same waste facility to be 'encapsulated' in tailings paste. This significantly reduces the oxidation risk and reduces the number of waste facilities requiring closure.

With the possibility of engineering the paste to become an effective encapsulating material, other wastes can be effectively sealed into the paste, subject to local and european regulatory approval.

For some mines, such a concept could be logically extended to include non-mining hazardous waste from other industries. This would also generate revenue streams for the mine. Such a concept would truly result in the mine becoming a waste management company. There are significant permitting and regulatory impacts of such a concept. However, the recent publicity regarding the possible use of a closed open pit in Northern Ontario to take domestic waste from Toronto highlights the possible synergy between mine waste handling and general waste management. In addition, at the time of writing this paper, a company in England is considering re-opening the South Crofty Mine (tin) in Cornwall with additional revenue streams from the storage of incinerator ash underground when mixed with tailings for backfill. The concept should certainly be discussed more openly.

Paste Preparation – Tailings Dewatering

The dewatering method for paste backfill made from run of mine tailings is normally a two-stage process. The tailings are conventionally thickened and then filtered to form a wet cake. This material is then re-pulped under closely controlled conditions to accurately prepare the correct consistency paste.

Recent equipment development has allowed paste to be prepared in a one-stage process. These systems are called 'deep tank dewatering systems' and there are manufacturers that have succeeded in constructing such units. Essentially, the thickeners retain the tailings for longer and are higher, which allows for the added dewatering associated with compression of the tailings. The consistent preparation of paste from such equipment is tailings dependent and testing is required.

When Alcan developed a thickening technology for their red mud stacking disposal system, they wanted to prepare stable slurry that could be placed sub-aerialy from a central stacking unit to form a shallow cone, reducing the water management at their tailings facility, Figure 2. The method has proved successful and is in use around the world. Indeed the perforated pipe disposal method for stacking has been adopted at Bulyanhulu for their paste disposal.

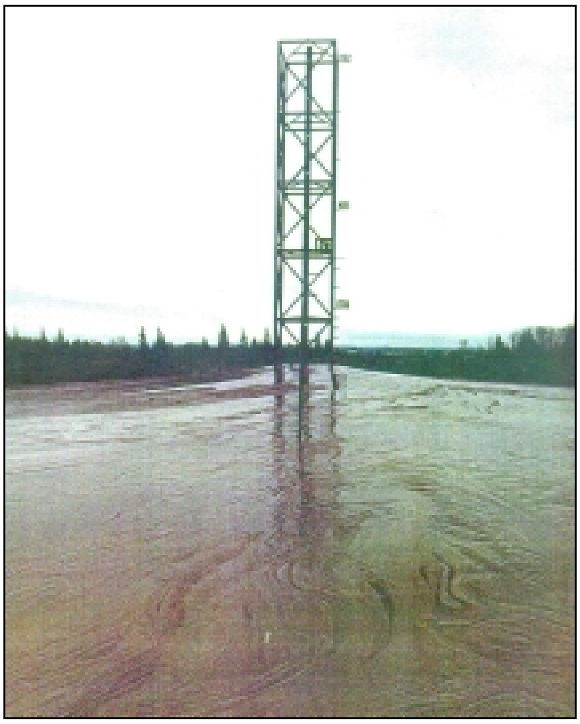

Figure 2 – Stacking of Red Mud Aluminium Tailings

Paste Preparation – Tailings Transportation

For paste backfill careful transportation design is required to ensure a full line which reduces hammer and wear, in turn reducing the risk of plugging the line. For surface disposal the transportation issues are more straightforward, normally related to finding a pump that can provide the necessary driving force with the required availability to operate 24 hours a day. Positive displacement pumps can provide the necessary pressure and capacity.

As discussed above, additives have the potential to reduce friction losses. Experience gained to date has been inconclusive but this may be because commercially available plasticisers were developed for concrete pumping and act on the cement fines. For paste backfill, cement content is minimal and for the surface disposal of paste, there is unlikely to be any cement.

Acid Generating Tailings

Reactive tailings need to be protected from oxidation and this is normally achieved through sub-aqueous disposal that inhibits oxygen contact with the tailings. Conventional sub-aerial disposal of reactive tailings as slurry results in segregation of the tailings that can result in accelerated oxidation leading to acid generation. Paste is homogenous and has a low permeability such that only a thin exposed layer can oxidise.

Hence, a possible paste solution is to ensure that each layer of tailings is subsequently covered with fresh tailings before oxidation takes hold, effectively ensuring acid generation does not gain impetus. The practicalities of such a method have not been fully investigated and there are a number of questions that remain to be answered. However, the Kidd Creek Mine in Timmins, Ontario (Canada) stacks thickened tailings (very little segregation) and has found that as long as tailings are covered with a fresh layer within 12-18 months then acid generation does not become a problem. However, many tailings are much more reactive and covering of old tailings may have to be far more frequent and the issue of total coverage can become problematic.

Research into opportunities with paste and reactive tailings is to start in Europe during 2001 and will involve colloidal chemistry and careful site design and management in order to be successful. Pre-treatment of reactive tailings or the concept of a rolling continuous cover, akin to a domestic landfill site, may sound far-fetched and excessively expensive but recent tailings failures in Europe are increasing the requirements for more control at tailings disposal areas.

Regulatory Concerns regarding Tailings Disposal

Within the European Community there are a number of Directives, Decisions and Regulations governing the management of waste. The Integrated Pollution Prevention Control (IPPC) Directive (96/61/EC) is a wide-ranging edict that stipulates the use of best practice in a range of industrial installations including waste management sites. It should have been brought into force in the Member State in October 1999 and all new installations falling within its remit should be permitted under its aegis. Existing waste sites have until 2007 to comply with its requirements. The IPPC Directive expands on the more general Waste Framework Directive (from 1975, amended 1991) that introduced the requirement to permit facilities with the stated objective of ensuring "waste must be recovered or disposed of without endangering health and without using processes or methods that could harm the environment"

More recently the Landfill Directive (1999/31/EC) was enacted in July 1999 with Member States required to bring it into force by July 2001. The definition of a landfill site is very wide ranging and includes both surface and underground disposal of all types of waste (as defined in the Waste Framework Directive including tailings) that can be considered permanent. The Directive defines permanent as more than three years. All liquid waste is banned from landfill disposal and this may impact severely on current mine waste practices. Excluded from the Directive is "..unpolluted soil or non-hazardous inert waste resulting from..." mineral activities. In addition to this exception, member states can choose to further exempt "..the deposit of non-hazardous waste, to be defined by a committee established under Article 17 of this Directive..." (Technical Adaptation Committee or TAC) from the provisions of the Directive.

Hence, it will be the definition of "non-hazardous waste" that will define whether mine tailings are exempt from the Landfill Directive.

It is unlikely that sulphide tailings will be classified as non-hazardous and although historically, such directives have been resisted by interested member states, legal challenges will force the issue in the next few years. As a result of such a challenge the mining industry may find itself tied to the same waste management practices currently employed at mainstream landfill sites.

Do the regulations really apply to mining? In the past year, there have been at least two separate communications from the EC (COM(2000) 265 and 664) that have explicitly stated the desire for mine tailings to come under the legislative umbrella of the Landfill Directive.

In addition the recently published Baie Marie Task Force report (set up after the cyanide spill in Romania) recommends that the storage of tailings slurry containing cyanide in surface impoundments should cease forthwith. The larger impact of the report may be felt in a general increase in resistance to all type of wet surface storage systems. They can be no mistaking the powerful lobby within the European Union that wants to see significant changes in the way mine waste is currently regulated.

If a tailings pond is classified as a landfill site then paste can offer a semi-dry alternative to full filtration that may prove acceptable to the authorities. In addition, the co-disposal possibilities discussed generally above could provide alternative revenue streams for the mine that could offset the paste preparation and landfill management costs.

It is interesting to note that companies that began their lives as mineral extraction (quarry) companies are active in the mainstream landfill industry in the UK. The future of the mining industry in Europe may see mining companies becoming more and more like waste management companies and the advantages of having a large permitted waste disposal site with an effective encapsulation process (paste) could, with time, generate more income for some mines than actual metal extraction.

Case Study

In the case study prepared we have invented a fictitious (new) mine located in Europe that will produce 1,000,000 tonnes of tailings per year for 10 years. The tailings are non-acid generating but do contain heavy metals and stringent leachate production controls have been imposed on the mine.

Assumptions

Particle (tailings) density	= 2.9 tonnes/cubic metre
Total tailings to be disposed	= 10 million tonnes
Dry density of placed tailings	= 1.43 (placed as slurry), vol. req. 7 million m^3
	= 1.8 (placed as paste), vol. req. 5.6 million m^3

Site Description

The mine is located at the head of a gently sloping v-shaped valley with a distance of ~ 1 km between the mill and the TMA.

Conventional Disposal

The tailings will be thickened from flotation to about 55 wt% solids and then pumped to the TMA. Water reclaim will be done using a floating barge that will return the water to the mill for re-cycling. At year 4, the dam will be raised to the final profile (Figure 3) and it is assumed that mine closure will take place in year 11 and will involve the draining of the facility and placement of a permanent soil cap.

Paste Disposal
Tailings will be dewatered to a paste consistency using a tank dewatering system. Positive displacement pumps will transfer the tailings to the TMA. There will be no water reclaim arrangements from the TMA. Precipitation run-off and limited water bleed from the paste will be collected in the water retaining dam and this will be treated locally prior to discharge at acceptable quality levels. Run-off from the valley is diverted around the TMA. As above the construction will be phased with completion during year 4 and closure assumed in year 11, although some rehabilitation will likely start in year 6 (Figure 4).

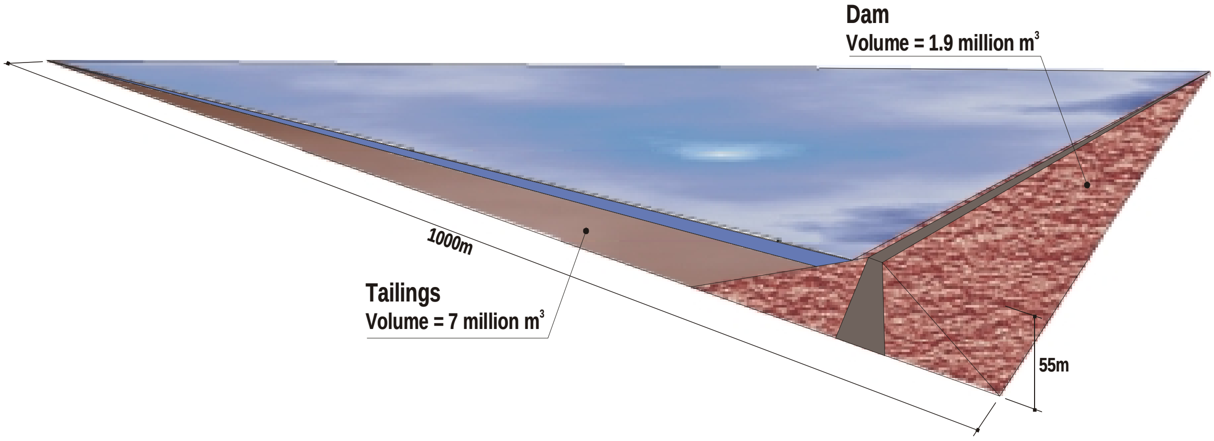

Figure 3

Schematic Cross-Section - Conventional Slurry Tailings Dam

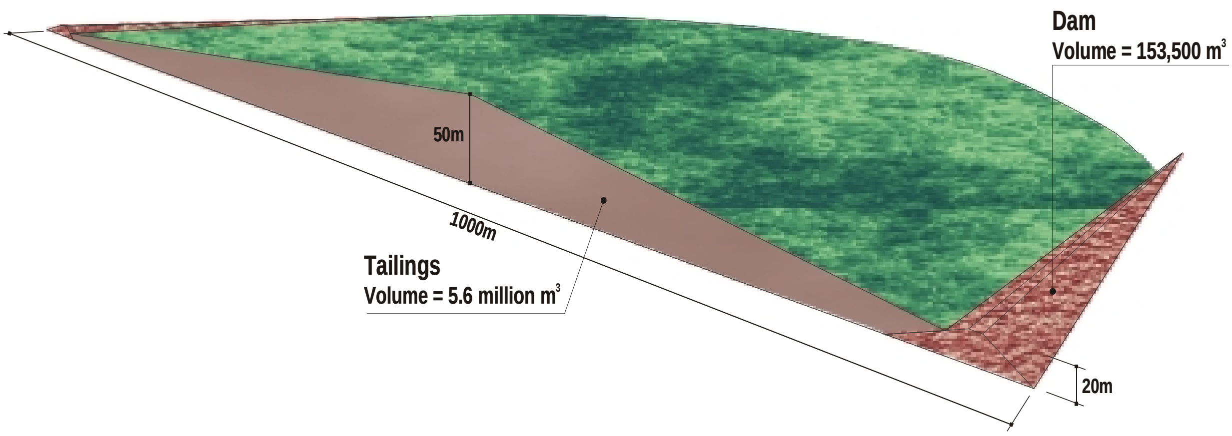

Figure 3

Schematic Cross-Section - Surface Paste Disposal Dam

Capital Costs

The capital costs have been estimated based on recent European tailings management projects and assume that the area is cleared of moderate woodland and prepared for a full lining system as currently required under IPPC regulations. Such facilities have been constructed recently in Ireland (Galmoy and Lisheen Mines) and are currently being designed in Greece.

The capital cost of the TMA includes clearance, foundation preparation, liner (500mm of clay plus 2mm geomembrane), diversion ditches and general dam fill. The smaller dams (or berms) required for the paste solution reduces the capital cost although the saving is offset by the paste plant capital cost (~$3.15 million).

The delayed capital cost (yr 4) is also higher for conventional slurry and the closure costs are significantly higher given the drainage and stabilisation work required before rehabilitation can begin.

Operating Costs

The operating costs are not dissimilar for the two options since some thickening is assumed in both cases and flocculent consumption will be the same. The tank dewatering system for paste production achieves higher solids content through compression thickening and more precise automation and process control.

Labour costs will be slightly higher for the paste operation, as would power consumption and maintenance costs, mainly associated with the operation of the positive displacement pumps.

NPC Analysis

The NPC (Net Present Cost) analysis (Table 1) assumes a discounted cash flow (10%) over the mine life. The results show that the adoption of a paste solution, although requiring a slightly higher initial capital expenditure, $10.3 million vs. $9.8 million, the final NPC values are essentially the same, $15.3 million vs. $16.1 million.

The following additional advantages are not included in the cost analysis but are considered to be of significant value to the project:

- elimination of a tailings ‘dam’ and the associated negative public perception of the dam
- reduction in environmental disruption afforded through increased management of the facility and the use of concurrent rehabilitation of the site
- significantly reduced liability for the mine with respect to any TMA failure that may occur, this may impact on bond payments or insurance premiums
- possible co-disposal of other mine waste (notably acid generating waste rock) that reduces the number of waste areas requiring closure and monitoring
- possible additional revenue streams through the expansion of the paste facility to take other waste streams
- possible time saving from reduction in permitting constraints by the company adopting a more pro-active, waste management orientated approach to its regulatory interaction

Discussion and Summary

Approximately 10 years ago the use of paste technology for backfill was considered by many as an unrealistic goal. Paste backfill was considered a high risk / high cost option. It was the commitment of a few mines and individuals that proved the technology as a viable backfill method and thousands of tons of paste are poured each day without problems.

It appears that history may repeat itself with paste for surface disposal. It is accepted that the operating costs are higher but regulatory pressure to eliminate the liability of tailings dams are the driving force with some cost savings being realised through reduced capital expenditure and faster permitting. The savings associated with water conservation is driving the technology in more arid countries (Southern Africa) and their experiences will further reduce the costs. Indeed, it may be the success of Barrick Gold (Bulyanhulu) and DeBeers (2 projects expected in 2001 in South Africa) that will drive the authorities to identify paste as a low risk "best practice" for surface disposal.

Major mining companies such as Rio Tinto, Anglo and Billiton are committed to ever increasing environmental standards, pushing the bar higher in terms of compliance. It may appear that paste tailings disposal is the natural progression for this race for the moral high ground in an environmental sense. In Europe, regulatory pressure has increased significantly in recent years and many companies will have to adopt significantly more controlled waste management practices.

If a mine that could take 7 – 10 years from discovery to production can be in positive cash flow in 5 years with no tailings dam to consider, what financial impact will that have on a major mining company?

Mining activities in Europe have reduced significantly over the years and the challenge for paste technology is to offer a new alternative to existing waste management problems. The application of paste is more likely for an existing mine applying for a tailings dam extension and such a move may prolong the life of the few remaining mines in Europe.

Technology continues to drive down the cost of mining production and paste, although it may increase day to day operating expenses it will save significant amounts of money over the life of the mine and, subsequently, add value to the mining company operating the facility.

References

Cincilla, W., Landriault, D., Newman, P. and Verburg, R. 1998: Paste Disposal. Mining Environmental Management, May 1998

Verburg, R.B.M., 1997. Environmental Benefits Associated with the Use of Paste for Surface Disposal of Tailings. Proceedings of the 50th Canadian Geotechnical Conference of the Canadian Geotechnical Society. 20-22 October 1997, Ottawa, Canada. pp. 484-491.

Table 1 - Net Present Cost Analysis of Base Case versus Paste Disposal

Assumptions

Paste Disposal

Capex - Paste Plant	**3,153,300**
TMA Capex, Yr 0	**7,177,885**
TMA Capex, Yr 4	**4,213,275**
Reclaim Cost, Yr 6-11	**800,000**
Operating Cost	**290,668**

Yr	0	1	2	3	4	5	6	7	8	9	10	11
Investment Required												
Paste Plant	3,153,300											
Surface Installation	7,177,885				4,213,275							
Total Capex	10,331,185				4,213,275							
Operating Costs												
Operating Costs		290,668	290,668	290,668	290,668	290,668	290,668	290,668	290,668	290,668	290,668	
Rehabilitation Costs							50,000	75,000	100,000	100,000	100,000	375,000
Total Opex		290,668	290,668	290,668	290,668	290,668	290,668	290,668	290,668	290,668	290,668	
Total Cash Flow	**10,331,185**	**290,668**	**290,668**	**290,668**	**4,503,943**	**290,668**	**340,668**	**365,668**	**390,668**	**390,668**	**390,668**	**375,000**

Net Present Cost	**$ 15,320,699**

Base Case

Capex - Thickener	**400,000**
TMA Capex, Yr 0	**9,405,356**
TMA Capex, Yr 4	**6,406,297**
Reclaim Cost, Yr 10-11	**3,600,000**
Operating Cost	**112,500**

Yr	0	1	2	3	4	5	6	7	8	9	10	11
Investment Required												
Plant (thickener)	400,000											
Surface Installation	9,405,356				6,406,297							
Total Capex	9,805,356				6,406,297							
Operating Costs												
Operating Costs		112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	
Rehabilitation Costs											500,000	3,100,000
Total Opex												
Total Cash Flow	**9,805,356**	**112,500**	**112,500**	**112,500**	**6,518,797**	**112,500**	**112,500**	**112,500**	**112,500**	**112,500**	**612,500**	**3,100,000**

Discount rate	**10%**

Net Present Cost	**$ 16,151,509**