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Pit Lake Formation and Mitigation Options For The Barite Hill Mine

By Michael J. Gobla, P.E.
U.S. Bureau of Reclamation, Denver, Colorado
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When open-pit mining ends the pumps are turned off and water begins to accumulate in the excavation. As water from precipitation and groundwater inflow accumulates in the mine excavation, a pit lake is formed. Depending upon climatic and geologic conditions, a pit lake will either become a terminal lake (typical in a dry climate) or a flow through lake (typical in a wet climate). Pit lakes have a wide range of water quality. Pit water chemistry is influenced by the presence of reactive minerals in the pit walls and backfill which are acted upon by chemical, physical, and biological processes. The depth to width ratio of pit lakes is greater than that of most natural lakes. Natural lakes tend to be shallow and wide. For this reason pit lakes often behave differently than natural lakes. Often, pit lakes show chemical/water density stratification which can prevent them from having a seasonal water turnover as happens in most natural lakes.

Pit Lake Hydrology

Pit lakes receive water input by three natural processes:

- Direct Precipitation
- Runoff from adjacent watersheds
- Groundwater inflow

Pit lakes loose water by two natural processes:

- Evaporation
- Groundwater outflow

Pit lakes may also gain or loose water by human intervention. Pumping water in to accelerate filling has been performed at several pit lakes (i.e. Sleeper, North Pit, Island Copper). The climate and water balance will determine if a pit becomes a terminal lake or a flow through lake. In the arid southwest states like Nevada and Arizona, pit lakes are typically terminal lakes. Evaporation rates exceed the rate of water inflow and as a result the water table does not fully recover after mining ends. Depression of the groundwater table is the long-term condition which results in a sustained groundwater inflow to the evaporating pit lake.

In wet climates such as in South Carolina, South Dakota, and Montana, pit lakes typically continue to fill until they become flow through lakes. The inflows from precipitation and runoff exceed the evaporative and seepage losses resulting in a mounding of the water table. These pits typically fill to the surface and have both groundwater and surface

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water discharge. In rare cases a flow through lake may loose all of its water to groundwater outflow if the upper walls of the pit are comprised of very pervious material.

The Barite Hill pit is expected to be a flow through lake. Seepage from the pit to the unnamed tributary to Hawe Creek was recently estimated to be around 5 gpm. The upper pit walls, while allowing some acid seepage to flow to the adjacent creek, do not appear to be pervious enough to prevent the pit from filling completely. It is expected that the pit lake level will continue to rise until it begins to spill to surface flow pathways. In its present condition, the upper portion of the pit rim is likely to fail in an uncontrolled manner due to the presence of soil and weathered bedrock. The unconsolidated material needs to be removed and a stable spillway constructed.

Pit Lake Water Quality

Pit lake water quality is influenced by chemical, physical, and biological processes. The chemistry is controlled by chemical reactions between the minerals in the pit rocks and the surface and groundwater inflows; and by the action of physical and biological processes taking place in and adjacent to the pit. Non-reactive wall rocks tend to form pit lakes with neutral pH water having moderate to low levels of total dissolved solids (TDS). In contrast, chemically reactive wall rocks result in highly mineralized water. An abundance of pyrite and other sulfide minerals usually results in formation of an acid lake, with high iron, sulfate, and TDS concentrations. An abundance of carbonate minerals usually results in formation of a pH neutral to slightly alkaline lake with high TDS concentrations, and if sulfides are present the water will contain significant amounts of heavy metals.

Pits with reactive pyrite and other sulfide minerals in the pit walls and rubble tend to have very poor water quality upon filling. Blasting, and excavation during mining causes the pit walls to become highly fractured exposing more rock surface area to oxidation. In addition to the fractured rock walls, open pit mines also contain significant amounts of waste-rock rubble. Miners are not good housekeepers. This rubble results from several sources including:

- Dumping of blasted waste rock in mined out pit areas to save on waste haul costs
- Rock falls and slope failures
- Waste rock placed as pit road surfacing
- Waste rock used to construct required safety berms along pit roadways
- Fly rock from blasting
- Waste purposefully backfilled into the pit at the end of mining

The Barite Hill Mine Pit contains large amounts of acidic waste-rock rubble below the water line which originated from the sources listed above. The rubble likely amounts to several tens of thousands of tons, or more at Barite Hill. Having rubble under water (a single release of acidity upon flooding) is preferred to having it deposited above the pit lake where it will contribute acid runoff into the pit for thousands of years (multiple releases of acidity by precipitation runoff).

At mines where pyrite and other sulfide minerals are present above the water table, the exposed mineral grains will begin to oxidize during humid conditions. Saturation from rainfall will mobilize this acidity and carry it away. As the pyrite mineral grains dry out, more acid salts are deposited on the mineral surfaces which remain until the next flush. Current knowledge of the formation and chemistry of acid pit lakes at metal mines comes from experiences and numerous investigations at many mines including the following more notable ones:

- Island Copper Mine, British Columbia
- Sleeper Mine, Nevada
- Ketchup Flat Pit, Paradise Peak Mine, Nevada
- Berkeley Pit, Montana
- Champion Pit, Haile Mine, South Carolina
- South Pit and North Pit, Ridgeway Mine, South Carolina
- Anchor Hill Pit, Dakota Maid Pit, and Sunday Pit, Gilt Edge Mine, South Dakota

As these pits filled with water at the end of mining operations, there have been as many as five sources contributing acid water to the pit lakes by:

- Release of stored acid salts from rubble and fractured rock walls upon saturation by rising pit lake water levels
- Inflow of acid stormwater runoff from adjacent unsaturated areas as a result of precipitation and snowmelt events
- Oxidation of pyrite rubble and fractured rock highwalls by interaction of the upper aerobic water layer with the pit shoreline and shallow submerged zone.
- Infiltration of water into adjacent underground mine workings which turns acid and then discharges into the pit lake
- Dissolution of pyrite in the anaerobic zone by Fe^{+3} ions to release acidity and Fe^{+2} ions into the pit lake (iron cycling) This source turns off at most pits once the limited supply of Fe^{+3} ions in the anaerobic zone are consumed by the reaction.

In time three of the sources normally diminish in their rate of acid input. Once a mine pit reaches a relatively stable reservoir level, the acid input from rising water will diminish. Some or all of the underground mine workings may completely flood and become stagnant pools thus shutting off their flow to the pit lake. Finally, the rate of acid generation from deeply submerged rubble and fractured highwalls (iron cycling) will diminish once the supply of Fe^{+3} in the anaerobic zone is consumed.

It should be noted that at a very few mines seasonal lake turnovers (i.e. Berkeley Pit) have been observed to reactivate the iron cycling process (Madison and Others, 2003). This reactivation is possible because Fe^{+2} in the near surface aerobic zone will slowly oxidize to form Fe^{+3}. A seasonal turnover causes colder surface water to sink and warmer deep water to rise thus mixing the aerobic and anaerobic zone waters. The turnover transports a new supply of Fe^{+3} down to the anaerobic zone reactivating the iron cycling process which continues until all of the is Fe^{+3} is consumed. Barite Hill likely has

become too deep and chemically stratified to turnover. If it is neutralized the water will certainly density stratify (because not all sulfate is removed) preventing turnover. Only if the pit is cleaned further by carbon addition could it turnover and this is not certain given its depth and being in a warm climate. If a clean carbon loaded lake does turnover it will not matter because the sulfate reducing bacteria will generate alkalinity to treat the minor amount of iron that would remain in solution.

The Barite Hill Pit has been filling for 12 years. It continues to receive acid input from rising pit water saturating the oxidized rubble and fractured walls, from runoff from an adjacent 10-acre disturbed area where pyrite containing waste rock was dumped, from oxidation of pyrite in the shoreline area by aerobic zone water, and possibly from iron cycling. There are no underground mine workings present at Barite Hill. ***Currently, the largest acid source at Barite Hill is runoff from the adjacent watershed, followed by interaction of the shoreline with the aerobic zone of water. The input from rising water and iron cycling are likely much smaller contributors at this point in time. Iron cycling causing iron dissolution in the anaerobic zone is likely a smaller source now that the pit is quite deep.*** Deep pit lakes like Barite Hill with a high mineral load are likely to have little to no turnovers, therefore iron cycling would be a very slow acid forming process at the site. Regarding input from rising water, once the pit lake fills to overflowing, the elevation of the reservoir surface will become relatively stable and this source will no longer be important.

Pit Lake Mitigation Strategies

Mine pit mitigation methods have evolved over the past two decades. Initially the options were do nothing, treat the water and backfill the pit (like the Rainsford Pit at Barite Hill), or if the pit was too large, treat the water in perpetuity (Berkeley Pit). Recently success with methods like accelerated flooding, capping reactive pit walls, in-pit lime neutralization, and carbon addition to establish sulfate reducing bacteria treatment have expanded the available mitigation options. Table 1 summarizes experiences with more notable acid mine pits. It serves to illustrate the experiences with acid pits at other sites.

Table 1. Experiences at mines with acid pit lakes

Location	Description	Status
Berkeley Pit, Butte, Montana	In 1982 the 5,000 gpm pumps were turned off allowing the underground mines to flood. Connected to the 10,000 miles of underground mine workings, the pit began filling in 1983. The pit lake now contains about 35 billion gallons of pH 2.5 water. The pit lake had a seasonal turnover each spring and iron cycling was active in the lake (Madison and Others, 2003). During 2000 to 2003 mining in the nearby Continental Pit was suspended allowing cleaner water to flow into the Berkeley Pit. This chemically stratified the lake and it no longer turns over.	EPA has ordered that water treatment must commence when water levels rise to 50 feet below the surface alluvium layer. This will keep the lake drawn down to maintain it as a terminal lake. Flow through conditions will not be allowed because it would contaminate the alluvium.
Ketchup Flat Pit, Paradise Peak Mine, Nevada	This pit was mined from 1986 until 1993, and then reopened shortly in the late 1990's. The pit lake is located in a hot and very dry part of Nevada. Evaporation has concentrated this terminal acid lake into the worst water in the state.	The unstable pit walls are sliding in. The lake will eventually be filled in by slope failures (100+ years).
Island Copper Mine, British Columbia, Canada	Mined from 1971 until 1995, 360 million tons of pyrite rich tailings were disposed of in an adjacent ocean inlet without any significant impact (Wilton and Lawrence, 1998). The mine pit was flooded with sea water to fill it rapidly. Near the end of filling, the lake was topped off with fresh water to stratify the lake and prevent turnovers. Acid drainage from the mine waste dumps is injected into the bottom of the lake for disposal. The pit was carbon loaded with wood chips and fish waste in an attempt to set up a passive sulfate reducing bacteria treatment system in the lake. In the interim, a liquid fertilizer is applied to the top of the pit lake to create algal blooms which scavenger metals and keep the upper layer of the lake within discharge standards.	Acid has stayed in the deep levels of the lake as hoped. The fresh water has shown partial mixing with the underlying saltwater layer. Due to the large lake volume anoxic conditions are only slowly developing in the saline zone. Sulfate reducing bacteria are beginning to establish. For now periodic fertilizer treatment is maintained with the hope that the sulfate reducing system will soon become operational.

Flambeau Mine, Wisconsin Flambeau Mining Company (Kennecott)	Reclaimed from the fall of 1996 until the fall of 1997. This copper mine located on the edge of a river had reactive pyrite waste rock. Groundwater levels were very close to the surface. The pit was backfilled with clay amended material placed against the pit walls to form a low permeability zone. Next 2.1 million cubic yards of acid waste was amended with lime to neutralize current acidity (but not future acid potential) and was backfilled below the expected final water table (Sevick and Others 1988). Clean waste was backfilled in the transition to and above the water table.	The lime amended backfill saturated and it has not re-acidified. Groundwater is observed to flow around the pit being deflected by the low permeability pit liner. No impacts to the river have been seen.
Champion Pit and Snake Pit, Haile Mine, South Carolina Kinross Gold Corp.	Mined 1985 to 1991, the two pits have been closed using submergence of the acid wastes. The Champion pit was lime neutralized, the water discharged, and acid wastes were lime-amended and backfilled into the pit. A layer of organic matter and lime-amended soil covered the backfill and then the pits were allowed to re-flood.	Champion pit now supports healthy fish population and is a self-sustained lake. Snake pit also has excellent water quality and is allowed to overflow offsite (Rowe and Turner, 2005).
South Pit and North Pit, Ridgeway Mine, South Carolina Kennecott Ridgeway Mining Co.	Mining began in 1988 and reclamation commenced around 1999. The South Pit was reclaimed first. Sulfide waste was amended with slaked lime and placed as a partial backfill into the mine pits (Willow and Duckett, 1999). Exposed reactive zones in the pit walls were blasted to reduce the slopes, and the flatter sloped areas were covered with soil. The lime amended backfill was placed in the pit bottom with a cover of soil and topsoil. Slaked lime was also used to maintain the pit lake water at 100 mg/l of calcium carbonate alkalinity.	The South Pit has excellent water quality. The North Pit has been reclaimed in a similar manner and is currently being filled with water. It appears that it too will achieve a lake with good water quality.

Sleeper Pit, Sleeper Mine, Nevada Amax Gold Co.	This mine was operated for about 10 years creating a mile long by 580-foot-deep pit. Large quantities of sulfide waste without amendment were backfilled into the lower portion of the pit. Alluvial groundwater amended with lime was pumped into the pit at a rate of 11,000 gpm for 2 years to fast fill the pit with the hope it would not turn acid (Atkin and Schrand, 2000). The filling resulted in an acid lake which was not expected. The company lime neutralized the acid lake which eventually stabilized with a neutral pH (Dowling and Others, 2004). Shortly after completing the project a large slope failure occurred putting a large amount of acid rock into the pit. The pit lake turned acid again. The company made another lime addition to neutralize the pit.	The water quality has stayed near neutral and is considered a successful case of submergence of reactive sulfide waste followed by neutralization of the pit water (Miller, 2002). At present the pit receives minimal levels of monitoring. Considered to be a near walk away condition, this project proved that acidic waste could be put into a pit lake and it could later be neutralized.
Anchor Hill Pit, Dakota Maid Pit, and Sunday Pit, Gilt Edge Mine, South Dakota	Anchor Hill Pit has about 1/3 of perimeter as reactive sulfide rock including a scree slope extending down into the water. Upon the end of mining in 1997 the pit had a few feet of good water quality. Heavy rains required transfer of 60 million gallons of pH 3.5 acid water from Sunday Pit to Anchor Hill to prevent the Sunday Pit from overtopping. The initial closure plan recommended Anchor Hill be reclaimed as a pit lake using new technology for sulfate reduction by carbon addition. A patented process to neutralize pit and use methanol and molasses as carbon sources (Harrington, Wangerud, and Fundingsland, 2004) was implemented in 2001on an experimental basis. After some modification (addition of wood chips to provide surface area for bacteria) sulfate reducing bacteria were able to precipitate iron sulfide and other metals and generate alkalinity to form a self sustaining neutral pit lake.	Pit lake would have been walk away, but because the site contains other acid sources (two acid pits, an acidic heap leach pad, and an acidic waste rock dump) it was recently decided to convert the Anchor Hill Pit to become the primary acid storage reservoir at the site. The Anchor Hill experience is notable because it is the first time an acid lake was passively treated to meet trout stream discharge standards using a sulfate reducing bacteria system. About 30 million gallons of water were discharged to the creek before the experiment was ended. This project has advanced the state of the art.

The concept of submerging acid generating material under water has emerged over the last two decades as a superior means of disposing of reactive sulfide wastes. The technique has been studied in Canada since 1988 (Tremblay and Hogan, 2001). It is based upon the fact that the maximum amount of dissolved oxygen that water can contain is approximately 30 times less than air. Furthermore, once this oxygen is consumed, the diffusion rate to transfer additional oxygen through the water to oxidize the waste is almost 10,000 times slower than the oxygen transfer rate in air. Therefore,

storage under a permanent water cover has been shown to be the most effective means of sulfide waste disposal.

Several terms have evolved with respect to water covers:

- Subaqueous disposal is the placing of waste material into water
- Flooding is a reclamation method where a pit or in-place wastes are subsequently inundated with water

It is preferable if the sulfide containing waste has not yet sufficiently oxidized to turn acidic. Such freshly mined and milled material can be placed into relatively shallow water such as a natural lake with good results. Where the waste has already turned acid, there will be a release of acidity when the material becomes saturated. A natural lake would be contaminated by such an addition of acidic material and would require treatment of the water. For mine pits the release of acidity into the water can be mitigated by subsequent neutralization (i.e. Sleeper Pit, Champion Pit, Anchor Hill Pit, etc.).

Neutralization creates a neutral to alkaline water with high sulfate and some metals content. If the water must be treated to very stringent discharge standards, then additional treatment may be required. For this reason, carbon addition is gaining acceptance as a method to establish a sulfate reducing bacteria system to remove metals and sulfate by precipitating metal sulfides. It has been shown to be effective on neutralized acid waters and on alkaline leach pad process waters. Sulfate reduction reverses the acidification process to form and deposit pyrite in the bottom of the pit where it will remain, but for the bacteria to flourish, the water needs to be near neutral to slightly alkaline in pH. Prior to this development, final polishing of neutralized water required costly treatment methods like ion exchange and or reverse osmosis to meet stream discharge standards. ***In summary, submergence has been proven its value in acid prevention and if coupled with neutralization and carbon addition a self-sustaining system with good water quality can be created.***

Barite Hill Pit Mitigation

Mitigation of the acid pit lake at Barite Hill can be accomplished by one or more of the following alternative options:

1. No action, accept the consequences of the acid pit lake
2. ***Construct spillway and fencing***
3. Perpetual water treatment
4. Neutralize, backfill, and reclaim
5. Blast the pit rim, partially backfill, and reclaim as a dry basin
6. ***Minimal waste backfill, lime neutralization, and carbon addition***

These options are explained and contrasted as follows:

1. No Action

This is not a viable alternative for Barite Hill because of the danger of a catastrophic release of acid water if the pit rim fails.

2. Construct Spillway and Fencing

At a minimum the low pit wall must be stabilized by construction of a spillway to prevent a catastrophic release. The upper part of the ridge forming the low end of the pit would be excavated to remove the loose soil ridge and weathered rock to eliminate the potential for a catastrophic release of water from the pit lake. A spillway capable of handling a large flood would be installed in a notch cut into the rock. Site perimeter fencing and or signage would be installed to discourage trespass access.

This option would eliminate the risk of a catastrophic release of more than 40 acre-feet of acid water. The pit will still fill to overflowing in a few years time and the receiving creek will continue to experience acid seepage. Fish kills in Strom Thurmond Lake would still be a likely outcome after large precipitation events. A 1" rain would cause 500,000 gallons of acid water to flow out of the pit.

3. Perpetual Water Treatment

Perpetual water treatment would be performed to maintain the pit lake at a level below the current pit rim and prevent acid releases. Grouting of the north side of the pit, or a major drawdown of the existing pit level would be necessary to eliminate the acid seepage to the creek. Because of the very acidic nature of the pit water (negative pH water) off-the-shelf semi-passive lime addition systems are not likely to be effective. A conventional water treatment plant with an estimated 250 to 300 gpm capacity would be needed to deal with storm surges and unusually wet years to keep the pit lake level drawn down. In an average year the plant would operate at around 100 gpm. The highly acid nature of the site water would generate large volumes of sludge. Sludge storage and disposal would become a significant cost issue in the long term.

This option would prevent acid releases from the site. Ongoing treatment costs would be substantial to maintain a full time presence at the site to operate the treatment and sludge disposal facilities ($1 million/year cost range). There would always be an acid lake at the site which is a hazard to wildlife. There would also be a significant capital outlay to build a water treatment plant and sludge disposal facility. This option is not recommended for further consideration due to the high long-term costs and continual presence of a very acidic pit lake.

4. Neutralize, Backfill, and Reclaim

The acid pit lake would be neutralized, discharged to the creek, and then an estimated 1.5 million cubic yards of waste would be hauled in to fill the pit to the level of the low north rim thus eliminating the pit lake. The volume of fill is a rough estimate because current topography of the final pit excavation does not exist which would allow a more accurate volume to be computed. The fill would also rise to cover the sulfide bedrock exposures on the west and north sides of the pit, and a low permeability soil cap would be placed over the backfill. A growth layer of soil would be added and the surface would be amended with organic material and seeded. The spent ore in the Heap Leach Pad and the Solid Waste Disposal Landfill is probably not acceptable for use as backfill material due to its ongoing release of selenium. Waste Area A is the default source of the fill. This fill would be lime amended to eliminate its current and future acidity.

This option has a high construction cost because of the requirements to transport a large amount of material and needs for extensive amounts of lime for both pit neutralization and then fill neutralization. A small amount of acid seepage to the creek is likely to continue since the north pit wall would remain as a source, although this could be corrected by an extensive grouting operation. This option would have the highest capital construction costs (at least $10 million) but minimal long-term costs.

5. Blast the Pit Rim, Partially Backfill, and Reclaim as a Dry Basin

The acid pit lake would be neutralized, discharged to the creek, and then the north wall would be drilled, blasted, and excavated down to near the creek level (about elevation 400). The portion of the pit below the creek level would be filled with the blasted material to eliminate any remaining part of the lake. The upper 20 feet of the waste placed below the water table would need to be heavily lime amended to account for existing and future acid generating potential because it would be in the saturated aerobic zone where groundwater flow could be significant. Below 20 feet the submerged waste would be in the anaerobic zone and would only require a modest neutralization of present acidity. The waste piles deposited in the adjacent 10-acre area on the west side of the pit would also be placed into the deep fill. Steep pyrite-containing highwalls on the west side of the pit either would be blasted, grouted, or covered with backfill to prevent acid generation. Any rock blasted for highwall reduction would also require either deep burial or shallow burial with full lime amendment and capping. After the pit shaping and filling was completed, the ground would be covered with lime, and low permeability clay soil to

form a cap. A layer of growth soil would be placed and heavily amended with organic material. This would then be seeded and the result would be a free draining pit with clean runoff. A storm-drainage channel with rock armoring would be placed in the main drainage pathway through the reclaimed pit and some small wet boggy areas may be present in the bottom of the pit. This option is similar to that originally proposed by the mining company's consultants and was permitted by the State of South Carolina. Current pit topography is not available to precisely evaluate the quantities of materials to be blasted and to evaluate the volume of the pit floor below the creek level to be filled.

This option has the excellent chances for success with little to no acid seepage reporting to the creek. It would eliminate the pit lake and provide clean vegetated surfaces for surface water runoff. In time a stable forested surface would be established. The construction costs are likely less than option 4 but more than option 6.

6. Minimal Waste Backfill, Lime Neutralization, and Carbon Addition

An estimated 50,000 cubic yards of pyrite waste in the adjacent 10-acre disturbed area would be pushed into the deep part of the pit. The pit lake would be neutralized and the upper 10 feet of the lake may need to be discharged to facilitate reclamation of the final littoral zone (shoreline area) of the lake. Exposed pyrite containing highwalls would be evaluated for blasting, grouting, or backfilling to eliminate this acid source at and above the final water level of the lake. A spillway would be constructed to prevent failure of the north wall of the pit, and to help establish a relatively stable pit lake water surface elevation. The spillway would include a concrete overflow structure and grouting of the surrounding rock to minimize seepage and strengthen the rock for anchoring the spillway. The adjacent disturbed area to the west of the pit and the reduced highwall slopes to remain above the water line would be covered with lime, clay soil, and growth medium. The growth medium would be amended with organic material and would be seeded. Organic carbon would be added to the pit to establish a sulfate reducing bacteria treatment zone to mitigate remaining acid sources.

This option eliminates the acid pit and replaces it with an initially alkaline pH lake that in time will move to near neutral pH conditions. The carbon addition will in time reduce the metals and sulfate levels in the water. Long term maintenance would be minimal and would entail pH monitoring and occasional minor additions of lime and or organic material. This option is estimated to cost approximately $3 million. ***Option 6 is the favored option. It has moderate costs compared to options 4 and 5 and does not preclude the other options from being implemented if performance is not fully satisfactory. In fact, both options 4 and 5 would utilize the actions taken under this option as a first step, therefore this could be implemented and the site further studied for remedial action if necessary.*** Only the spillway construction would be an unnecessary expense if options 4 or 5 were later chosen. Option 6 is the favored option for a response at Barite Hill Mine and should be implemented.

Some Good Internet Papers on this Topic:

Link to a good slide show on pit lake concepts

http://www.unr.edu/mines/adti/ElkoPresentation/PitLake.pdf

Link to paper on the Haile Mine:

http://www.kinross.com/investors/pdf/hardrock-nomination-haile.pdf

Link to info on Ridgeway Mine Reclamation

http://www.kennecottminerals.com/krmc/KRMC/IRCP.html

Link to Dr. Miller's paper on Nevada Pit Lakes:

http://www.swhydro.arizona.edu/archive/V1_N3/featurette3.pdf