

CONCEPTUAL METHODS FOR RECOVERING METAL RESOURCES FROM PASSIVE TREATMENT SYSTEMS¹

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Abstract. Recovering mineral resources retained in passive systems for treating acid drainage may be a way for mining companies to achieve sustainability goals. While the development of metallurgical methods for Fe oxide recovery from passive systems is underway, no parallel research effort has apparently been undertaken for the recovery of precious metals, sulfides, or carbonates from sulfate reducing bioreactors (SRBRs), another effective passive treatment technique. The examination of conceptual beneficiation, pyrometallurgical, and hydrometallurgical processes that might be used in resource recovery is a logical first step in this effort. Resource recovery process challenges include dealing with the abundance of organic matter in the SRBR substrate media and the dispersed and probably microscopic character of the metal precipitates.

Screening, wet classification, and roasting of the SRBR media appear to be common threads for recovering the four elements considered in the paper: copper, gold, silver, and uranium. As the SRBR technology matures further, research could help close the loop in a process that is now considered to be solely treatment.

Additional Keywords: sustainability, recycling, metals, beneficial uses, sulfate reducing bioreactors

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Introduction

There are two kinds of passive biological treatment cells for treating net acidic and net alkaline mine drainage or collectively mining influenced water (MIW). Aerobic cells containing cattails and other plants are typically applicable to coal mine drainage where Fe and Mn and mild acidity occur. Sulfate reducing bioreactors (SRBRs) are typically used for metal mine drainage with high acidity and a wide range of metals. Most passive treatment systems employ one or both of these cell types. The track record of aerobic cells in treating coal MIW is impressive, especially in the eastern coalfields of the United States. SRBRs have potential at metal mines and coal mines but have not been widely applied.

In the correct application, passive treatment systems for dealing with MIW have been shown to be more economical than hydrated lime or similar neutralizing reagent methods (Gusek, 1995). Some effort has been focused on the beneficial use of precipitated metals in these systems to further enhance their economic potential. The metals in passive systems are usually retained as oxides, carbonates, or sulfides – they probably form a mineral suite similar to the original mined deposit or the waste rock surrounding the deposit. Recovering base mineral resources retained in the passive systems will probably not be as profitable as the mine itself, primarily because of the slow kinetics of the process and the small size of the “deposit”. However, preliminary economic analysis suggests the contrary for passive systems recovering precious metals (Gusek and Clarke-Whistler, 2005). Markets for the recovered minerals exist; for example, Fe oxide from passive systems associated with coal mines is being recovered and processed for paint pigment and similar uses (Hedin, 2002). A similar situation may be possible for the recovery of native elements (e.g., Au or Cu), oxides (e.g., U), sulfides or carbonates from SRBRs.

While the development of metallurgical methods for Fe oxide recovery is underway, no parallel research effort is apparently being undertaken for the recovery of metal precipitates from SRBRs. The examination of potential pyrometallurgical and hydrometallurgical processes that might be considered in sulfide/carbonate/native metal recovery is a logical first step toward developing methods that “close the loop” in passive treatment systems and integrate their operation into resource recovery efforts, perhaps as part of sustainability initiatives. Challenges include dealing with the abundance of organic matter in the SRBR substrates, the dispersed and probably microscopic character of the metal precipitates, and other currently unforeseen factors.

Before economic recovery of metals from the depleted substrate of an SRBR is considered, however, the question of whether the material qualifies as a hazardous waste needs to be addressed. Hazardous elements such as Cd, Pb, and As are sometimes sequestered in the substrate. Less often, Hg and Se may be present. The mixing of the substrate with an acetic acid solution at a pH of 5, which is the protocol for the Toxicity Characteristic Leaching Procedure (TCLP) test, could release toxic hydrogen sulfide gas and mobilize metals thereby rendering the substrate a hazardous waste. The added cost of residue disposal in a hazardous waste landfill could overwhelm any economical resource recovery of metals, precious or base. Therefore, the initial handling of the substrate to minimize the uncontrolled release of hazardous materials is a recovery process consideration.

Considering these issues, the objectives of metals recovery from SRBRs that will be discussed in this paper include the following:

1. Establish methods to handle substrate so that the likelihood of the material being classified as a hazardous waste is minimized or eliminated.
2. In the tradition of passive treatment technology, emphasize the use of low cost and low-technology recovery processes.
3. If possible, develop methods that will make the substrate an “ore” that could be sold or at least not have excessive disposal costs.

In addition to these objectives, certain sought-after metals will determine whether a SRBR substrate is an economic resource. Therefore, metallurgical methods that recover or concentrate Au, Ag, Cu, and U will be emphasized. There has been little work done on processing materials from SRBR-dominated passive treatment systems; thus, the metal recovery methods discussed in this paper should be considered candidate technologies based on assumptions and hypotheses tempered by limited information. The authors hope that the assumptions or hypotheses presented will be tested by future developers in a rigorous research effort.

Geochemistry of Metals Precipitation in SRBRs

In SRBR cells, the geochemical conditions are predominantly reducing (that is, oxidation reduction potentials less than -100 millivolts) and neutral to slightly alkaline pH. In the presence of dissolved sulfide ions (H_2S), metals can be precipitated/formed as the following:

- Sulfides (Wildeman et al., 1993),
- Hydrous sulfates (Thomas, 2002),
- Carbonates (Wildeman et al., 1993),
- Oxides (Grunig, in Kuhn, 1981), and
- Native elements (Jensen and Bateman, 1981; Columbia Encyclopedia, 2001-2005)

The precise nature of the precipitates and where they form are discussed in more detail later in this paper.

Hazardous Waste Prevention

In a SRBR that is functioning correctly, most metals will be in the sulfide or carbonate phases except for Al, which will be in a hydroxy/sulfate phase. These sulfides, including FeS, will be acid volatile compounds that are fine-grained and poorly crystallized. Consequently, it is assumed that H_2S will be generated when the substrate interacts with acetic acid in a TCLP leachate test (Machemer, et al., 1993, US Environmental Protection Agency, 2002). Because Ag, Cd and Pb sulfide are quite insoluble, these contaminant metals should not leach from the substrate to produce a hazardous waste. However, in the reducing environment of an SRBR substrate, As in a sulfide phase is assumed to be mobile. Consequently, this material has to be considered a hazardous waste because of the possible liberation of H_2S and As.

To eliminate the possibility of a hazardous waste, the mineral phases deposited in an SRBR's substrate will have to be crystallized and perhaps oxidized so that they are stable. The hypothesis is that a fresh, water-saturated substrate is reactive and will have to be dried and aged. If the substrate

material is removed from the SRBR cell, the suggested procedure is to spread it out to dry with the objective of oxidizing the sulfides and producing crystalline oxides. It is assumed that this will eliminate the H₂S and stabilize the As by adsorption onto Al and Fe oxides. One possibility that should be considered is whether to undertake a physical separation step while the substrate is still fresh. Addition of water could float off remaining organic material and settle the inorganic phases. Also, processing the material through a sieve could remove un-reacted limestone and organic material. Such a physical separation could reduce the volume of material of interest to less than half the volume of the original substrate.

Typical SRBR Organic Media

The media or substrate typically used in SRBRs is comprised of three major components:

- Crushed limestone;
- Organic matter; and
- Bacterial inoculum (which is also organic).

The relative proportions of these components may vary. Limestone has been omitted from substrates used to treat net alkaline MIW; limestone has typically been included in substrates used to treat net acidic MIW. The grain size distribution can vary from poorly sorted gravel with a upper particle size of about 5 mm to fine-to-coarse grained sand. Cement kiln dust has also been used to supplement limestone in SRBR substrate, especially when the MIW is highly acidic.

Organic matter sources are influenced by the regional availability of cellulose-dominated materials, and may include the following:

- Wood chips (multiple tree species),
- Sawdust,
- Rice hulls,
- Yard waste,
- Mushroom compost,
- Animal manure (multiple types),
- Hay and straw (spoiled),
- Nut shells,
- Cardboard,
- Soy bean hulls,
- Waste dairy products,
- Sugar cane processing residue (Bagasse),
- Rice straw, and
- Cotton waste.

The grain size distributions of these materials will vary widely; wood fragments generated by commercially-available shredders or grinders or chippers are probably the largest organic particles found in SRBR substrates. Chipped wood particles are typically rectangular shaped and several millimeters thick. Shredded wood particles tend to be stringy with large length to diameter ratios. These unique characteristics might be used to an advantage in substrate processing steps to recover retained metals provided the fabric of some of the original material is preserved.

Animal manure and mushroom compost have been the most common bacterial inoculum used in SRBR systems. These materials typically account for a small percentage of the total substrate mass and any organic matter they contain is thought to be consumed within a year or two of a SRBR's

commissioning. Data from early systems that were dominated by these two components showed that metal removal performance could not be sustained because of premature organic matter depletion. Also, based on experience at the Big Five Tunnel, (Wildeman, et al., 1993) a substrate consisting primarily of compost and manure becomes soupy after a few years.

Metallurgical Flowsheet Development

Wilson and Dawson (in Mular & Bhappu, 1980) outlined the basic steps of metallurgical flow sheet development and they included:

- The determination of the values present and the minerals involved, followed by
- Choosing the process or processes; followed by
- Laboratory testing to identify the appropriate methods.

The first two steps are the focus of this paper; it is the authors' hope that the findings presented may prompt further laboratory-based research; that is, Step 3.

Values Present and Minerals Involved

The metal values in the substrate can be estimated in two ways: by direct chemical analysis of representative substrate samples or by the mathematical analysis of flow rates coupled with influent and effluent sample analytical results. Due to the conservation of mass, differences in influent and effluent chemistry should account for the metal values sequestered in the substrate. Retention times in some SRBR systems can be on the order of several weeks, particularly for MIW with elevated metals concentrations. For MIW with varying chemistry, this lag time might introduce some mass loading bias if differences in spot influent and effluent sample results are used to estimate metal retention in the cell. This influence can be minimized by tabulating cumulative influent metal loading and cumulative metal effluent loading separately and determining the difference between the two. However, for Ag and Au, the detection limits applicable to most routine methods of analysis are above the likely aqueous concentrations in the MIW and SRBR effluents, so the spent substrate itself should be analyzed for these two elements.

Collecting “representative” samples of substrate should follow standard random or uniform grid sampling protocol over the surface of the SRBR cell (Smith, et al., 2000). Compositing samples collected from various depths within the SRBR should be considered with caution, as there may be different vertical horizons of elevated or depleted metal concentrations as further discussed below in the section on Visual and Horizon Sorting.

Nature of the Metal Precipitates

Studies of metal precipitates in SRBR's using spectroscopic and extraction techniques have shown that many of the sulfide and hydroxide precipitates are so fine grained as to be X-ray amorphous (Thomas, 2002; Wildeman, et al., 1993; Machemer, et al., 1993). Through analysis of solubility products and spectroscopic studies, the solid forms of some metals are fairly well established and are shown dramatically in Fig. 1. The primary sulfide phase is as an acid volatile sulfide (Machemer, et al., 1993) and extraction tests show that Cu, cobalt, Cd, and Pb are in this sulfide phase. For a number of metals, the carbonate solubility and sulfide solubility are close, and these metals could be in either form. Zinc, Ni, and Fe, fall in this category. Aluminum precipitates could be in two forms. It would be advantageous if aluminum hydroxyl sulfate is the predominant

phase because this would not clog reactors. However, in some systems gibbsite may be the predominant form of Al precipitate. No studies have been made on the phases of Ag, Au, and U in an SRBR, so the following assumptions are made:

- Silver is in a sulfide phase and is associated with Pb and/or Zn,
- Copper is likewise in a sulfide phase,
- Gold is the native state, and
- Uranium is in a reduced oxide phase, probably as UO_2 .

Available Metallurgical Processes

The goal of utilizing low cost and simple metal recovery technologies is consistent with the likely sporadic schedule of metal recovery from SRBR substrates and the relatively small volumes involved. The simple technology goal is also consistent with the likelihood that the metal recovery facility will be located in a remote location with little, if any, infrastructure since the mine or mill facilities have probably been removed during mine closure.

For these reasons, the process flowsheets will not include “exotic” processes such as solvent extraction/electro-winning in the case of Cu, or froth flotation for the separation of sulfides from non-sulfides. Similarly, magnetic separation is a specialized process that might be applicable in recovering iron sulfide that has been oxidized to hematite, perhaps in roasting, but this issue is not considered here. Some of the more energy-intensive processes, like crushing and grinding, are not appropriate as very little, if any, ore dressing, size reduction, or mineral liberation is needed. Classification processes are attractive because they rely on separation of particles of various sizes, shapes, and specific gravities in fluids (e.g., water and air) (Gaudin, 1939). Gravity separation and screening are two common classification processes (Wills, 1979).

The processes most likely to be employed in processing SRBR substrate have been known to man in some cases for centuries (Tagart, 1927) and include the following:

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|------------------------------------|----------------------------|
| • Visual Sorting, | • Roasting, |
| • Dewatering/Drying, | • Composting, and |
| • Gravity separation (wet or dry), | • Leaching (vat and heap). |
| • Screening, (wet or dry), | |

These processes, alone or in combination, have been configured by process engineers for the recovery of a variety of metal products to a stage where they can be shipped as a concentrate or high-grade product for further processing (e.g., smelting and refining). The focus of the processes under consideration does not extend into the smelting and refining realm. However, the inclusion of some constituents (e.g., As and Hg) in concentrates can result in significant smelter or process penalties. Thus, segregation of these two materials from SRBR substrates is subsequently addressed

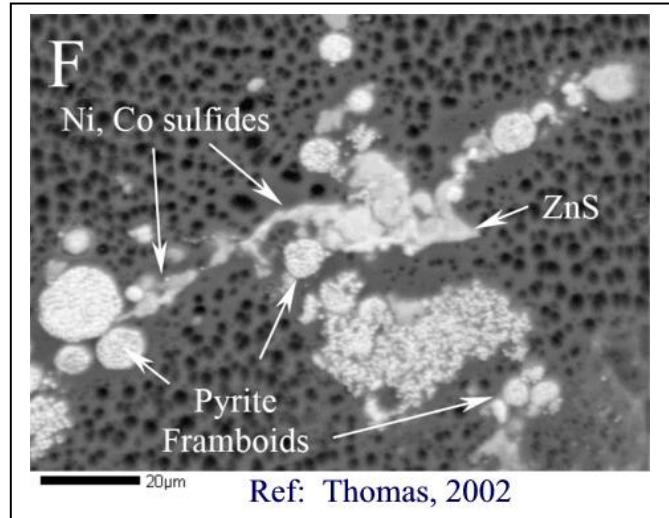


Figure 1 – Metal Sulfides in Wood Fragment

in greater detail. Brief discussions of the individual processes follow.

Visual or Horizon Sorting

Based on the observations of Thomas (2002) regarding his Limestone Buffered Organic Substrate (LBOS), the depleted substrate in an SRBR is likely to be comprised of three different layers (Fig. 2):

- Oxide,
- Transitional, and
- Sulfide.

Assuming that the SRBR cell was configured to be a vertical flow bioreactor, the oxidized layer will occur at the top of the cell. If Fe was present in the MIW, this layer will be stained red with iron oxyhydroxides and Fe oxides. If As was present in the MIW, it would likely be retained in the oxidized layer. Thus, using a color-driven sorting protocol, an As-rich material that could be hazardous might be physically separated from low-As materials in the transition and reducing zones.

It is likely that the SRBR substrate will exhibit zoning similar to that found in nature due to geochemical processes like supergene enrichment. Thus, there may be “high-grade” zones of Hg, Ag, Cu, Pb, Zn, Cd, Ni, and Fe. By selective recovery of substrate materials in certain vertical horizons, some level of beneficial sorting can likely be achieved.

Dewatering/Drying

While the SRBR is in use, the substrate is completely saturated. In some situations, before the beneficial recovery of the entrained metals can begin, the solid/liquid separation of the retained water and the solid material containing the metal values may be required. Due to the coarse-grained nature of most SRBR substrates, gravity dewatering on a pad or within the geomembrane- or clay-lined SRBR cell will likely be the only dewatering effort required. Mechanical filters (e.g., drums, disks, or presses) are probably not needed. Neither are thickeners or

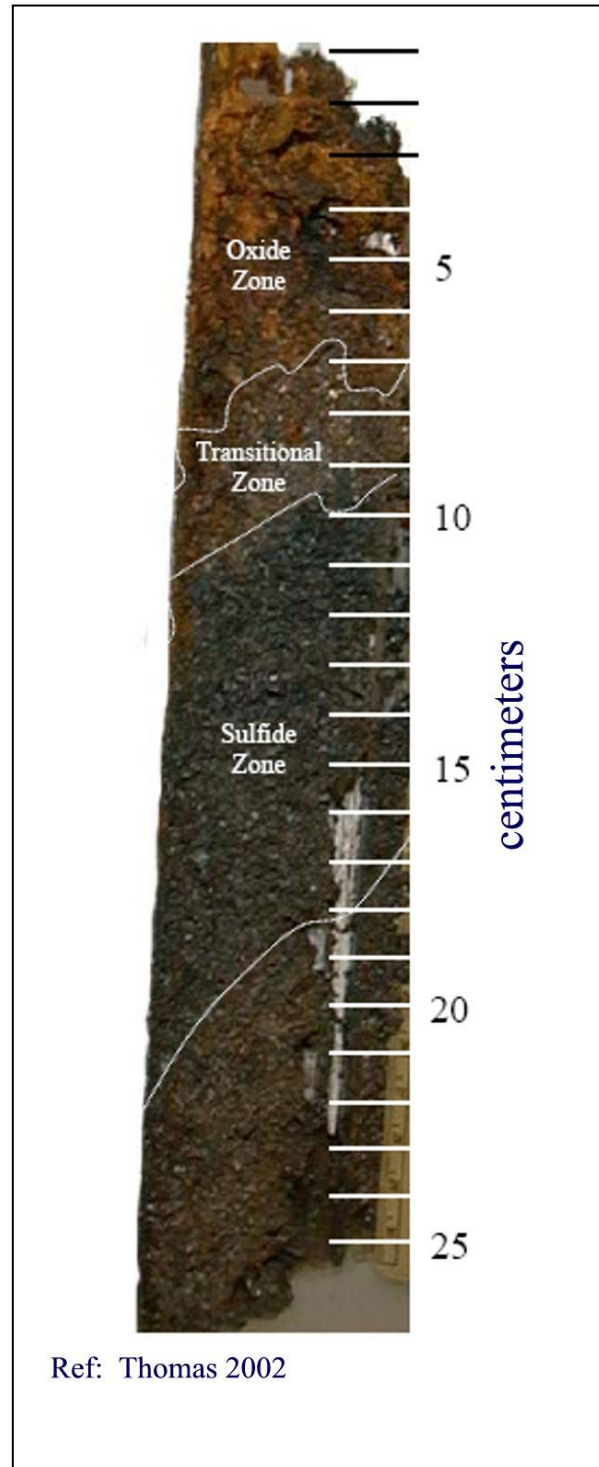


Figure 2 – SRBR Substrate Zones

inclined plate settling units.

Drying to lower moisture contents may be required to facilitate other process operations. For example, an air-dried substrate may provide a better gravity separation between organic and non-organic fractions. The density difference between a dry porous organic fraction and a denser limestone/gypsum fraction might be magnified several fold by air drying, resulting in less “middling” losses. There may be a danger of over-drying, however. Fine-grained non-organic particles might stick to lighter organic fragments and the separation efficiency might be adversely affected. Static air-drying would likely be preferred to mechanical or forced drying due to its economy, simplicity, and low power requirements. The use of drying is assumed to be practical in net-evaporative climates or climates where a distinctive dry season occurs. Specifying a drying circuit process step may not make economic sense in a rain forest environment but it should certainly be considered in a desert or temperate climate.

Gravity separation (wet or dry)

Panning for Au is the simplest of gravity separation processes; the heavier Au particles sink to the bottom of the pan and the lighter non-Au particles float to the top. The separation process relies on the differences in the specific gravity of the particles being processed (assuming they are nearly the same size) and the action of Stoke’s Law of settling particles. In processing SRBR substrates, if the metal values are retained in the lighter organic fraction, the sink-float relationship is reversed: the heavier material will be rejected. There are many off-the-shelf devices that have been developed for exploiting the gravity differences between minerals and waste. Most of these use water as the settling media and include the following:

- Jigs,
- Spiral classifiers,
- Heavy media tanks,
- Shaking tables, and
- Hydrocyclones.

Shaking tables, hydrocyclones, and spiral classifiers are appropriate for very fine grained materials. However, it is unlikely that these processes would be efficient at separating metal from non-metal particles. Pulsating jigs might be applicable for separating the limestone from the organic fractions. In dry to temperate climates, air-classifying might be appropriate for the same purpose.

Roasting

As discussed earlier, SRBR substrates typically contain a significant amount of organic matter where the sulfide metal species are likely to reside. This organic material can interfere with many metallurgical processes, including leaching. The roasting process has been a simple, economical process that has been used for hundreds, if not thousands of years, to “pre-process” ores to make them more amenable to smelting. Georgius Agricola, in his landmark book De Re Metallica, (Hoover and Hoover, 1950) discussed the process at length; see Fig. 3. Roasting involves slowly heating a material to a moderate temperature, about 800°C (Julian, et al., 1921).



Figure 3 – Roasting circa 1540

Roasting temperature can have a significant effect on metal recovery; Guay (in Schlitt, et al., 1981) reported that Au liberation in carbonaceous Carlin ores was the best in the range between 500 and 550°C. In the past, roasting has typically been used to pre-condition hard ores for crushing and/or oxidizing sulfides to oxides in preparation for smelting. In the SRBR substrate processing situation, it would be applied to reduce the organic content (where the metals are bound); sulfide oxidation would also occur.

Air pollution production and control will be a concern in the roasting process. Roasting would not be appropriate for SRBR substrates containing As, Se, and Hg as these elements could be volatilized in the roasting process. In these situations, composting might be a more appropriate method for reducing organic content. The process decision to separate residual limestone and/or aluminum

hydroxysulfate prior to roasting would also need to be carefully considered. Residual limestone in the roaster feed could provide a sulfur dioxide scrubbing benefit; limestone is frequently included in fluidized bed desulfurization boilers in coal fired power plants and it would likely bind to any sulfur liberated in the roasting process. Agricola (Hoover and Hoover, 1950) recorded the use of water-cooled Fe flues for sulfur emission control; native sulfur collected on the inside of the flues and was periodically recovered.

Screening

In situations where separation of metal-barren fractions of the SRBR substrate from the metal-rich fractions is desired, it might be accomplished with simple screening. The limestone fraction may be comprised of grain sizes less than 2 mm and the organic fraction (composed of wood chips) may be comprised of larger fragments. Screening dry or wet needs to be carefully evaluated. Experience has shown that a dried SRBR substrate will appear to have less of the finer grain size fraction than a wet-screened sample because these smaller particles adhere to the larger particles in the drying process. This effect appears to be preserved for a short time after a dried sample is re-wetted.

Composting

Composting is not a process that would normally be found in metallurgical texts. While it is typically associated with agriculture and waste management, it could be an important process step in metal recovery from SRBR substrate because it consumes organic carbon that might interfere with other recovery processes and it does so without resorting to high temperatures that could volatilize hazardous constituents that might be in the substrate (e.g., As, Se, and Hg). It also is a simple way to reduce the volume of the substrate mass requiring material handling or processing.

The composting process requires an organic source, which might consist of the residual organic fraction in the substrate. The composting process may involve the addition of nitrogen to balance

the preponderance of carbon in the substrate, especially in the form of composting-resistant wood chips or sawdust. A carbon to nitrogen ratio of 30C:1N is typically recommended to speed the composting process; nitrogen sources could include fresh animal manure (especially from chickens), fresh seaweed, and ammonium nitrate fertilizer.

The composting process requires period mixing/turning which increases the metal recovery process cost. It can be labor intensive, but this could be used to advantage to create local jobs.

Leaching

Leaching of metal-bearing materials has been practiced for hundreds of years. It is beyond the scope of this paper to address the multiple chemical reagents that can be used to dissolve metals in metallurgical extraction processes. Noteworthy, however, are the uses of the following:

- *Aqua Regia* and *Aqua Valens* (“strong water”) which were discussed in *De Re Metallica* (Hoover and Hoover, 1950) to separate Au from Ag or from Cu.
- Cyanidation can be used to extract Au and Ag; but it also can be used to leach trace amounts of Hg and Cu.
- Caustic solutions can be used to extract As.
- Sulfuric acid or NaHCO_3 is used for the leaching of U (Wilson and Dawson in Mular and Bhappu, 1980).
- Chlorination is a process that is used to oxidize organic matter while simultaneously mobilizing Au and Ag.

Two characteristics of SRBR substrate are detrimental with respect to some leach solutions. The presence of organic matter is a known “preg-robbler” with respect to cyanidation due to the tendency of Au to adsorb to humic acids (Guay in Schlitt, et al., 1981). Second, the presence of limestone precludes economical leaching of SRBR substrates with acidic solutions to promote metal recovery. Clearly, these two issues need to be addressed with other separation/modification processes prior to a leaching step; or tailoring the leach solution itself so that its effect is not impeded by the organic matter or the limestone. The use of a bicarbonate leach for the recovery of U would be a good example of this approach.

Theoretical Process Flowsheets for Copper, Gold, Silver and Uranium Recovery

As previously noted, the presence of As or Hg could cause the removed SRBR substrate material to be classified as a hazardous waste. In some cases, the substrate would be considered a hazardous waste regardless of whether metals removal would be attempted, so removal of hazardous constituents may be a moot point. In other cases, however, elimination of the contaminants that could render the substrate a hazardous waste may be required for the metal recovery process to be economically viable. This factor will need to be factored into flowsheet development for metals recovery, along with the primary unit operations discussed in the following sections.

Gold, Silver and Copper Recovery

The primary issue with Au, Ag and Cu recovery is the uncertainty as to their specific chemical form within the substrate matrix. The assumption has been made that Au is in a reduced native state dispersed throughout the substrate matrix and that Ag and Cu are in a sulfide form, likely in the

sulfide zone in the bottom portion of the substrate matrix. Various forms of leaching, with subsequent recovery of metals from the pregnant solution, have been used successfully for many years. These are the processes of choice for Au, Ag, and Cu recovery from SRBR substrates. However, in order for leaching to be effective the organic and limestone fractions of the substrate may need to be separated.

If the physical location of the metal within the substrate column is known, visual sorting may be used to reduce the overall volume of material requiring subsequent treatment. Basic dewatering, prior to other processes, may also be beneficial. For example, air drying could reduce energy costs associated with roasting, or improve the separation efficiency for limestone materials.

After basic pretreatment, roasting would be a potential process to be used for separation of the organic fraction. An alternative approach would be composting. Additional oxidation of the remaining organic substrate material, using a process such as chlorination, may also be required prior to leaching to remove remaining refractory organic compounds, as even trace organic concentrations can adversely affect the leaching process.

Screening or gravity separation would be potential processes for separation of the limestone fraction. Air-drying of the substrate may provide for better separation if composting is used for organic removal. If roasting is used for organic removal, screening will be even simpler as the limestone will easily separate from the dry ash and solid residue.

Following removal and separation of the organic and limestone fractions, actual leaching of Au and Ag could be done with cyanide (Au and Ag), H_2SO_4 (Cu), or HNO_3 (Ag). The pregnant solutions could then be processed through conventional adsorption processes, such as activated carbon or ion exchange, for final metals recovery.

One aspect of the metals recovery process described above that must be evaluated is the potential acceptability of pretreated materials at existing recovery facilities. Pretreatment of the SRBR substrate for separation of organic material and limestone may produce a material that could be shipped directly to an existing facility. This could have a significant positive impact on the overall economic viability of metals recovery from SRBR substrates.

Uranium Recovery

Trace levels of soluble U found in waste streams are typically found in the form of the mobile uranyl tricarbonate or uranyl sulfate complex. When these waste streams encounter the reducing conditions of a SRBR, the U changes oxidation state and can form a variety of reduced U species in the tetravalent form such as the insoluble UO_2 . The presence of organic matter in the SRBR provides the reducing environment for this precipitation to occur. In order for the U to be removed from the SRBR media, an acid or carbonate leach with oxidation of the U will have to occur. The process would initially involve the screening of the limestone material, where the presence of U will likely not occur, and the subsequent processing of the residual organic matter to recover the U.

Removal of the organic matter can be done in two possible ways. The organic matter could be roasted and the residual ash and residue, containing the U, could be recovered or sold to a U processing facility for further recovery. The organic fraction could also be leached with a bicarbonate/hydrogen peroxide solution to solubilize the U as the uranyl tricarbonate complex and the U recovered on ion exchange columns. The ion exchange columns would be eluted to produce a stream from which the U could be directly precipitated as a purified product. The use of oxidant

(hydrogen peroxide) would have to be carefully evaluated due to the presence of the residual organic matter as this could consume the oxidant and cause the chemical cost of the lixiviant to be very high.

An alternate to bicarbonate leaching is the use of sulfuric acid (with possible addition of an oxidant, as needed). This process would likely recover more of the U from the SRBR media and could be somewhat more economical as long as the limestone was first removed from the substrate. The disadvantage is that a secondary waste stream of sulfuric acid solution would require management.

Similar to Au, Ag and Cu, a project where U recovery is contemplated would need to evaluate the possibility of direct shipping of the substrate (possibly pretreated by screening or drying) to an existing mill facility.

Summary

The hypothetical processes presented in this paper for recovering metals from depleted SRBR substrate should be considered a baseline starting point for future focused research into this issue. Screening, wet classification, and roasting appear to be common threads for recovering the four elements considered and research might begin with these processes. As the SRBR technology matures further, this research will help close the loop in a process that is now considered to be solely treatment.

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