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Review

Policy guidance for identifying and effectively managing perpetual environmental impacts from new hardrock mines

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ABSTRACT

Perpetual environmental management at operating and proposed hardrock mines is a rapidly expanding global dilemma. While economies of scale have encouraged larger mines, improved models routinely predict long-term water quality degradation at sulfide metal mines. Technical causes include oxidation of sulfide minerals and seepage from waste rock, tailings, and pit wall rock. Perpetual treatment is usually less expensive than permanent stabilization, even using 2% ''risk-free'' investment return rate; but this option greatly increases the social and financial complexity. A few regulations address perpetual management, but specific requirements range from formal acceptance to complete prohibition. With vague regulations, predictions of long-term impacts often delay permitting as operators and regulators grapple with model uncertainty and regulatory ambiguity. Risk management tools (e.g., insurance, inflation-protected investments, etc.) can reduce but cannot eliminate risk, and their continued availability is uncertain. What regulators and mine operators need – but do not have – is a clear framework to guide them in developing perpetual management plans that balance risks (e.g., uncertainty in predictions, cost, finance, and governance) and ensure responsible environmental and social stewardship. This paper responds with a review of perpetual mine management issues, including technical causes, policy examples, investment tools, case studies, technical remedies, and principles for successful long-term management.

1. Introduction

In the 40 years since the United States began requiring Environmental Impact Statements for disturbances on public lands, environmental analyses have determined with increasing certainty that many (and maybe most) new hardrock mines in sulfide rock will require continuous management to prevent perpetual water quality degradation. The primary cause of the degradation – oxidation of sulfide minerals in exposed rock and mine waste – is well understood. Yet after decades of committed research, affordable remedies remain elusive. The root cause of long-term contaminant leaching is the high mobility of atmospheric oxygen. Unless the spoils of mining – waste rock, tailings, and the walls of pits and tunnels – are permanently submerged under water, oxygen reaches and reacts with the excavated metal sulfides, producing long-term release of sulfate, acidity, and various metals and metalloids. Designs that permanently isolate mine waste

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from water or oxygen exist, but remain undemonstrated at full scale. Physical management of waste poses important secondary concerns, including steep-walled pits and resulting pit lakes that may remain attractive nuisances, and tailings (the crushed remnants of processed ore) in dammed impoundments, which are destined to eventually load particulate metals to surface waters unless the earthen dams are maintained perpetually.

A prediction of perpetual management presents the mine operator, regulators, and stakeholders with multiple complex decisions. How reliable are the predictions? Would the mine be consistent with sustainable development? Is it legal to allow perpetual treatment? If so, how much will it cost, when should the money be delivered, and how should it be invested? Who should manage the funds? Invariably, predictions of long-term impacts delay permitting as operators and regulators grapple with this model uncertainty and regulatory ambiguity. A framework is beginning to emerge, but a complete strategy for perpetual mine management plans remains unformulated. What regulators and mine operators need is a clear framework to guide them through the gauntlet of technical, permitting, financial, and governance requirements for perpetual post-closure management. We present here a start to such a framework, with reviews of water quality model predictions, relevant laws and policy, case studies, explanation of practical risk management tools, and the emerging technical options for perpetual benign stabilization.

2. Causes of perpetual impacts from hardrock mining

Numerous field studies at operating and recently closed hardrock mines have led to improved models for predicting water quality degradation. The predictive framework begins with conceptual models describing contaminant fate and transport as they apply to hardrock-mine waste: waste rock, tailings, and wall rock in pits and adits. Key model components models include contaminant release (oxidation), transport (surface or pore-water flow), chemical attenuation (adsorption, precipitation, acid neutralization), and dilution. Specific examples here illustrate how conditions led to prediction of long-term water quality degradation.

2.1. *Waste rock*

Water quality degradation from waste rock arises when atmospheric oxygen encounters sulfide minerals that are wet enough to oxidize, and the oxidation products, primarily sulfuric acid and soluble metals, leach to surface or groundwater by runoff or percolating pore-water. Contaminant loads from waste rock thus depend on the oxidation rate (a function of pore-gas oxygen concentration, temperature, fragment size, sulfide-mineral surface area, pore-water chemistry, and biological activity), the rate that contaminants are flushed by flowing pore-water, and chemical attenuation (Lefebvre et al., 2001; Malmstrom et al., 2000). Active oxidation in sulfidic waste rock is nearly ubiquitous. Moisture is generally higher than the few weight percent required to sustain oxidation, even in semiarid climates (Swanson et al., 2000; Kempton et al., 1997). And some oxygen always enters the rock – diffusion drives oxygen into waste rock surfaces, and advection near exposed slopes commonly produces widespread oxygenated zones deep into piles (Lefebvre et al., 2001). Specific examples of long-term waste rock impacts from models calibrated to field sites include a prediction of peak metal loading to surface water at an unnamed tropical (1450 mm/year precipitation) waste rock and tailings site that is ''well above the applicable 'low-risk' trigger value'' arriving between 150 and 400 years (O'Kane and Wells, 2003), a prediction that metal-laden acid drainage from the copper operation at the Mt. Lyell Mine in Tasmania will continue ''for many hundreds of years'' (Koehnken et al., 2003), and a post-closure analysis at the Island Copper Mine on Vancouver Island, British Columbia, suggesting that ''planning for in perpetuity costs is essential, and that the concept of financial closure for these mines is unrealistic'' (Pierce and Wen, 2006). Impacts on receiving water can be delayed in semiarid climates, where slow unsaturated flow in waste rock can delay for decades the onset of discharge; but oxidation continues in these low-moisture environments, and long-term degradation of receiving waters is the general outcome (Kempton and Atkins, 2000). A compilation of US environmental studies identifies several sites (e.g., Golden Sunlight Mine in Montana; Iron Mountain Mine in California; Phoenix Mine in Nevada) with a potential for continued groundwater degradation for thousands of years (Kuipers et al., 2006). Collectively, these predictive studies suggest that sulfide-hosted hardrock mines in general, and acid-generating rock in particular, should be considered as potential sources of long-term water degradation.

Lined heap-leach facilities are special cases of waste rock that may require long-term management. Alkaline cyanide leachates used for gold recovery often contains dissolved anions (e.g., arsenic, selenium, antimony, and cyanide) and cyano-metallic complexes (copper, mercury, cadmium, and zinc; US EPA, 1994). And sulfuric acid heap leaching used on copper ore dissolves numerous heavy metal cations. Water rinsing to remove contaminants generally fails, in cyanide heaps because redox and pH shifts resolubilize metals (Bowell et al., 2009), and in all heaps because contaminants slowly diffuse out of fragments. And where residual sulfides remain, heaps may eventually produce acidic effluent. In response, some heap-leach closures omit rinsing, focusing instead on minimizing infiltration and long-term effluent treatment or evaporation.

2.2. *Tailings*

Water quality degradation arising from unlined tailings impoundments reflects the spatial gradation in fragment sizes and associated distribution of water. During construction, a typical tailings impoundment includes a dam (coarse sand or larger), a beach produced by discharge of tailings slurry (medium sand, grading to finer with distance from the dam), and fine sand to silt and clay slimes farthest from the dam in a layer sufficiently impermeable to maintain an overlying pond. Because the coarse beach must be conductive enough to remain perpetually drained to maintain strength in the dam, unlined tailings facilities typically have a zone of unsaturated sulfide-bearing coarse sand. After closure, fine saturated tailings under ponds remain effectively isolated from oxygen; but oxygen diffusion into the unsaturated tailings can produce 10 kg SO_4/m^2/year or more, along with soluble acid and metals (Nicholson et al., 1995). A coupled model of hydraulic flow and diffusion-limited sulfide oxidation at a semiarid South African tailings facility, calibration to observed conditions (tailings height = 50 m, sulfide S = 0.89–3.8 wt%, oxidation rates from kinetic tests, and moisture content from soil water characteristic curves and climate), predicted concentrated acidic seepage (tens of thousands mg/l SO_4^{2-}) continuing for over 2000 years (Govender et al., 2009).

2.3. *Pit lakes*

Conceptual models of mine pit lake evolution consider water inflow by groundwater and precipitation, solute loading from oxidation of sulfide minerals in wall rock and groundwater inflow, and chemical attenuation by precipitation and adsorption reactions in the lake (Ross, 1992). Perpetual impacts are common when sulfide wall rock remains above the lake surface and provides a long-term source of acid and metals, or when evaporative concentration causes solutes from groundwater to continuously increase. Direct measurements and calibrated models indicate that oxidation rates in sulfide-bearing pit wall rock ranges from ~1 to several tens of kg SO_4/m^2/year (Kempton and Atkins, 2009; Fennemore et al., 1998), and blast-induced wall-rock porosity can extend to 15 m (McClosky et al., 2003; Radian, 1997), producing thick reactive zones that are long-term source of solutes to mine lakes. This wall-rock load effect is seen in water quality evolution in the Lone Tree Mine in Nevada, USA, which contained ~20 million m^3 of water two years into closure (based on stage-volume curves; WMC, 2004). Lake pH is 3.1; but at ~200 mg/l $CaCO_3$ total acidity, this could be neutralized for US\$0.01/m^3 in CaO (assuming US\$100/tonne CaO). However, where wall rock and groundwater loads accumulate as lake water evaporates, concentrations of toxic oxyanions that remain soluble in alkaline water, such as antimony, arsenic, and selenium may perpetually increase (Kempton et al., 1997a), and treatment costs can be many times higher.

3. Existing regulations for perpetual mine management

Our discussion of regulations follows from a review of current policies, laws, and guidance, primarily in the US and Canada, that relate directly to perpetual environmental management. It is not an exhaustive review of world law, but does illustrate the range in philosophies with useful exemplars.

Mines are regulated on both the federal and state levels in the US. Owners and operators are ultimately liable for the release of hazardous substances (e.g., under statutes such as the Comprehensive Environmental Response, Compensation and Liability Act [CERCLA or "Superfund"; US EPA, 1986a] and under common law). However, these laws generally fail to adequately protect public assets because remediation costs often greatly exceed the resources available to operators or regulators after the cessation of mining.

Several US government reports document the need for management of perpetual pollution problems, and the deficiencies in the current approaches. A 1997 US EPA report identified acid rock drainage as "the most serious environmental threat of current hardrock mining," noting that some mines "may require water treatment in perpetuity" (US EPA, 1997). Traditional closure activities (e.g., removing structures, reclaiming surfaces, etc.) are guaranteed by operator-funded bonds, and are, ideally, returned shortly after closure. In contrast, trust funds for long-term water treatment are permanent commitments of principal to fund perpetual treatment using after-inflation returns. The US National Research Council's review of US mining regulations, "Hardrock Mining on Federal Lands" (NRC, 1999), concluded that "there is inadequate consideration of protection of the reclaimed land from future adverse uses [or] of very long-term or perpetual site maintenance;" that "most land agencies do not require bonding for long-term or perpetual treatment of water at mine sites;" and that "if these costs are not assured, the public will eventually incur the costs of long-term water treatment." Even reports that postdate recent amendments to the mining regulations continue to identify shortcomings. A 2005 US Government Accountability Office report found that "financial assurances were not adequate to pay all estimated costs for required reclamation for 25 of the 48 operations," and that "cost estimates may be understated for about half of the remaining 23 operations" (GAO, 2005). The GAO recommendations include placing mine closure funds in a trust accounts that "accrue sufficient funds to be sustained in perpetuity." Based in part on concern over estimated total cleanup liability at US hardrock mines (US\$20 billion to US\$54 billion), the US EPA began the process in 2009 to establish federal financial assurance requirements for hardrock mining on all US lands, pursuant to section 108(b) of CERCLA (US EPA, 2009).

Several US laws seek to address contamination in a prospective manner. Examples include the Federal Clean Water Act (establishing drinking water standards for surface and groundwater and regulating point source discharges to surface water; US EPA, 1977), the Emergency Planning and Right to Know Act (requiring disclosures about hazardous substances; US EPA, 1986b), and the Safe Drinking Water Act (regulating certain discharges to groundwater and setting drinking water standards; US CFR, 1974; US EPA, 1996). Most specific in addressing long-term impacts is the National Environmental Policy Act (NEPA), which requires Environmental Impact Statements (EISs) for disturbances on public lands that include disclosure of "direct effects" and "indirect effects... later in time... but still reasonably foreseeable"; discussion of "the relation between local short-term use...and the maintenance and enhancement of... long-term productivity"; and consideration of how a project would "fulfill the responsibilities of each generation as trustee of the environment for succeeding generations" (CEQ, 1970).

Recent rules have begun to address post-closure requirements at mine sites. Regulations for mining on Bureau of Land Management (BLM) property addressed earlier criticisms (NRC, 1999), and now require, if necessary, "a trust fund or other funding mechanism available to BLM to ensure the continuation of long-term treatment to achieve water quality standards and for other long-term, post-mining maintenance requirements... for as long as the treatment and facilities are needed after mine closure'' (BLM, 2006a). (Draft regulations prohibited new mines that would require permanent water treatment, but BLM deleted that provision due to the difficulty of determining ''in advance when permanent treatment will be necessary'' and concern that it would have ''the unintended effect of encouraging prospective operators to claim that permanent treatment would not be necessary when, in fact, it would,'' BLM, 1999.) In the US State of Nevada, federal ''guiding principles for long-term (post-mining) trust documents'' require that trusts cover ''all anticipated post-closure costs,'' but explicitly requires that funds not be based on ''worst-case'' scenarios (BLM, 2005). These long-term funding mechanisms require operator estimates for the cost, timing, and duration of future expenditures, and government assessment of fund adequacy before mine closure and every 3 years after (BLM, 2006b).

Several US state laws locally restrict mines that will produce perpetual pollution. New Mexico and Michigan effectively prohibit mines that will require perpetual management (New Mexico, 2009; Michigan, 2004), and Wisconsin prohibits mining sulfide rock until a US or Canadian mine in acid-generating rock has been operated and closed for 10 years without causing ''pollution of groundwater or surface water from acid... or the release of heavy metals'' (Wisconsin, 1998).

The mining regulations in Saskatchewan, Canada, appear to have the most comprehensive planning for perpetual management, and suggest a belief that the government – not an individual mining company – is best suited to manage the risk of perpetual mine management. Mine operators are required to complete the province's environmental assessment process, create a decommissioning and reclamation plan, and then postfunds sufficient for complete decommissioning and reclamation in a form that is held by government (typically a letter of credit posted by a financial institution). After closure, the government can accept responsibility for land that ''requires long-term monitoring and... maintenance'' under the Institutional Control Program (ICP – a plan to track and manage waste after a project's closure [Saskatchewan, 2006]). The ICP requires operators to submit: (1) a detailed plan for long-term post-closure monitoring and maintenance for the site, and (2) ''a contribution to the Institutional Control Monitoring and Maintenance Fund (ICMMF) [that] must be of a value to generate revenue sufficient to pay those future costs in perpetuity'' (Saskatchewan, 2008). Net yields on perpetual funds are based on the difference between the return on government bonds and inflation, typically ~2% per year. This law requires that involved parties mutually agree to financial assumptions, but does not include risk management plans to limit costs and guarantee fund growth. Risk from management costs are reduced, however, by delaying acceptance into the ICP program until a mine has been closed and monitored for 10 years to identify water-quality trends, and by denying entry if water quality is trending worse (Cunningham, 2009). The government registry conducts the monitoring and maintenance, with funds ''managed by the province.'' To allay operator concerns over the security of financial allocations to specific sites, funds are held in commercial banks and ''legislated and stand alone from provincial revenue.'' This regulation explicitly identifies the value of unambiguous requirements to all stakeholders, noting that this ICP ''forms an integral part of the province's response to industry requirement for clarity in the investment climate and acceptance of safety and environmental responsibility of a sustainable mining industry to protect future generations.''

This Saskatchewan program is young, with only 6 sites accepted to date, none of which required active treatment to meet the surface water standards in receiving water. However, as many as 10 active projects are on track to enter the program in the next 5 years, which should provide experience with costing and managing more complex projects (Cunningham, 2009).

More globally, the International Finance Corporation's updated ''Environmental, Health and Safety Guidelines for Mining'' (IFC, 2007) addresses perpetual treatment only implicitly, requiring their collaborators to manage actual or potential ARD ''for as long as there is a need to maintain effluent quality to the levels required to protect the local environment, and, if necessary, into the decommissioning, closure, and post-closure phases of the mine.'' A World Bank working paper on financial surety for mine closure (the IFC is a member of the World Bank) recognizes that some sites will require ''long-term care and/or remedial action,'' and that these should have a separate fund that is ''self-perpetuating so that the regulatory authority is never left with a deficit'' (Sassoon, 2009). But this report also recognizes that there is ''considerable ambiguity surrounding the issue of the funding of long-term care of the site, or what time period the financial surety should cover after the rehabilitation work has been completed.''

4. A framework for perpetual mine management

Toward the development of a more consistent framework, we describe below the critical components for effectively planning perpetual management of today's mines. Two recent case studies are described in the supplementary data.

4.1. *Technical factors affecting post-closure management costs*

Cost estimates for active treatment of existing ARD flows are usually well constrained by physical ranges on concentration and flow (e.g., the actual water treatment costs at the Zortman-Landusky Mine in Montana between year 2000 and 2009 varied only by ~±13%, from US$734,000 to US$950,000/year; McCullough, 2005, and personal communication from McCullough in 2010).

In contrast, the cost estimates for perpetual post-closure mine water treatment have large uncertainty, particularly when required before mining has even begun. Some of the physical factors affecting actual post-closure costs include geographic scope and nature of the ultimate disturbance, reclamation effectiveness, the concentrations and volume of the effluent, climate variability, climate change, and the nature of effected resources. Reliance on model predictions greatly increases uncertainty, particularly in fracture-flow environments. Passive or semipassive technologies, such as permeable reactive barriers or carbohydrate addition, offer lower cost water treatments. But uncertainty in critical parameters, particularly system life, produce long-term cost estimates that range by factors of 2–8 (Martin et al., 2003), highlighting the need for more research into these technologies. More generally, future costs are uncertain, possibly reduced by technological innovations or increased by external factors (e.g., changes in energy costs or regulations). Standard engineering contingencies in reclamation costing, which involve more predictable costs such as earth moving, are thus inadequate for accommodating the large uncertainty in estimates of post-closure treatment costs that use predictive models. Given the long time period, it is also generally appropriate to assume government contracting costs, which are higher than costs if mining companies undertake the construction themselves. These uncertainties can be addressed by adding conservative contingency costs to scope, design, and construction estimates.

A diverse alliance of stakeholders has cause to resist the large financial assurance that adequately covers the large uncertainty in perpetual treatment. For operators, the additional expense complicates project financing; for politicians, operating mines bring jobs and tax revenues; and for insurers, litigation may be less expensive than funding treatment under conditions that were unforeseen when the original policies were created. A partial solution is commitment to periodic refinement of surety bonds using experience gained as the project proceeds (e.g., the US State of Montana requires that closure bond estimates be updated annually and reviewed comprehensively every 5 years; Montana, 2009).

4.2. *Investment and inflation assumptions affecting post-closure management costs*

When the onset of long-term management is delayed for decades (Kempton and Atkins, 2000), the estimate for the initial capital investment is extremely sensitive to the assumed rate of return, and cost forecasts can vary enormously. Estimates of net-present value for a perpetual water treatment fund at the Newmont Phoenix Project in Nevada, USA, ranged by a factor of 82 (US$408,000 by the BLM to US$33.5 million by the EPA), with the disparity caused by differences in discount rates (6.5% real by BLM and 2% real by EPA), pricing of post-closure components (e.g. lime treatment plant at US$2 million by BLM and US$6.7 million by EPA) and mark-ups for contingencies and third-party contracting (US EPA, 2002).

The real return rate on these funds must consider the estimated return on investment, inflation, taxes and investment expenses. A 2% ''risk-free'' net rate of return (i.e., after interest but excluding taxes or fees) is a good first estimate for fund growth (Davis, 2000). This is generally consistent with historic yield on US Treasury-backed Treasury Inflation-Protected Securities (TIPS), which provide a guaranteed rate of return over inflation (recent yields ~1–2%, though rates have been higher in the past), and with the net return of 1.4% estimated in the Saskatchewan Institutional Control Program using inflation and bond yields in 2007 (Saskatchewan, 2008). The BLM's long-term fund for the Barrick Gold, Inc. Betze Pit in Nevada, USA, grew from US$1 million in 1991 to ~US$2.2 million in 2009 (Laird, 2009) – a net return of ~5%, or ~2.5% net after inflation. The US Office of Management and Budget Circular A-94 provides annual estimates for long-term real (after inflation) and nominal discount rates for cost benefit analysis (but not public investments). These real interest rates in 2010 ranged from 0.9% (3-years) to 2.7% (30 years; OMB, 2009).

Other investment options include: (1) federal, state or municipal securities (including tax-free instruments); (2) insurance instruments such as Guaranteed Investment Contracts (GICs) or annuities; (3) private bonds or bond funds; and (4) equities (stocks). Each of these instruments offers potentially higher rates of return but at higher risk, and they usually do not include express inflation protection. US equities have generally produced higher inflation-adjusted returns over a 30-year period than other instruments, but can lose real and nominal value in many years. In addition, the timing of a severe market failure (such as occurred in 2008) might coincide with the time that funds are needed to implement the post-closure remedy. These periods of economic recession can persist for several years, consuming principal and leaving projects severely underfunded. Conversely, low returns on secure government bonds could leave projects underfunded. Modern portfolio theory and the prudent investor rule can be applied to create a mix of investments, based on project needs, timing and risk tolerance; however, that approach is usually not acceptable for funds owned by the government. Inflation is also a significant risk, particularly because inflation is autocorrelated in time and the effect compounds. While inflation in the United States has averaged ~4% since 1945 (and 2% more recently), a period of high inflation could severely increase the future maintenance costs beyond predictions based on average inflation. One approach to overcoming these uncertainties is to permit the operator to assume a higher rate of return (and thus a lower initial capitalization value), but with a contingency (also guaranteed by appropriate financial backing) to augment the fund during the investment period if that higher investment return is not met. A 2009 World Bank working paper describes the various surety mechanisms applied to mining projects, and summarizes regulations and tax implications for mine closure surety in 8 regions (Ontario, Canada; Nevada, USA; Queensland, Australia; Botswana; Ghana; Papua New Guinea; South Africa; Sweden; and European Union) (Sassoon, 2009).

Finally, fees and taxes can dramatically affected returns. Fees are nominal for larger investments, but taxes on funds can significantly reduce growth if the trust is obligated to pay the taxes (taxes can sometimes be passed through to the grantor of the trust, but problems can arise if the grantor is unable to pay those expenses). US tax law includes a ''468B Settlement Trust'' provision, which allows the grantor to deduct the initial deposit and allows the fund to grow tax-free, provided that certain conditions are met in creating the trust (including that the grantor surrenders claims on the funds; IRS, 2006). Superimposed on the tax implications is the stakeholders' decision as to whether funds are paid up front, or in stages while the mine is being developed.

4.3. *Robust legal structure*

Perpetual post-closure mine management requires a robust and durable legal structure to ensure that the funds are invested, managed and spent responsibly over decades or centuries. Each case will require project tracking over time and a structure of checks and balances to discourage misappropriation of funds. For example, with a private agency as trustee and a governmental agency as the beneficiary, the trustee owes a fiduciary duty to the beneficiary, and the beneficiary would monitor the trustee decisions. (In practice, government agencies are not generally set up to monitor those activities and manage finances, so additional care is needed to ensure long-term stewardship.) The cost of the structure must be funded as part of the trust. Other options for the decision-maker include a regulatory or mining agency, a local government, a state, a private trustee, university, mining company, or nonprofit environmental land trust or similar organization. Alternatively, legislation can be created to facilitate these structures, such as the approach used in Saskatchewan, Canada, or the US Nuclear Decommissioning Trust (Section 4.5). Finally, application of an adaptive management philosophy is attractive, allowing continued evaluation of developing technologies and, ideally, eventually eliminating the need for long-term management.

4.4. *Risk management tools*

Uncertainties associated with long-term mine management include increasing water flow, changing water quality, annual changes in precipitation, site failures, force majeure events (e.g., slope failures, earthquakes, fires), and changes in labor and material costs (e.g., electricity, lime). To this are added legal liability risks, such as changing discharge targets or unforeseen litigation. Environmental insurance tools that address these risks include cost-cap insurance (which pays for cost overruns), pollution legal liability insurance (which can protect the trust from lawsuits by third parties), and finite risk policies (which combine financial management, payment-timing risk, cost-cap insurance, and pollution legal liability insurance). While useful, particularly before a project is fully capitalized, to manage risk, they have important limitations, particularly for projects extending beyond 10 years. Further, these products are relatively new compared to most types of insurance, are less regulated than traditional insurance products, and are currently in a state of flux due to the financial markets' turmoil. Their continued existence over the next several decades is uncertain.

4.5. *Identifying durable institutions*

A search for existing institutions capable of providing long-term mine management is discouraging. Most corporations have existed far fewer than 100 years, and few modern governments have operated for more than 200 years. Many long-term government programs, like US social security (itself less than a century old), are currently underfunded, and highlight the difficulties of setting aside money today for future liabilities. Institutions of higher education and religion have proven more durable. The Universities of Bologna, Paris, and Oxford have each operated continuously since their origination in the 11th and 12th centuries; and the Catholic Church has maintained its central institutional authority since at least the 5th century (Bokenkotter, 2004). These venerable institutions are tempting models for stewards of perpetual management planning as they have demonstrated flexibility while staying on mission. But the range of stakeholders and management structures in churches and universities will be difficult to recreate for institutions designed to manage mine pollution.

The US Nuclear Decommissioning Trusts may be the most apt analog. These require the nuclear power industry to fund trusts "to provide greater assurance that an adequate amount of decommissioning funds will be available" (NRC, 2003). Given the long time periods required, some form of government stewardship will likely be required, albeit structured to ensure that funds are invested and available for their intended purpose, and that appropriate decisions are made with respect to their use.

5. Technical options for perpetual stabilization

Ongoing research has identified two options to perpetually stabilize subaerial sulfide mine waste. In semiarid to temperate climates, an "umbrella design," constructed using sloped layers of fine material within coarser mine waste, has been proposed as a method to permanently divert unsaturated water flow around net-acid-generating rock within waste facilities (Barbour, 2000; Wilson et al., 2000a). Alternatively, layers that blend tailing and waste rock (~1/3 tailings and 2/3 waste rock) produces a material with sheer strength comparable to waste rock alone but that can retain enough moisture to impede oxygen flow (Wilson et al., 2000b, 2006). Both of these technologies still need full scale testing to refine design costs and demonstrate long-term effectiveness.

6. Guidance for identifying and planning for perpetual mine management

Technical studies at existing and proposed mines point clearly to a short list of critical parameters that, if present, identify mines as potential candidates for perpetual management: (1) sulfide minerals in rock stored above the water table. (Excess neutralization greatly reduces concentration of sulfate and most metals in effluent, but does not eliminate potential for perpetual impacts.) (2) Potential for release of metals with high toxicity to site-specific receptors (e.g., arsenic, which is a human carcinogen, released to potential drinking water; or mercury, which can bioconcentrate). (3) Tailings impoundments, which can leach solutes and generally require perpetual, if infrequent, dam management. (4) "Terminal" (i.e., zero outflow) pit lakes or wetlands, where perpetually increasing solute concentrations can cause ecological risk. Mines with any of these conditions place a burden on the proponent to provide quantitative analysis of perpetual effects on water quality.

Finally, responsible stewardship of mining projects that anticipate long-term release of contaminants will require a detailed post-closure management plan that addresses explicitly the challenges in guaranteeing perpetual active treatment. The collective experience from analogous projects suggests that these perpetual management plans consider, at a minimum, an engineering cost estimate for implementing treatment, a financial plan to manage growth of funds for the long-term, a robust legal structure to ensure appropriate financial and legal decision-making, and a risk management vehicle to reduce uncertainty inherent in maintaining environmental compliance beyond the duration of most existing human institutions. In the spirit of adaptive management, closure planning during and after mine operation would benefit from allocating some funds to field-scale tests that evaluate the feasibility of promising perpetual stabilization technologies.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.envsci.2010.06.001.

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