Mine Tailing Waste in Arid and Semi-Arid Environments: A Particulate Matter Requiring Stakeholder Cooperation

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INTRODUCTION

Mining has been a principal global industry for over 150 years. Using copper as an example, the average car contains almost a mile of copper wire, and in total ranges from 44 pounds in small cars to 99 pounds in luxury and hybrid vehicles. In 2009 Chile produced 5,390 thousand metric tons (TMT) of copper, followed by Peru and the US at 1,275 and 1,180 TMT, respectively[11]. The US copper mining industry alone employs over 8000 people, and in 2010, a pound of copper averaged $3.25 per pound. Copper as well as other precious metals continue to provide society with many essential products as well as luxuries, yet the mining legacy is tarnished by the massive amount of toxic metal-containing waste rock and tailings that have been deposited at the soil surface of our world's landscapes. This is a conundrum where on the one hand the mining industry provides thousands of jobs, advances technology, and is a major global economic player. On the other hand the industry represents a set of environmental scars that may never heal and mine tailings wastes are a source for eolian and water-borne dispersion of particulates with potential health impacts due to their small size and, in some cases, associated toxic metals.

BACKGROUND

Mine tailings are large piles of crushed rock that are left over after the metals of interest like lead, zinc, copper, silver, gold and others, have been extracted from the mineral rocks that contained them. The mineral separation process in older mining or legacy operations was only partially efficient. As a result, after the crushing and grinding processes, some of the metal-containing minerals were left behind associated with tailings particles. Spread of metal toxicants in association with tailings particles, through a combination of wind dispersion and water erosion, has been shown to result in measurable elevated levels in wildlife and humans even significant distances from the tailings site[1,3]. In contrast, modern tailings generally have low metal content due to improved extraction processes but the size of the tailings particles is, on average, smaller. These small size particles form aerosols more easily and even though they are not associated with metals, these small particulates may impact human health especially in those with pre-existing respiratory conditions.

Particulate (dust) emissions from mine tailings is especially important in arid and semi-arid areas of the world where, due to dry conditions, wind dispersion suspends the fine tailings particles into the atmosphere and can disperse them throughout the environment as aerosols. Such tailings are a major source of dust that contaminates nearby communities and environmentally sensitive areas[3,6,7]. These problems can persist for decades because these sites have low pH and lack normal levels of soil nutrients. As a result these sites do not develop normal soil structure or support the establishment of a plant cover. Exacerbating the problem is population growth, which has led to increasing proximity of some mine sites to developing communities. Thus, there are both human and ecological health impacts that occur from exposure to dust that is blown from these sites. Mitigation of these impacts will involve reducing eolian and water-borne erosion processes. However, traditional mining practices, barriers to change, insufficient resources to address clean-up challenges, and contradictory regulation has delayed adequate consideration of this 21st century remediation challenge.

Mine tailings disposal sites from either inactive or abandoned mine sites are prevalent in arid and semiarid regions throughout the world, including western North America, South America, Spain, India, South Africa, and Australia[4,5]. The global impact of mine tailings disposal sites is enormous. There are approximately 500,000 abandoned hard rock mines in the United States.[8] Mexico alone is affected by 27.1 million hectares of mining activity[2,4,6]. Unreclaimed mining sites generally remain unvegetated for tens to hundreds of years, and as a result exposed tailings can spread over large land areas via eolian dispersion and water erosion[1,4,8].

SOLUTIONS FOR THE FUTURE

In June 2008, the University of Arizona Superfund Research Program (UA SRP) hosted a Workshop entitled: "Mine Tailings Stabilization in Arid and Semi-Arid Environments: Assessment, Problems, and Solutions" that was sponsored by the National Institute of Environmental Health Sciences. This Workshop brought together 48 experts from Australia, Mexico, South Africa, Tohono O'odham Nation and the USA, split between academia, consulting firms, mining industry and regulators. One of the major findings of the Workshop was that the first step in addressing the overarching challenge of developing workable solutions needs to be in **fostering communication between industry, regulators, the community and academia to reach a consensus on how to protect human health and ecological function.** By including members of the mining industry, regulatory agencies, academia, and the community the Workshop took a major step toward advancing the inclusion of all parties involved in the assessment, problems and solutions surrounding mine tailings. To this end, a desirable outcome would be to build an international web of dedicated experts from various sectors of society to work together to share knowledge, overcome barriers to change, design for closure, and in turn influence environmental regulation to solve the enormous challenges mine tailing waste has presented to our communities. The remainder of this document is divided into three parts to capture the essential actions necessary to mitigate the human and ecological health risks posed by mine tailing waste in arid and semi-arid environments.

PART I: Aligning Efforts to Solve Future Research Needs

Challenge:	How do we work together to solve the research needs of the future?
Solution:	Recognize the research priorities of industry, regulatory agencies, academia and the community, and move forward by designing research agendas and teams of experts to tackle the research challenges identified below.

To combat all research needs and challenges posed by mine waste landforms, there needs to be effective collaboration between industry, regulatory agencies, engineers, agronomists, microbiologists, ecologists, and others. Discussion platforms need to be designed and maintained to allow for the cross-pollination of disciplines and ideas to creatively solve the issues stated above, and the research needs that will be mentioned below. To move forward, and solve the research needs of the future, the priorities of each stakeholder group needs to clearly stated, and understood by the rest of the stakeholders at the table. To illustrate the differences in priorities of stakeholders, a survey was distributed to the 18 remaining participants at the end of the Workshop. The participants were given a list of 14 research areas that were identified as important during Workshop discussions (see Appendix), and were the asked to "rank these research areas in importance". Participants self-identified themselves by as either: 1) Industry/Consulting Firms, 2) Regulators, or 3) Academia.

Below are the research area rankings regardless of stakeholder affiliation (**Table 1**). The number one research area was "Particle emissions (dust)-measurement and health effects". Closely following were: "How can we encourage design for closure?", "Optimizing and evaluating phytostabilization", "What is the major cause of toxicity in tailings-humans vs. ecosystem" and "Development of financial and environmental success criteria". These results demonstrate that as a whole, Workshop participants were particularly interested in particle emissions from tailings and their health effects, toxicity, and designing for closure – possibly indicating the future trends for research needs and inquiry related to mine tailings.

Table 1. Research Areas Ranked by Workshop Participants as a Whole Regardless of Stakeholder Affiliation

Research Area
1. Particle emissions (dust)-measurement and health effects
2. How can we encourage design for closure?
3. Optimizing and evaluating phytostabilization
4. What is the major cause of toxicity in tailings-humans vs. ecosystem
5. Development of financial and environmental success criteria
6. What is the best disposal technology?
7. Phytostabilization vs. capping
8. Optimizing and evaluating capping
9. Sequestration of contaminants within tailings
10. Development of educational tools for people exposed to tailings
11. Development of in plant metal stabilization
12a. Development of risk maps that are site specific
12b. Development of whole life economic assessment models
12c. How can you get around using the net present value approach to determine how tailings are deposited?

The responses were then divided into the three stakeholder groups: 1) Industry/Consulting Firms, 2) Regulators, and 3) Academia, and their top research areas tabulated (**Table 2**). "How can we encourage design for closure?" was the top response from Industry/Consulting Firms. The industry is increasingly aware that this is an important topic for two reasons. The first is that siting new mines is becoming more difficult and an ever more important part of the process, in both developing and industrialized countries, is addressing how the mine will be closed and the possible human and environmental impacts associated with the operation and closure of the mine. The second is that as large mining companies acquire or take over existing operating mining properties, the acquisition often brings with it legacy mining wastes that the company must deal with.

Table 2. Top Research Areas Identified by Three Different Workshop Stakeholder Groups

Stakeholder	Top 5 Research Areas
Industry/ Consulting Firms (N=7)	1. How can we encourage design for closure?
	2. Optimizing and evaluating phytostabilization
	3. Sequestration of contaminants within tailings
	4. Development of risk maps that are site specific
	5. Development of in plant metal stabilization

Stakeholder	Top 2 Research Areas
Regulators (N=4)	1. Optimizing and evaluating capping
	2. How can we encourage design for closure?
	2. What is the major cause of toxicity in tailings-humans vs. ecosystem?
	2. Particle emissions (dust)-measurement and health effects
	2. What is the best disposal technology (slurry vs. paste) (cost vs. environmental impact)?
	2. Phytostabilization vs. capping
	2. Development of financial and environmental success criteria
	2. Sequestration of contaminants within tailings

Stakeholder	Top 5 Research Areas
Academia (N=7)	1. Particle emissions (dust)-measurement and health effects
	2. Development of educational tools for people exposed to tailings
	3. What is the major cause of toxicity in tailings-humans vs. ecosystem?
	4. Optimizing and evaluating phytostabilization
	5. What is the best disposal technology (slurry vs. paste) (cost vs. environmental impact)?

Optimizing and evaluating capping strategies was the research area that stood out for the regulators. Currently, capping seems to be the most cost-effective remediation strategy available, but many questions still remain about its long-term effectiveness and cost-benefit analysis. Regulators also showed concern for a wide distribution of additional research needs, the 7 research areas listed below the top category received the same number of rankings, and a prioritized order could not be determined. This likely reflects the fact that regulators have to take into consideration numerous factors, which include human and environmental health, in their decisions regarding evaluation, management, and eventual remediation of mine waste sites.

For academia, "Particle emissions (dust)-measurement and health effects" was the top research concern. This group noted that very little data exist on dust emissions from tailings in arid and semi-arid environments. The lack of these data currently makes it impossible to quantify risk associated with living in proximity to mine tailings sites. It is interesting that while

"Particle emissions (dust)-measurement and health effects" was important for both the Regulator and Academia stakeholder groups, it was not listed among the top 5 research areas for the Industry/Consulting Firms stakeholder group. This is a good illustration of how the different stakeholder groups are interested in very different questions regarding mining wastes.

These initial results provide evidence that all stakeholders share some goals in common, particularly the goal of developing remediation technologies that will allow the mining industry to operate in a more environmentally sustainable manner. Thus, regardless of stakeholder affiliation, there are similar research interests that can be identified; meaning we can all work together to move forward. This finding leads to one recommendation of this workshop: that efforts need to be invested to overcome the barriers to collaboration between all stakeholder groups. Such collaborations will allow optimization of resources that go into dealing with mine tailings waste because they will identify and focus efforts on issues important to all stakeholders. Such issues are likely to have a larger overall impact on promoting environmentally sustainable mining than issues of relevance to only a single stakeholder group.

Recommendation 1: Invest effort into overcoming the barriers to collaboration between all stakeholder groups

Part II: Working Together to Dissolve Barriers to Change

Challenge:	How to foster communication between industry, regulators, community and academics to ultimately reach a consensus on how to protect human health and ecological function?
Solution:	All stakeholders must be represented equally, operate transparently, and share knowledge. The existing barriers to change must be dissolved.

Perspectives, examples and case studies from around the world were presented at the Workshop, and as alluded to in Part 1, a common theme that emerged beyond the basic science was the need for communication beyond discipline and affiliation. At the end of the Workshop participants felt it ended too early, and that "we were just getting started". The Workshop itself served as a model for how to overcome barriers to change by having all stakeholders share their common challenges and insights while sitting equally at the discussion table regardless of affiliation. Participants treated each other with respect and actively listened to one another. This behavior generated trust between the participants, and demonstrated the equal importance each stakeholder has and brings to the table. Ultimately, to overcome the barriers to change and implement new technologies, all stakeholders must realize that mine tailings waste in arid and semi-arid environments is a multi-stakeholder problem and requires a multi-stakeholder solution. The challenges and barriers posed by mine tailings are site specific, and the discussion making process tend to be local. To degrade barriers to change all stakeholders needs and strengths must be captured.

Overcoming barriers to change requires effective communication. The Workshop identified several communication tools that already exist which could be used more effectively to facilitate the transfer of knowledge from one stakeholder group to another. Thus, the second recommendation of the Workshop was to utilize and contribute to programs that facilitate communication like the Interstate Technology & Regulatory Council (http://www.itrcweb.org/) and the Republic of South Africa's Sustainable Development Through Mining Program (http://www.sdmining.co.za/) by developing resource handbooks and case studies for others to use.

Recommendation 2: Utilize and contribute to existing programs like the Interstate Technology & Regulatory Council (ITRC; http://www.itrcweb.org/) and the Republic of South Africa's Sustainable Development Through Mining Program (http://www.sdmining.co.za/) by developing resource handbooks and case studies for others to use.

Dissolving Barriers to Change: Industry

In the mining industry, existing barriers are due to resistance to unproven or green technologies, and overall inflexibility due to ownership and company mind-sets. To dissolve barriers, industry needs to be willing to test and employ new technologies and to change traditional protocols, in other words, do what it takes to reduce the dispersion of their waste. Industry is driven by resource economics like commodity price, cost and shared value. Representatives from industry highlighted that corporate policy at times can contradict and conflict with the reality of specific site conditions and challenges. Policies sometimes do not meet the needs of a site's disposal and reclamation issues. Overall, mining companies are institutionalized, and are incorporated into our structured economy where there is a shared market value attributed to the commodity they provide society. These highly formalized systems tend to lack flexibility due to traditional practices and lack of incentive unless and until profit margin is impacted.

Dissolving Barriers to Change: Regulatory Agencies

Local, state and federal regulatory agencies have demonstrated that they are fundamentally risk adverse. Barriers to change that have formed within regulatory agencies are rooted in the this risk adverse nature, politically-driven goals, creative interpretation of regulations, and most importantly, the lack of power to create financial incentives to encourage improved performance by mining companies. To expand on risk, at times, the regulatory sector can set technically unachievable environmental standards due to lack of communication with industry and the availability of novel technologies. In cases where environmental regulations put human and/or environmental health before economic gain, these regulations need to be designed in collaboration with all stakeholders with appropriate incentives to achieve regulatory goals. Regulatory agencies need to lead this venture, eliminate special interests and set the pace to protect our environment and public health.

In other cases, regulatory guidance is exceedingly vague making it difficult to interpret and enforce. As one example, the Arizona State Legislature's Title 27: Minerals, Oil and Gas, Chapter 5: Mine Land Reclamation Article 4: Mine Unit Reclamation plan, under the "submission and contents of reclamation plan" (27-971), guidelines are given for what an owner or operator should include in a proposed reclamation plan. It states that a proposed reclamation plan shall include: existing and proposed final topography, measures that will be taken to address erosion control and stability and measures that will be taken to address revegetation. Yet it does not provide a set of metrics for the State Mine Inspector to use to quantitatively evaluate the reclamation plan. Additionally, in reference to tailings, waste dumps, abandoned mines and/or inactive mines, the legislation discusses preventing persons from entering the area; yet it does not refer to preventing eolian dispersion of the waste off of the site. Such guidelines can be interpreted in a wide variety of ways depending on the stakeholder that reads them.

Dissolving Barriers to Change: Academia

Academia is an educational and research resource and should be a politically neutral entity. Too often, academic professionals get caught up in the details of developing new research technologies and do not effectively communicate the existence of these technologies to regulatory or industry stakeholders. Also, too often academics invent a better "mousetrap" but the trap is prohibitively expensive. Another issue is that implementation of new technologies requires testing, first at the bench-scale and then in the field. Too often it is difficult to find industry partners that support field tests sometimes because of sensitivities that academic researchers might find something at the field site that is out of compliance or might make policy recommendations that would affect profit margins.

Dissolving Barriers to Change: Society

The general public and community members living near mining sites have limited access to information pertaining to mining waste and clean up technologies, and this poses a significant barrier to change. The mine typically employs the communities surrounding mining operations. Creating digestible and appropriate informational materials for the community, and providing them with a secure venue to participate in the decision-making process can dissolve the barriers to change. Specifically, in the US and Mexico, community members employed by the mine or family members of miners are hesitant to advocate for change due to fear of losing their job, and become voiceless in the decision-making process. As an example, mining companies sometimes support and fund community projects and provide community resources, but often this is done without incorporating the surrounding community in the decision-making process. It is important for communities to be part of the mine's sustainability planning. It was concluded that the micro-societies that form near mining sites are not barriers to change, but are essentially voiceless in the process due to the lack of effort from the mining company to incorporate them into the decision-making process, inadequate access to educational resources, corporate loyalties, and desire to avoid conflict.

Recommendation 3: In developing multi-stakeholder partnerships recognize that 1) industry needs more flexibility, 2) regulators need to develop clear policy guidelines based on reasonable remediation goals, and 3) academia needs to effectively and neutrally transmit information on new remediation technologies and their impact on human and environmental health. Together, these three stakeholders have the responsibility to effectively communicate risk to communities that neighbor mine waste sites.

Recommendation 4: This Workshop comprised three of the four stakeholders involved in mining; Industry/consulting, regulators, and academia. It did not include representatives from communities that neighbor mine tailings sites, but clearly dissolving barriers to change requires community inputs.

Part III: Workshop Highlights and Summaries

1. Designing for Closure

Current practices, or those used by closed mines have clearly demonstrated that mine tailing failures are due to landform slope (topography), lack of runoff management (no surface cover), inappropriate selection or placement of materials, and overall geographic characteristics of the mine tailings landform. These lessons of the past are the foundation for development of future mining practices. Mines must create an integrated landform design that includes the current and future land use of the land, and plan for closure. The design must consider and address the current challenges being faced by the mining industry today including: 1) controlling rainfall erosion; 2) minimizing fugitive dust emissions, 3) reducing water and oxygen infiltration in the tailings; and 4) creating a landform that is aesthetically acceptable, blending into the existing landscape. The diagram below shows how baseline data feeds into the design of the tailing impoundment, which overtime and constant monitoring will inform construction, deposition,

Challenge: How can we reduce eolian dispersion and water erosion of mine tailing waste from currently operating and future mines to confidently protect human and ecological health?

Solution: The mining industry must design for closure by having an integrated landform design procedure in place that plans for the land use during and beyond the life of the mine.

Workshop Presentations:

- *TSF landform design*
- *Mine Tailings Slope Stabilization Issues*

Workshop Contacts:

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Martin Rust, Rust Geotechnical Consultants
Michelle Theron, Rust Geotechnical Consultants

decommissioning and closure (**Figure 1**). The tailing impoundment configuration must consider slope length, angle, profile, and hydraulic roughness. It is crucial to be realistic in the design timeline and all anticipated outcomes must be considered. Planning for the appropriate land use beyond the life of the mine requires stakeholder communication, a defined closing criterion, flexibility pertaining to land use changes over time [short and long term], and the potential use of the landform in context of its surroundings.

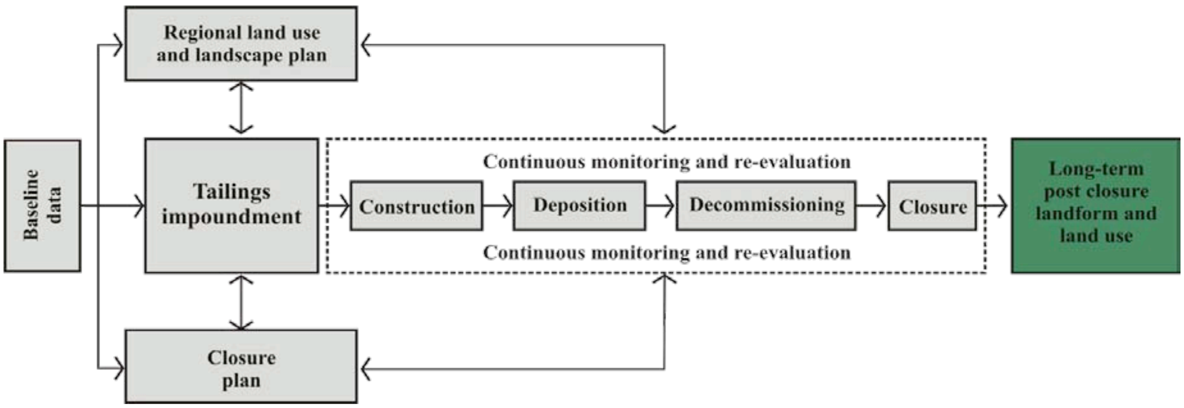

Figure 1. Integrating landform design with land use. Diagram by Brian Rademeyer, 2008.

These issues can be consolidated and understood in the context of the sphere of influence. The sphere of influence is visualized in **Figure 2**, and has defined areas of influence for water and air quality, as well as zones to delineate visual recognition, detection and awareness of a tailings impoundment. The sphere of influence considers visual aesthetics, anticipated movement of mine tailings in the form of slurry flow, surficial erosion, fugitive dust emissions, sedimentation, and proximity to sensitive communities and environments. A sphere of influence design requires and integration of environmental and engineering aspects to characterize and understand the constraints, requirements and limitations of the site to then determine, set and meet environmental standards. A successful sphere of influence design also requires stakeholder cooperation and

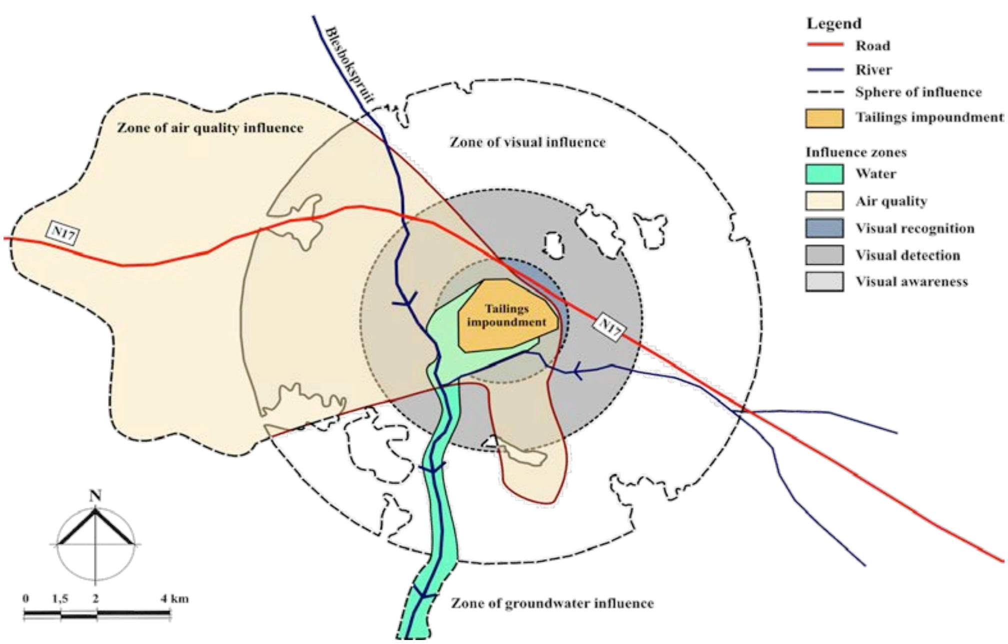

Figure 2. Existing and future use within sphere of influence. Diagram by Brian Rademeyer, 2008.

communication. Recent advances in creating a sphere of influence include quantifying visual impacts, modeling surficial erosion and field trials at actual mining sites.

2. Eolian Dispersion of Mine Tailings

Challenge:	How to mitigate the spread of mine tailings via wind and reduce human and ecological health impacts?
Solution:	Install dust collection instruments at mine tailing sites to determine particle number distribution, particle amounts and physiochemical characteristics of the dust moving off site. Use this knowledge to further understand the relationship between particles in the air, what is inhaled, and its human and ecological health effect.
Workshop Presentation:	• *Eolian Dispersion of Mine Tailings* (hyperlink ppt)
Workshop Contact:	Eric Betterton, The University of Arizona, USA

Dust is a function of weather and soil parameters such as crusting, management, vegetation, moisture, aggregate stability, size distribution and surface roughness. The modeling of wind-borne dust is challenging due to the various parameters listed above. Dust collection technologies are improving and are allowing for more specific information to be collected. A Scanning Mobility Particle Sizer Spectrometer can determine the particle number distribution and count the number of particles, and a Micro-Orifice Uniform Deposit Impactor (MOUDI) can allow physiochemical characterization of dust in different size fractions. These instruments are currently being used at several mine tailing waste sites in Arizona to determine eolian dispersion of lead, arsenic, cadmium, and chromium along with particle mass size. This information will then help human health and ecological risk assessors to determine environmental exposure. For example, health effects and toxicity can vary with particle size, and in general, particles greater than 10 um in diameter (PM10) impact the back of the throat and are swallowed, but particles smaller than PM10 are breathed into and can accumulate in the lungs.

3. Water-borne Dispersion of Mine Tailing Waste

Challenge:	How can we prevent mine tailing containment failures?
Solution:	Monitor the water cycle of mine tailing containment sites, and be aware of the mine tailing waste containment's operational water balance.
Workshop Presentation:	• *Tailings deposition strategies, water balance, and liners*
Workshop Contact:	David J. Williams, University of Queensland

Most tailings "failures" are due to poor water management, which in turn, leads to containment wall failures, acidity of tailings, high salinity, radon generation, seepage through tailing walls causing death to surrounding trees, and seepage to groundwater. Stabilization should aim to minimize wall seepage and risk to groundwater, by minimizing surface ponding, constructing an effective low net percolation cover, evaporation, and/or treatment. Drainage systems can be helpful for moving/recovering seepage. Unfortunately, drainage systems become less effective over time due to tailing consolidation, which limits the hydraulic conductivity to the drains. Further, as the depth of tailings containment increases, so does the number of flow paths. In response, geomembrane liners should be used in conjunction with drainage designs. This should be mandatory practice, especially if the tailings are close to human habitation.

Arid Climate Operational Water Balance

$TW + R + W_w = E_n + S + E_v$, where

TW	=	Tailings water input
R	=	Rainfall
W_w	=	Net waste water
E_n	=	Entrained water
S	=	Foundation seepage
E_v	=	Surface evaporation

Many mine tailing containment failures can be prevented through planning for mine closure during mining development, ongoing monitoring by understanding the mine tailing's water balance and maintenance. Overall, good tailings management practices should aim to:

- Exclude clean runoff
- Discharge thickened tailings
- Deposit in thin layers
- Cycle between lifts and cells
- Maintain a small decant pond
- Separate evaporation ponds

4. Ecosystem Consequences from Mine Tailing Waste

Challenge:	How do ecosystems function when they are under chronic stress from metal contamination?
Solution:	Determine the extent of damage by measuring ecosystem functions such as microbial respiration, soil microbial biomass and microbial community structure.
Workshop Presentation:	• Predicting and Quantifying Natural Resource Damage in Chronically Stressed Ecosystems
Workshop Contact:	James Gannon, University of Montana, USA

Ecosystem resilience is a function of many factors, and in response, the U.S. Department of Interior has developed a Natural Resource Damage Assessment and Restoration Program with the mission to "restore natural resources injured as a result of oil spills or hazardous substance releases into the environment…". Damage assessments are the first step toward resource restoration and, as described by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), the establishment of damage to natural resources requires documentation of the contaminants and demonstration of "change in the biotic properties". Damage to geologic resources must result in: 1) Concentrations of substances sufficient to impede soil microbial respiration to an extent that plant and microbial growth is inhibited; and 2) Concentrations in the soil of substances is sufficient to inhibit carbon mineralization and nutrient cycles resulting from a reduction in soil microbial populations. In order to assess the extent of damage, ecosystems functions like microbial respiration, soil microbial biomass, microbial community structure, and nutrient cycling must be determined.

5. Human Health Consequences from Mine Tailing Waste

Challenge:	How should a human health risk assessment be conducted in a mining community?
Solution:	Utilize a holistic risk assessment approach allowing a multi-disciplinary team of researchers to work together at every step of the risk assessment process.
Workshop Presentation:	• *Human Health Consequences*
Workshop Contact:	Fernando Díaz-Barriga Martínez, Universidad Autónoma de San Luís Potosí

The health concerns posed by mine tailings are complex and require a more **holistic form of the traditional human health assessment methodology**. Researchers from various disciplines need to work closely to connect the dots between the risk assessment factors shown in **Table 3**:

Table 3. Important risk assessment factors for mining waste sites

- History of the land from a social and historical use perspective
- Full understanding of the metals of concern
- Exposure pathways
- Exposure routes
- Potential health effects
- Impact on wildlife
- Community vulnerability
- A proactive health intervention plan using a cultural model of risk communication to mitigate exposure, and overcome the misconceptions of risk

At the Workshop, several case studies were presented where poverty-stricken communities are living immediately adjacent to, or on top of mine tailing waste sites, allowing vulnerable members of the population like children and pregnant woman be exposed to elevated arsenic and lead levels found in mine tailings. Children absorb 5 times the amount of lead as adults, and are particularly at risk because they play in soil and dust. Compounding the problem further, aggregation occurs where the same contaminant is absorbed by different means such as air, water, soil and contaminated food, and it is difficult to separate soil from dust ingestion of contaminants. Vulnerable populations are exposed to variety of heavy metals and metalloids simultaneously - both simple and complex mixtures, and the toxicity of the metal mixtures are poorly understood. Although, respiratory and cancer incidence appears to be low, neuropsychological developmental issues were found in Mexican children living in these communities due their exposure. Further, excessive metal exposure has been shown to be associated with damage to DNA in children and rats, and accumulation in various organs of laboratory rats.

6. Interventions to Protect Human Health

Challenge:	Poverty-stricken communities are living immediately adjacent to, or on top of mine tailing waste sites, and are culturally and historically connected to the land, how can their exposure to mine tailing waste be reduced?
Solution:	Immediately make site modifications to reduce physical exposures to surrounding mine tailings and implement an environmental education program using a cultural model of risk communication.
Workshop Presentations:	• *Historic Mining Sites in the Mexican Altiplane: A Case of Study* • *Nacozari Mine Tailings*
Workshop Contacts:	Israel Razo Soto, Universidad Autónoma de San Luís Potosí, Mexico Diana Meza Figueroa, Universidad de Sonora, Mexico

A proactive intervention plan needs to begin immediately at sites where neighboring populations are at high risk. The immediate site issues that need to be addressed to protect neighboring communities include: reducing water erosion and eolian dispersion of mine tailings and the physical stabilization of the mine tailings. Identifying the source of pollution, dispersion routes from abandoned or active mining sites, along with soil sampling can provide the necessary information to map the extent of soil pollution in a given area. These soil pollution maps, layered with the extent of bioavailability of metals such as lead and arsenic, in turn, provided risk assessors and decision makers with a map of risk for a given mining community. Risk maps provide a spatial variation of risk allowing the estimation of risk to be more comprehensible. Additionally, these maps can highlight areas for intervention, identify areas that need further research and characterization, and spot areas not suitable for urbanization.

The risk perception of mine tailings is very low in populations that have always been exposed to mineral processing. Low-income populations may have no option but to live close to tailings, and may be further exposed by their involvement in the crude processing of tailings to recover additional metals. It is for these reasons, that a proactive health intervention plan using a cultural model of risk communication to mitigate exposure, and overcome the misconceptions of risk is mandatory to protect human health. Educational programs were very effective in reducing children's exposure to the lead found in neighboring mine tailings. Most educational intervention plans begin with a series of ongoing community meetings to create a platform that allows for a safe 2-way dialogue. This dialogue will foster trust and community commitment to an agreed upon environmental education project.

7. Emerging Techniques To Facilitate Stabilization And Reclamation Of Mine Tailings

Challenge: How can we stabilize, control mine tailings, and reclaim the surrounding environments?

Solution: Innovated technologies such as: Solidification, Phytostabilization and Evapotranspiration Biocovers should be utilized, and the success of the selected technology should be determined by the measured decrease in metal bioavailability.

Workshop Presentations:

- *Solidification*
- *Plant Growth Promoting Bacteria Suitable for the Phytostabilization of Mine Tailings*
- *Phytostabilization in Arid/Semi-Arid Environments: Re-examining the Challenges*
- *Capping (ET caps)*
- *Testing for Success - Tools to Evaluate In Situ Remedial Options*

Workshop Contacts:

David Bentel, SRK, Geotechnics, Austraila
Raina Maier, The University of Arizona, USA
Christopher Grandlic, USA
Monica Mendez, University of Texas, USA
Isabel Weiersbye, University of the Witwatersrand, South Africa
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As previously stated, characteristics of mine tailing waste include elevated levels of metals, acidity, low nutrient levels, minimal soil structure and a decreased number of microbial communities. These characteristics pose a complex remediation challenge. There is a need for engineers and scientists to combine forces, the engineers providing temporary physical stabilization, and the scientists providing sustainable vegetative stabilization – the challenge of mine tailings in arid and semi-arid environments call for Ecosystem Engineers. In the following sections, a brief description of a variety of emerging technologies is provided, as well as the necessary tools to evaluate reclamation success.

Solidification

Solidification typically refers to the addition of pozzolans (cement, fly ash, lime, slag, etc.) to the tailings to produce structural underground backfill. This involves dewatering the tailings to a paste by adding binders, and delivering them underground by pipeline. Chemical stabilization in the form of adding pozzolans reduces the solubility of heavy metals, as well as the potential for acid mine drainage. Overall, solidification substantially reduces water losses and seepage through tailing walls, and to groundwater. It can aid in mine tailing containment rehabilitation, but can be costly in terms of production and transport. Additionally, solidification limits the potential for reprocessing, which economically, it not a favorable solution for the mining industry as reprocessing is becoming another viable income.

Plant Covers - Phytotechnologies

The establishment of a plant cover on mine tailings reduces erosion and contaminant mobility, and is a visually appealing technology due to its low cost and use of native vegetation. Such covers often focus on phytostabilization processes which use native plants that do not accumulate metals in their shoot tissues and that promote metal precipitation in the rooting zone. Another important concept is that of evapotranspiration covers which minimize percolation through the use of design components that aid in controlling water balance. These cover systems promote vegetative transpiration of water as well as evaporation of water from the soil surface. Design components can include natural shallow slopes which sustain patterned or banded woody vegetation, which attenuates flow paths, trapping moisture and resources for plants and reducing erosion.

The challenges associated with revegetation include plant selection and amendment impacts and amounts. Based on greenhouse and field studies to date, a number of plant characteristics and expected microbial and soil improvements have been documented (**Table 4**). Further there is evidence that plants can naturally develop tolerance for growth on mine tailings. As an

Table 4. Characteristics of plants used in phytostabilization and microbial and soil parameters that can be used as indicators of phytostabilization success.

Optimal plant characteristics	Expected microbial improvements	Expected soil improvements
Good biomass production	Increase in heterotrophic bacterial and fungal counts	Improved soil aggregation and water holding capacity
Self-propagating	Decrease in autotrophic iron- and sulfur-oxidizers	Improved nutrient status
Native colonizers	Overall increase in diversity and activity	Reduced erosion and runoff
Metal accumulation in plant shoots is less than the USDA Domestic Animal Toxicity Limits		Decreased metal bioavailability and mobility

example, between 1995-2005, 418 plant species were found colonizing 56 gold and uranium tailings dams in South Africa – supporting that notion that there are genetically distinct plants and microorganisms on tailings, which tolerate tailings conditions. Several presentations remarked that there is not enough carefully collected long-term data sets to allow good prediction of the success of any given revegetation project, particularly in arid and semi-arid environments where water availability is an issue. As a good illustration of this point, in the past, pasture grasses were planted on limed and heavily fertilized mine tailing slopes of up to 30^{o} and irrigated. Initially this reclamation strategy work as the grasses responded to the fertilizer and irrigation, but eventually fails within 3 to 4 years due to little root mass, making this process unsustainable and extremely costly.

Tools to Evaluate In-Situ Remediation Success

Evaluating the outcomes of a remediation strategy is essential to ensure the technique is minimizing exposure pathways, exposure routes and/or toxicity of the metals. Sites can be remediated to look aesthetically pleasing, but what is the chemical speciation and bioavailability of the metals of concern at the site? The appropriate tools must be used to determine whether the in-situ remediation technique will indeed protect human health and ecological function. For humans, direct soil ingestion is the primary risk pathway for lead and arsenic, and it is crucial to measure the changes in bioavailability of these elements before and after the selected remediation strategy is employed. Additionally, conducting a full ecosystem risk assessment to model the potential for food chain transfer requires information concerning the: 1) availability and leaching potential of metals in the environment; 2) ecosystem diversity and function including plant and microbial communities; 3) plant uptake of metals; and 4) herbivore and carnivore pathways. The ultimate goal is to relate the mineral form of the contaminant to its bioavailability, and to show that the in-situ remediation strategy implemented protects human health and ecological function.

References

1. Castro-Larragoitia J, Kramar U, Puchelt H. 1997. 200 years of mining activities at La Paz, San Luis Potosi, Mexico - consequences for environment and geochemical exploration. J Geochem Explor 58:81-91.

2. Engels J, Dixon-Hardy D. 2004. Tailings disposal - today's storage of high volumes of wastes from mines In: JKMRC International Student Conference, 27 Aug – 12 Sep, 2004, Brisbane, Australia. Brisbane, Australia:Julius Kruttschnitt Mineral Research Centre.

3. Gonzalez RC, Gonzalez-Chavez MCA. 2006. Metal accumulation in wild plants surrounding mining wastes: Soil and Sediment Remediation (SSR). Environ Pollut 144:84-92.

4. Morris BL, Lawrence ARL, Chilton PJC, Adams B, Calow RC, Klinck BA. 2003. Groundwater and its Susceptibility to Degradation: A Global Assessment of the Problem and Options for Management. Early Warning and Assessment Report Series, RS. 03-3. Nairobi, Kenya:United Nations Environment Programme.

5. Munshower FF. 1994. Practical handbook of disturbed land revegetation. Boca Ratton, FL:Lewis Publishing.

6. Schwegler F. 2006. Air quality management: a mining perspective. In: Air Pollution XIV (Longhurst JWS, Brebbia CA, eds). WIT Transactions on Ecology and the Environment, Vol 86. Southampton, UK:WIT Press, 205-212.

7. Tordoff GM, Baker AJM, Willis AJ. 2000. Current approaches to the revegetation and reclamation of metalliferous mine wastes. Chemosphere 41:219-228.

8. U.S. EPA (U.S. Environmental Protection Agency). 2004. Abandoned Mine Lands Team: Reference Notebook. Available: http://www.epa.gov/aml/tech/refntbk.htm [accessed 1 May 20011].

9. U.S. EPA (U.S. Environmental Protection Agency). 2006. Fact Sheet: Final Revisions of the National Ambient Air Quality Standards for Particle Pollution (Particulate Matter). Report No. R-307-310. Washington, D.C.:U.S. Environmental Protection Agency

10. Warhurst A. 2000. Mining, mineral processing, and extractive metallurgy: an overview of the technologies and their impact on the physical environment. In: Environmental Policy in Mining: Corporate Strategy and Planning for Closure (Warhurst A, Noronha L, eds). Boca Raton, Florida:CRC Press LLC.

11. US-Geological Survey. Copper Statistics and Information. 2010. Copper Statistics and Information. Available at: http://minerals.usgs.gov/minerals/pubs/commodity/copper/mcs-2010-coppe.pdf [accessed 31 May 2011]