Final Report Project 3.6

Developing the business case for responsible acid and metalliferous drainage (AMD) management

October 2022

crctime.com.au

CRC TiME Transformations in Mining Economies

Australian Government Department of Industry, Science and Resources

AusIndustry Cooperative Research Centres Program

PROJECT PARTNERS

ISBN 978-1-922704-23-8

Date of publication

October 2022

Cover photo

Cover photo copyright CRC TiME

Corresponding author

Professor Carolyn Oldham
carolyn.oldham@uwa.edu.au

CRC TiME contact

info@crctime.com.au

Author affiliations

a – The University of Western Australia
b – CRC for Transformations in Mining Economies

Citation

Singh, A[a,b]., Bourgault, C[a]., Kanse, L[a]. and Oldham, C[a,b]. (2022). Developing the business case for responsible acid and metalliferous drainage (AMD) management. CRC TiME Limited, Perth.

TABLE OF CONTENTS

Figures

Tables

Executive summary

Acid and metalliferous drainage (AMD) is currently a global environmental, social and economic problem, reported in many countries, on nearly all continents, and across a wide range of mining commodities, including coal, gold, copper and uranium. The frequency and severity of AMD impacts continues to grow due to the worldwide increase in mine sites and the scale of mine operations. Stakeholder awareness of this issue has escalated pressure on the industry to improve the transparency of its impact and management. The mining industry has responded by adopting international standards and best practices, creating new technical solutions, enhancing their mining processes, developing new risk management strategies and establishing collaborative partnerships between regulatory agencies and non-governmental organisations. Nevertheless, despite the application of agreed principles throughout the industry, the risks associated with AMD remain a worldwide problem contributing to the global water crisis and resulting in a complex interplay between technical, socio-economic and regulatory/political aspects. The question, therefore, emerges whether the business case for improved AMD prevention and management is sufficiently understood, developed and communicated to effectively mitigate its impacts. In addition, there is a need for consensus amongst multi-stakeholders on what additional instruments, policies and initiatives are needed to create sustainable AMD prevention and management, and advance the benefits of mining economies.

Over the years, there have been different approaches to this problem, with a predominant focus on technological solutions. The science and technology of AMD has had significant improvements, with its treatment becoming increasingly more sophisticated. However, these solutions have become increasingly expensive and of limited efficiency when applied as an end-of-pipe solution. As a result, the focus is no longer solely on the treatment aspects and instead, awareness and management approaches are moving to earlier stages of the mining process, requiring focus on remedial activities at source control, and looking for incorporating risk assessment tools and opportunities to mitigate AMD impact throughout the life of mine. Despite this greater understanding of pro-active management aspects, there are still barriers to their implementation.

This project was established under the CRC TiME Operational Solutions program, to trial the application of participatory approaches and thematic mapping, to help identify those aspects and blind spots that may be preventing effective management of AMD. The project team engaged with a global and multi-stakeholder group via real-time participatory workshops and undertook structured thematic mapping of workshop discussion points. This report presents a brief overview and analysis of past and current global activities relating to AMD. The report then presents the outcomes of the participatory workshops and thematic mapping, that is, identifies the underlying issues that stakeholders believe contribute to the AMD management challenge, and finally the stakeholder-identified opportunities for improvement.

One of the striking comments that frequently came through, both during the workshops and afterwards as various stakeholders reviewed this report, was that similar opinions would have been expressed at a similar workshop run 25 years ago – so what is the root cause of the failure of the sector to implement solutions over these 25 years? This report has started an analysis to identify that root cause (noting that there may be more than one in such a complex issue), and to create a roadmap for CRC TiME to address the root cause(s).

Specifically, we were able to identify five thematic issues and five opportunity themes running across all comments made in the workshops. These ten themes span across scientific understanding, technology, processes, management, engagement, communication, business models and industry culture. The identified issues and opportunities were used to define a roadmap of five research priorities to guide future work for CRC TiME (Table 1). While this roadmap does not specify a detailed list of actions or criteria for improved AMD management, it highlights areas stakeholders believe are critical to better manage the AMD problem:

- The use of improved metrics, tools and models to enhance the AMD business case.
- The need for training and knowledge-sharing on AMD risks, across professional teams.
- The need for improved engagement and communication with traditional owners and regional communities, to better understand their aspirations.
- The need for improved standards and governance.
- The need for some improved AMD science (tools, methods and scale-up).

It is noted that the latter four aspects all contribute to the first i.e. to enhance the business case for improved AMD management.

These core themes highlight the areas where CRC TiME can demonstrate transformational value to AMD management, with the recommended actions in the roadmap providing a preliminary approach to address each theme and improve the understanding of their interactions.

Table 1: Roadmap for CRC TiME activities under the five core areas identified by this project.

SHORT TERM (0–3 YEARS)	MEDIUM TERM (3–6 YEARS)
ENHANCING THE BUSINESS CASE FOR IMPROVED AMD MANAGEMENT	
Develop methodologies to support the required transitions in organisational maturity relating to mine closure generally, and AMD management specifically. Undertake a case study audit of KPIs and their timeframes, across the whole of business, identifying where conflicts arise for AMD management.	Improve frameworks to adequately quantify risks and opportunities throughout life-of-mine, particularly for mine closure planning and associated residual risks.
EDUCATE AND INFORM CROSS-DISCIPLINARY PROFESSIONAL TEAMS	
Identify skills needs and education required to capture closure challenges in the business case for improved AMD management.	Deliver educational resources for cross-disciplinary teams, to facilitate a shared understanding of AMD risks.
UNDERSTAND COMMUNITY ASPIRATIONS FOR AMD-AFFECTED LANDS	
Explore how to improve traditional owner and community awareness of AMD. Explore opportunities for two-way science with traditional owners of AMD-affected lands. Use traditional owner and community aspirations for the future use of AMD-affected lands, to drive AMD and closure research.	Develop effective AMD communication resources with adequate language and messages for different stakeholder groups, based on their concerns. Develop platforms to share (focused) operational data for benchmarking and to improve community and investor engagement. Select demonstration sites and develop case studies of both failures and success in AMD management and the relinquishment of AMD-affected land.
ENHANCE STANDARDS, GOVERNANCE AND REGULATION	
Develop approaches for governance of regional-scale AMD management, with consideration for cumulative impacts on regional economies. Assess operational and regulatory barriers that may limit social and environmental monitoring and reporting, and the associated liabilities.	Review and evaluate the decision-making processes that underlie the existing permitting conditions with respect to AMD (water pollution). Develop new regulatory approaches that can be used to improve outcomes, based on specific site-level environmental constraints.
IMPROVE KNOWLEDGE OF SOURCE CONTROL, REMEDIATION AND VALUE OPPORTUNITIES	
Improve our understanding of source control and materials handling through accurate forecasting of AMD. Through geochemical risk assessments, evaluate opportunities in reprocessing waste and converting AMD into a valued product.	Develop predictive models of current and future AMD risk, to support long-term AMD governance. Validate remediation and valued-added technology focused on scale-up studies.

The critical need for integrated management of AMD throughout the life-of-mine is the common thread across the five themes; this has long been known, yet continues to be perceived as currently lacking in most organisations. A change in organisational culture is now required; the above activities will support such cultural changes.

This recommended roadmap for future CRC TiME work on AMD was based on our analysis of the participatory workshop discussions. Our ability to detect consistent themes emerging from the diverse stakeholders who attended the workshops, has demonstrated the power of participatory methodologies in exploring problems and possible solutions, in detecting underlying issues and surfacing collective tacit knowledge. Similar participatory approaches should be used to identify other intractable management aspects of the broader mine closure challenge.

Acronyms

AMD: Acid and metalliferous drainage

CRC TiME: Cooperative Research Centre for the Transformation in Mining Economies

CSR: Corporate Social Responsibility

DES: Department of Environment and Science

DMIRS: Department of Natural Resources, Mines and Energy

DNRME: Department of Natural Resources, Mines and Energy

ESG: Environmental, social and governance

IBIS: Issue Based Information System

ICMM: International Council on Mining and Metals

INAP: International Network for Acid Prevention

ISG: Industry steering group

KPI: Key performance indicator

MOP: Mining operations plan

NGO: Non-governmental organisation

NPV: Net present value

OECD: Organisation for Economic Co-operation and Development

OST: Open Space Technology

POC: Proof of concept

REE: Rare earth elements

ROM: Run of mine

SEIA: Social and environmental impact assessment

SLO: Social license to operate

STAG: Science, technology and academic group

UWA: University of Western Australia

WRD: Waste rock dump

1 Introduction

1.1 Growing demand for mined resources and its impacts

Mining is a crucial sector for human and economic development and has had unprecedented growth in light of increased world population. As the world population and the associated economic activities continue to grow, so does the demand for mined resources. In addition, more metals are increasingly required for scaling up renewable energy technologies and enabling infrastructure with the global demand of extracted materials expected to double in the next fifty years (OECD, 2019). This surge in demand has created significant changes in the mining industry over the last decades, with site operations rapidly evolving from low tonnage underground activities to large-tonnage open-cut processes to respond to and maintain increased economic growth (Australian Government, 2016).

However, despite the positive contributions of the mining industry to local and national economies, mined resources frequently come with environmental and social costs; this is seen specifically when mining triggers the formation of acid and metaliferous drainange (AMD). AMD is formed when sulfide minerals are exposed to oxygen and water, resulting in their oxidation. Microorganisms catalyse the oxidation of ferrous iron and reduced sulfur compounds to ferric iron and sulfuric acid, which further accelerate the solubilisation of sulfide minerals and release of protons, metals, metalloids and sulfate. The acidity, metals and sulfate in AMD cause detrimental environmental impacts in receiving water bodies and soil, resulting in toxicity, loss of biodiversity, highly disturbed ecosystems, and potential risks to human health.

AMD may be as old as mining itself; indeed, there are mine sites along the Iberian Peninsula Pyrite Belt that produced AMD in Roman times. After the Industrial Revolution, large-scale mining grew during the 19th and 20th centuries, with legacy environmental impacts often neglected and associated socio-economic costs hidden. One of the critical aspects of dealing with AMD risks is the typical time lag between the exposure of ore minerals to oxidative conditions and the manifestation of its impacts; abandoned mines are significant sources of AMD. Although the scale and impact of AMD may not have been apparent when a mine is first started, the evidence of its legacy accumulates when mines are closed and left unattended. The lack of timely management combined with the challenges of waste containment, have caused environmental impacts with long-lasting, irreversible perturbations in biodiversity. There are many well documented historical examples of AMD environmental and human health legacies worldwide, caused by long-lasting water and soil pollution and other resource degradation. For local communities affected by the degradation of local ecosystem services and loss of livelihoods, the impacts on their economic and social fabric can lead to physical and mental health issues.

1.2 What is AMD?

AMD is a result of an oxidation process that occurs in both active and abandoned mines and is formed when oxygen and/or oxygenated water meets exposed mine rock surfaces containing sulfides (e.g pyrite, pyrrhotite, chalcopyrite, covelite and galena) (Thisani et al., 2021), some sulfate minerals such as jarosite (Kocaman et al., 2016) and elemental sulfur (INAP, 2009). The process occurs via an abiotic mechanism (reactions 1–5 below) catalised by bacteria such as *Acidithiobacillus* spp., and archaea such as *Sulfolobus acidocalderius* (Chen et al., 2016), which thrive under acidic conditions (Küsel, 2003) and oxidise ferrous iron to ferric iron and/or reduced sulfur compounds to sulfuric acid.

For the majority of geological formations, pyrite is the ubiquitous sulfide mineral and its oxidation is generally regarded as the strongest AMD producing process known to occur in the natural environment (Gomo, 2018). As such, the following net reactions describe a simplified chain of pyrite oxidation and associated production of acidity (protons):

$$FeS_2 + 7/2O_2 + H_2O \Rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad (1)$$

$$Fe^{2+} + 1/4O_2 + H^+ \Rightarrow Fe^{3+} + 1/2H_2O \quad (2)$$

$$Fe^{3+} + 3H_2O \Rightarrow Fe(OH)_{3\,(s)} + 3H^+ \quad (3)$$

$$FeS_2 + 15/4O_2 + 7/2H_2O \Rightarrow Fe(OH)_{3\,(s)} + 2SO_4^{2-} + 4H^+ \quad (4)$$

$$FeS_2 + 14Fe^{3+} + 8H_2O \Rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \quad (5)$$

Reactions 1 – 4 describe mechanisms under oxygenated conditions. However, reaction 5 perpetuates pyrite oxidation under anoxic conditions. Oxidation by ferric iron (reaction 5) is faster that any of reactions 1–4, and generates four times more acidity (Gammons, 2009). Therefore, this reaction describes a critical process and highlights the importance of restricting contact with oxygen at the source level, and thus restricting acidification to reactions 1–4.

The release of acidity can lead to the dissolution of metals such as iron, aluminium, manganese, cadmium, copper, lead, zinc, arsenic and mercury. In other cases, the acid produced by the primary oxidation of sulfides is neutralised by existing natural minerals such as carbonates, resulting in a near-neutral pH. Nevertheless, even as the pH increases, certain metals such as zinc, chromium, manganese and cadmium, and metalloids such as arsenic and selenium, can remain in solution resulting in neutral drainage of poor quality. The oxidation state governs the mobility of several environmentally significant trace metals. Hence, as conditions become gradually more alkaline, some of these metals eventually precipitate as carbonates or hydroxides (e.g. zinc and manganese) whilst arsenic, selenium and chromium may remain in solution and aluminium can be remobilised into solution. When these metals are not present in solution, near-neutral drainage may have low concentrations of metals but have high concentrations in sulfate/magnesium/calcium, resulting in high salinity.

The dependence of these processes on weather, temperature, oxygen and water levels, type of ore deposits, metal sulfides and carbonates content and exposure and biological activity, influences the extent of generation of AMD and its composition. These aspects combined with a complex interplay between thermodynamics and reaction kinetics often result in a long interval between the start of AMD formation and the manifestation of its impacts. This latent behaviour makes the hydrogeochemistry of AMD and the prediction of its impact, a complex challenge.

1.3 Mining cycle and AMD formation

The five stages comprising a typical mining cycle:

1. Pre-feasibility.
2. Detailed feasibility.
3. Design engineering and construction.
4. Mine operations.
5. Decommissioning and closure.

Each entail activities with different risks of formation and impact of AMD.

Project scoping and exploration undertaken in the first two stages, have limited contribution to the formation of AMD and associated environmental impacts. However, activities undertaken in stage 2 are critical for assessing AMD formation potential and informing subsequent stages on the best approaches to mitigate AMD. The assessments that occur during feasability investigations include excavation of test pits, drilling holes, mineral, soil and water sampling, and the formulation of social and environmental impact assessments (SEIA). These studies typically rely on data collected within the boundaries of the proposed mining lease and rarely consider the intrinsic geological variability of the surrounding catchment, the cumulative regional impacts of multiple mines, nor the multiple mine processes and operations that influence the formation and impact of AMD across the whole mine life cycle.

Stage 3 and 4 contain the greatest risks of AMD formation due to operations that disturb and displace previously buried materials. Activities such as land clearing, geotechnical investigations, the construction of infrastructure, roads, metallurgical processing plants and tailings dams, and associated traffic movements, all affect soil characteristics by causing detachment, increased erosion and ultimately promote the release of sulfidic soils and sediments (Gorman & Dzombak, 2018). There is also frequently an increase in impervious surfaces across the mine site, which influences hydrological responses and the mobilisation and transport of AMD.

Stage 4 operations include drilling and blasting to remove overburden rock and allow the extraction of ore; this activity causes fragmentation, fractures, or cracks, alters the texture and porosity of materials and may further expose reactive minerals to weathering agents. In addition, dewatering operations combined with subsequent mineral processing requiring large quantities of water from groundwater or surface water sources, can lower groundwater tables and alter surface flows. These mining-induced changes in the hydrological cycle can promote AMD transport, and thus increase acidity and associated pollutants in receiving waters (rivers, streams and reservoirs). Lowered groundwater aquifers expose previously buried sulfidic rock formations to oxidising conditions leading to further AMD formation and creating a self-sustaining loop whilst dewatering continues and until aquifers recover post-mining.

1.4 Operational sources of AMD

Many mining activities contribute to the formation of AMD, including:

- Tailings impoundments.
- Waste rock dumps (WRD).
- Open pit walls.
- Heap leach pads.
- Ore stockpiles.
- Sludge treaments.
- Land vegetation clearing.
- Excavation, rock cuttings and milling.
- Erosion and transport of sulfidic sediment via vehicle traffic.
- Rock used in construction of roads, dams, and other infrastructure.
- Diffuse sources from replaced overburden areas.

Large-scale excavations, drilling, blasting and crushing combined with removal of overburden during the extraction of ore, are examples of activities that not only expose large quantities of ore but also increase minerals surface areas, prompting greater ingress and oxidation rates. Operations during mineral processing further reduce particle size and can generate solid sulfidic wastes (e.g. waste rock or dust) (Bernal & Martinez-Alcala, 2020). In addition, processing to extract ore solutions often creates large quantities of residual mine tailings and acidic wastewater polluted with metals. Runoff from mineral wastes such as overburden material, ore stockpiles, heap and dump leach residue materials, tailings, waste rocks impoundments and bedrocks areas, all significantly contribute to the release and transport of AMD (Gomo, 2018; Habib et al., 2020).

In stage 5, decommissioning and closure followed by the post-closure phase, are when most of the impacts of AMD manifest. This phase is marked by operations shut down and cessation of dewatering resulting in groundwater upwelling. In turn, the absence of water discharges related to mine operations can cause a sudden decrease in surface water flows. Both aspects affect the local hydrological system resulting in the mobilisation and transport of contaminants from oxidised sources, increased AMD loads and leaching of heavy metals, which are likely to be magnified by the increasing climatic variability.

1.5 AMD treatment and prevention

AMD environmental and socio-economic impacts have stimulated strategic development of cost-effective prevention and remediation solutions. Nevertheless, developing a universal solution for AMD has proven difficult due to the variation in site geochemical characteristics, hydrological and climatic conditions and the lag time for impacts to manifest (Thisani et al., 2021).

1.5.1 Prevention processes

Large mining companies actively develop AMD mitigation measures using early prediction of drainage chemistry and AMD risk assessment (Price, 2009). These mitigation measures are driven by environmental, social and governance (ESG) factors, such as social license to operate, contribution to sustainable development goals, company reputational risk, legal requirements and the need to reduce remediation costs. As the formation of AMD is triggered by the presence of oxygen and microorganisms, the implementation of preventative approaches aims to eliminate or reduce contact time with these reaction components, followed by controlling the release and transport of AMD at source. A number of approaches and methods are designed to prevent the formation and minimise transport of AMD; at source controls are considered more sustainable than traditional end-of-pipe treatment methods (Park et al., 2019). Broad categories of prevention processes are:

- Physical barriers or covers – dry or wet.
- Microbial inhibition.
- Microencapsulation.
- Desulfurisation.
- Electrochemical systems.
- Chemical barriers – organic or inorganic.

The decision process for implementing a particular approach is influenced by site-based characteristics such as material type, geology and mineralogy, mining method, local hydrology and climate.

During pre-feasibility, feasibility and operational stages, an extensive range of laboratory tests and prediction methods are used for the assessment of the acid generation capacity of mineral ores and wastes, and their leaching rates. These tests, which are considered best practices in AMD management (INAP, 2009; Price, 2009), are routinely used to predict potential AMD formation and accordingly classify and segregate mine waste for appropriate disposal and remediation/mitigation efforts. Although preventative strategies aim to reduce AMD production at source, they are less widely implemented and remediation strategies remain the most widely adopted approach for treating AMD at most mining sites (Naidu et al., 2019a).

1.5.2 Remediation treatments

AMD management strategies have historically been developed in response to observed environmental impacts, often when appropriate operational options that could have be cost effective are no longer available. There may be extensive damage to nearby natural resources with substantial associated remediation costs. Treatment techniques have historically relied on proven technologies adopted by the wastewater treatment industry. These treatment approaches aim to meet specifications required for a particular waste stream or water end-use, or as specified in environmental regulations. Classic categories of techniques used for treatment of AMD are:

- Active treatments
  - Neutralisation (using limestone, quick lime, hydrated lime, magnesium hydroxide, magnesium oxide or caustic soda)
  - Aeration
  - Desalination or membrane processes
  - Sufidogenic bioreactors
- Passive treatments
  - Oxic, open limestone drains
  - Wetlands or compost reactors
  - Permeable reactive barriers
  - Iron oxidation ponds

Physical, biological and chemical processes are often used to lower acidity, toxic metals, sulfate (and often salinity) concentrations and raise pH; these treatments may be passive or active. Selection of the appropriate AMD treatment method (or combination of methods) invariably depends on site-specific conditions, the availability of water and the required treatment objectives. The efficiency, robustness and overall operational performance of such treatment approaches has resulted in global adoption and implementation of these techniques at many mining sites.

Active treatment remains the most common approach, typically involving chemical neutralisation. The commercial availability of neutralising agents such as lime (quicklime, hydrated lime), caustic soda (sodium hydroxide), magnesium hydroxide, magnesium oxide and limestone, and the existence of well-proven mixing and dosing technologies for large-scale centralised treatment plants, make this the most cost-effective and widely used method. However, this treatment method creates ongoing operational challenges related to subsequent treatment and management required of the hazardous end-product brine and/or sludge (often containing contaminants like sulfate and metals). These challenges and the additional maintenance costs make this option economically and operationally unfeasible for abandoned mines with no income stream, and are gradually becoming less attractive in active mines due to increasingly stringent environmental and economic requirements for waste containment and disposal (Thisani et al., 2021).

Whilst active solutions offer high efficiency and reliability to achieve compliance criteria, the associated energy, chemicals, capital and maintenance costs are significant. Furthermore, the increasing likelihood of extreme weather events and their possible impact on waste containment and treatment facilities, is demanding the redesign of treatment processes, escalating operational risks and associated costs.

In contrast, passive treatments are designed to be self-sustaining, naturally occurring geochemical, physical and biological processes requiring minimal operational effort. For example, applications such as wetlands, although not a ‘walk-away’ solution, are an attractive remediation approach to near neutral AMD with low acidic characteristics and minimal water flow rate fluctuations from an economic perspective. Under these conditions, correct implementation will not only minimise their maintenance and maximise their life expectancy it will also potentially achieve better effluent quality compared to active neutralising treatment (Naidu et al., 2019b). However, they cannot rapidly adjust to a sudden deterioration in water quality or to a major short-term increase in flow.

Although AMD remediation methods are widely adopted at most mining sites, their suitability and performance vary depending on site-specific characteristics such as geochemistry, mineralogy and climate. Variability in AMD composition, together with required compliance with multiple environmental regulations and site-specific bio-ecological contexts, commonly result in highly tailored treatment sequences involving combinations of several methods (Thisani et al., 2021). As a result, additional operational challenges, risks and costs are created. A less costly yet robust, regulatory compliant technology that avoids further environmental footprint is not yet available.

Currently, the application of end-of-pipe remediation approaches requiring continuous maintenance to mitigate AMD impacts and closure liabilities are increasingly seen as economically unfeasible and unsustainable (Park et al., 2019). However, in emerging economies where appropriate tests for pre-mine geological and ongoing wastes characterisation are a logistical challenge and represent a high cost, active and passive remediation methods are considered the most practical option for treating AMD (Naidu et al., 2019b).

1.5.3 Emergent technologies and strategies

Due to more complex, lower-grade deposits and greater emphasis on sustainability, AMD is increasingly recognised as a source of valuable resources such as metals and rare earth elements (REE), the recovery of which could generate revenue to offset ongoing treatment costs. As such, there is currently an increased demand in developing alternative AMD treatment approaches to focus on the reuse of waste (industrial) products. AMD could be used for remediation of other areas, water reuse, or for the recovery of sulfuric acid, valuable metals and REE. Some technologies can recover up to 97% of metals and produce freshwater for reuse, these include electrochemical processes, optimised membrane and adsorption processes such as semi-permeable ion-exchange electrodialyses, forward osmosis and membrane zeolite sorption. Sulfate reduction-based bioreactors remove acidity, metals and sulfate from AMD, and facilitate the recovery of metal sulfides for reuse. AMD from a specific site may continue for decades or in perpetuity, so the application of these technologies creates opportunities for ongoing generation of metals and associated revenue streams. In addition, the use of no-value industrial wastes or low-cost minerals for AMD remediation treatments will decrease treatment costs and are currently receiving attention as a complementary approach.

Despite the progress on developing effective treatment technologies, the continuous requirement, particularly for active treatment, for materials, chemicals, energy, labour, automated control and maintenance inevitably results in additional costs.

1.6 Environmental impacts of AMD

AMD is a global environmental threat associated with mining activities and recognised worldwide for the magnitude of its impacts. AMD contamination leads to extremely low pH and high concentrations of metals and metalloids, elevated sulfate levels and excessive suspended solids and siltation (Abandoned Mine Reclamation Clearinghouse (AMRC), 2021). There are many studies and reports from across the world, on AMD's adverse impacts on the chemistry, physiology, biology, ecology and biodiversity of terrestrial and aquatic ecosystems (Alissa & Ferns, 2011; Jennings et al., 2008; Monachese et al., 2012).

In plants, AMD associated heavy metals have been shown to accumulate and affect the absorption and transport of essential elements, disturb metabolism and have an impact on growth and reproduction. Oxidative stress leads to cellular damage and disturbance of cellular ionic homeostasis, disrupting the physiology and morphology of plants. Highly acidic environments ($pH < 4.8$) affect the solubility of ions, and promote the capture of H^+ ions interrupting cellular processes crucial for plant growth. Acidity causes plant root dysfunction and decreased vegetation growth leading to inability of native flora to recolonise mined areas (Bernal & Martinez-Alcala, 2020).

Salinity associated with AMD can lead to structurally unstable soils that are highly prone to erosion, and thus promote transport of AMD-associated contaminants into fresh waterbodies. Increased soil salinity can also alter plant species composition. AMD-associated acidity affects the abundance and activity of soil organisms (from microorganisms to arthropods) that are responsible for breaking down organic matter and transforming nutrients. Over time this increases soil retention of phosphorus, potassium and nitrogen (Beck et al., 2020).

Fish accumulate heavy metals directly from contaminated water and indirectly via the food chain and sediments. Metals such as Cd, Cu, Pb and Zn are particularly toxic in aquatic environments leading to mortality or non-lethal effects such as stunted growth, reduced reproduction, deformities or lesions. Al is associated with acute impacts, decreases the ability of fish to absorb oxygen and accumulates in invertebrates. Other metals such as Hg and Ni cause a decrease in abundance and richness of taxa leading to substantial changes in the structure and function of benthic communities and food webs (Jennings et al., 2008). AMD-associated acidity affects productivity and biomass accumulation, leading to extermination of sensitive aquatic species; mosquitoes are typically more acid tolerant and mosquito plagues have been reported in the presence of AMD. Acidity can also stunt the growth of frogs, toads and salamanders (Sangita et al., 2010). Excessive salinity in fresh waterbodies increases the concentration of particulates/suspended solids causing reduced habitat viability, and affecting photo-biological processes, both resulting in the decline of biodiversity. AMD-associated precipitation of iron and other metals in water bodies decreases light penetration and decreases primary production impacting food webs (Hogsden & Harding, 2012). The reduction of sulfate in the sediment of water bodies can result in the generation of H_2S which is toxic to fauna.

In some mine sites, AMD is also a source of radioactive contaminants leading to radioactivity in water, soils and agricultural products (Villa et al., 2011; Hadjipanagiotou et al., 2020). It is important to note that the cascading ecological effects caused by AMD do not stop by neutralising the acidity or removing heavy metals. Once AMD is formed, the downstream repercussions on wildlife can propagate to the top of the food web (Alissa & Ferns, 2011).

1.7 Socio-economic impacts of AMD

AMD contamination of water resources and food chains can have serious impacts on human health due to the mobilisation and accumulation of toxic metals. Consumption of water polluted with heavy metal and ingestion of contaminated food are two main exposure pathways to humans, leading to chronic degenerative changes in the nervous system, liver and kidneys, resulting in carcinogenic diseases, stunted growth and mental impairment (Alissa & Ferns, 2011). The accumulation of heavy metals in vital organs such as the heart, brain, kidneys, bone and liver disrupts their functions by inhibiting the absorption of vital elements and interfering or displacing vital minerals from cellular roles.

AMD environmental and health impacts have spurred worldwide concerns, making AMD a highly contested issue by local communities, activists, and non-governmental organisations (NGOs) in both developed and developing economies. The nature and extent to which AMD threatens community welfare near mining sites negatively impact their sustainable social and economic development.

Mining operations are frequently located in remote and water-scarce areas where local communities typically rely on untreated water from streams, springs or wells, for drinking, food preparation and hygiene. AMD impacts on those precious water resources can contribute to significant social effects and economic vulnerability. Irrigation with polluted water can lead to the contamination of crops, ingestion of contaminated food and in long-term inability to grow crops. Many emerging economies rely heavily on the mining sector, yet may have inadequate water resource governance and AMD management strategies. Socio-economic impacts of AMD can affect a large segment of the population and contribute to an ongoing cycle of social conflict and poverty that undermines public confidence in the mining industry (Mpofu et al., 2018).

In developed economies, adverse impacts have occurred predominantly at abandoned or prematurely closed mine sites where historical limitations of regulatory policies resulted in poor monitoring and/or rehabilitation, and potential exposure of local communities to health risks that continue to the present day (Tabelin et al., 2019). There are constrained financial instruments to offset treatment costs in these legacy sites. In a post-mining scenario, ongoing AMD management has a critical economic impact on host communities when land typically remains vacant, unable to be transferred to other alternative productive uses and therefore impairing local economic development. Management options have predominantly focused on technological approaches to containment and rarely address the linkage between legacy AMD and socio-economic challenges, often leading to tensions between government, communities and the mining sector.

The community perception of the severity of AMD impacts is often dependent on the expectations of post mining land-use and the cultural values of land and water held by the host communities. Ecological damage can be associated with feelings of desolation, dispossession and mental distress in communities who have strong cultural connections and spiritual obligations to the land, and therefore link the health of their environment to the health of the community and individuals (Roche & Judd, 2017). Risk assessments and social and environmental impact assessments (SEIA) do not typically capture this spiritual – cultural impact. The associated social costs therefore typically remain unaccounted for. Increased culturally sensitive community engagement during the mine planning stage is required, to better understand community values of land and water.

1.8 AMD as a mine closure liability

Mine closure risks are strongly associated with the liabilities driven by AMD impacts, derived predominantly from waste rock dumps (WRDs), tailings storage facilities and mining pits. The nature of the risks and their impacts on a large number of stakeholders reflect the often increased levels of AMD intractability during (and post) closure phases. The extended delay between actions taken to prevent or minimise AMD and the impact of those actions, creates a perception that AMD is a predetermined closure liability that will occure over an uncertain (future) timeframe. There is also a perception that management of AMD risk is not a key driver of mine operational priorities and decision-making. However, if AMD risks are not identified early in mine planning and the associated environmental risks are not managed appropriately throughout the life-of-mine, AMD presents a substantial environmental, social and financial liability in mine closure sites, particularly where premature and unplanned closure occurs.

In areas with a significant number of abandoned mines, considerable attention is focused on addressing the environmental legacy problems from these orphan sites. In many jurisdictions, there is lack of clarity on which individual or entity is legally responsible for the pollution produced or the rehabilitation costs; the company or organisation responsible for the original mining activities may no longer exist (Masocha et al., 2019). AMD impacts derive from interrelated financial, regulatory and technical challenges that consistently expose non-company stakeholders to under-valued or undetermined risks.

In an industry strongly characterised by efforts to control costs, an aspiration to provide an integrated approach to AMD management throughout the mine-life cycle creates tension when the costs associated with pro-actively managing AMD risks from the start of operations are evaluated. Challenges remain to adequately communicate to management and operations teams the AMD risks, impacts and costs, and this frequently constrains implementation of pro-active AMD management from the early stages of a mine project. Delayed implementation of source control measures can result in increased contamination and impact propagation at closure stage, and thus increased management costs. As a result, remediation actions are often required in perpetuity, which constitute a critical cost challenge that can outweigh the (relatively short-term) economic benefits of the mining project and become a persistent and ever-growing social-economic liability, typically borne by governments and taxpayers.

In some jurisdictions, closure bonds and levies have been implemented. However, mounting evidence indicates that these are insufficient to cover the actual remediation cost when operations cease (Roche & Judd, 2017). Thus, even in these cases, there are concerns about the ability of the operator to mitigate impacts and the likelihood of ongoing risks and legacy costs.

To mitigate AMD as a closure liability, its management increasingly requires focus on operational stages, through innovation in AMD source control methods and improved analytical prediction tools, materials characterisation and mineralogy analysis. Furthermore, the increased understanding of waste rock material behaviour and other AMD pollution sources, together with their predominant transport mechanisms, allow management to focus mitigation efforts on specific operational processes to prevent the initiation of oxidation and therefore minimise its later impacts.

In comparison, there has been relatively little attention given to the commercial value of AMD environmental and social risks nor developing robust economic arguments for improved AMD management; the lack of attention to these aspects constrains early implementation of appropriate technological solutions.

1.9 AMD as a wicked problem

The frequent failure in AMD management results from a complex interplay between environmental, social-economic, cultural and historical contexts, coupled with corporate practices and norms that typically don't embrace methods suitable to tackle such challenges. Divergent responsibilities, conflicting key performance indicators (KPIs), narrow risk assessment approaches, and short-term decision-making strategies often conflict with the long-term and interdisciplinary approaches required for optimal AMD management and prevent its effective incorporation into the whole mine life cycle. In addition, dynamic societal attitudes, stakeholder expectations and regulatory policies, together with a drive to better understand community values and aspirations, means governance of mines is increasingly challenging and enhanced strategies for decision-making are required. AMD can be considered a classic *wicked problem,* where dynamic and complex situations arise, involving stakeholders with different value systems. Tackling *wicked problems* using classical engineering problem-solving methods is fraught.

As described in the previous section, AMD risks span environmental, human, organisational, and technological domains and impact the social-economic, political, regulatory, and corporate governance dimensions. At a societal level, all these areas interact and influence each other. However, these areas have different players, operate under different norms, and are characterised by institutional segregation. When framed by different stakeholders separately, the description of the AMD problem is biased and incomplete because it derives from a unique and separate set of experiences and interpretations gained in a specific and limited context. As a result, proposed solutions are typically based on limited understanding and often use approaches without consensus across stakeholders.

As outlined above, historically, the proposed solutions to AMD risk management have relied on technological approaches. However, commitment to technological approaches often fails to consider the costs of long-term treatment which may continue in perpetuity, nor the environmental impacts of the treatment itself. These aspects exemplify a key characteristic of wicked problems: historically they have been tackled via implementation of 'targeted' solutions generating unforeseen consequences that often outweigh the desired benefit and the requirement for integrated approaches.

Another aspect that defines wicked problems relates to stakeholder roles and their social weight. A wicked problem has different explanations, each with different social weights; this creates pressure to consider solutions that serve the interest of a particular group of stakeholders. For example technological expertise has typically been privileged over community experience and aspirations. However, local communities are increasingly emerging as important governance players in the mining sector, demanding greater involvement in decision-making related to issues that affect their way of life. This has led to shifts in approaches that increase weighting towards solutions targeting particular stakeholder concerns; these proposed solutions may not align with operational requirements and may place productivity and cost reduction at risk.

A wicked problem is often a symptom of a deeper underlying problem. However, the interrelation between the different aspects makes the understanding of the deeper problem difficult and uncertain. Consequently, assessing potential solution(s) and achieving a shared understanding of the problem can only be done by considering a complete range of experiences and involving all perspectives. A well-established approach to this challenge is through participatory dialogue with diverse stakeholders in a collaborative analysis, to discuss 'the problem', to establish a common understanding, and unveil explicit and tacit knowledge.

2 Using collaborative stakeholder dialogue to identify opportunities for action

This project utilised a participatory dialogue approach to engage a diverse AMD stakeholder group from around the globe, in an assessment of the issues and opportunities surrounding AMD risk management, and to support the refinement of the AMD management business model. A process called Open Space Technology (OST) was used for this work.

The OST process has long been successfully used to explore wicked problems. It aims to deepen the understanding and reach common ground by bringing people together to engage in dialogue and promote plural perspectives. This process has been used in a multitude of scenarios to deeply and creatively engage people across different disciplines and backgrounds, with common issues of concern and harness their relevant insights.

This project engaged with diverse stakeholders via collaborative-dialogue workshops using OST processes; more information on this methodology and our workshops is provided in the Appendix. During the workshops, all participant comments were transcribed and later collated for structured thematic analysis. We then undertook two sessions, supported by a expert facilitator, to analyse the consolidated workshop transcripts and identify the underlying core themes. This thematic mapping allowed us to identify five core Issue Themes and five core Opportunity Themes (Figure 2). Each of these is discussed in more detail in the following chapters.

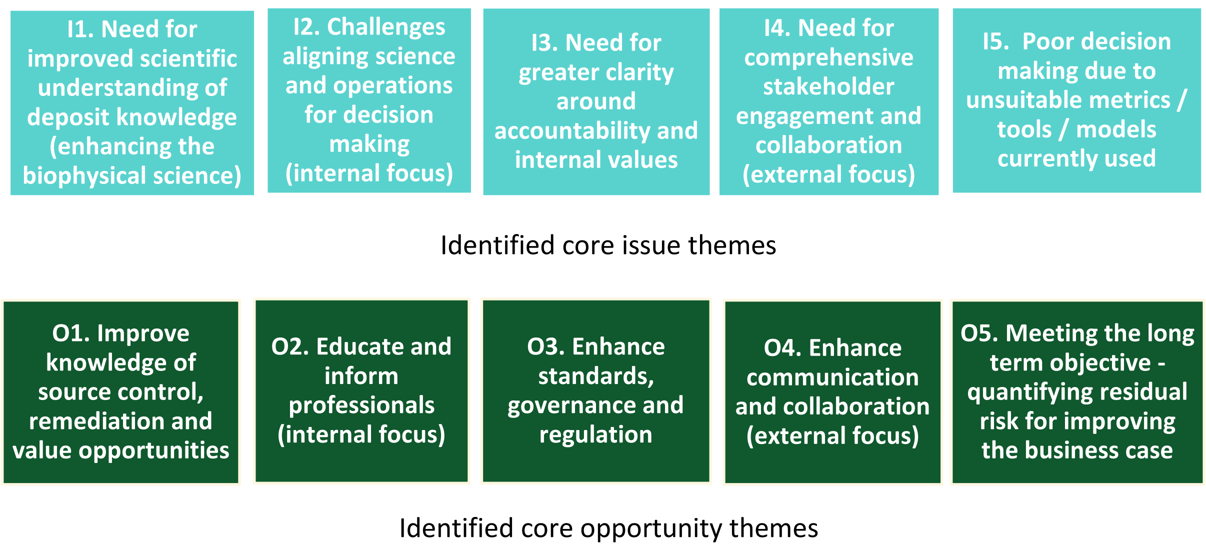

Figure 1: The identified core issue themes (I1-I5) and opportunity themes (O1-O5) that resulted from open space and dialogue mapping processes.

Under each of these ten themes were many sub-aspects, as detailed in the transcripts of workshop discussions. It became obvious from analysis of the sub-aspects that there was alignment and interactions between the issues and opportunity themes (Table 2).

Table 2: Links across issue and opportunity themes.

Issues / Opportunities	I1. Need for improved scientific understanding or deposit knowledge (enhancing the biophysical science)	I2. Challenges aligning science and operations for decision making (internal focus)	I3. Need for greater clarity around accountability and internal values	I4. Need for comprehensive stakeholder engagement/ collaboration (external focus)	I5. Poor decision making via unsuitable metrics/tools/ models currently used
O1. Improve knowledge of source control, remediation and value opportunities	✓	✓			
O2. Educate and inform professionals (internal focus)	✓	✓	✓	✓	✓
O3. Enhance standards, governance and regulation			✓	✓	✓
O4. Enhance communication and collaboration (external focus)			✓	✓	
O5. Meeting the long-term objective – quantify residual risk for improving the business case		✓	✓	✓	✓

Issues I3 and I4 impacted on most opportunity themes (O2-O5), and were therefore considered highest priority for resolution. Similarly, opportunity themes O2 and O5 have sub-aspects common to most issue themes (I1-I5) and have therefore potential to influence many outcomes; these opportunities are considered highest priority for action.

The identified ten issues and opportunities were initially categorised into four broad themes:

1. Enhancing the business case for AMD management.
2. Engagement, communication and education.
3. Standards and governance.
4. Understanding the science of AMD.

3 Enhancing the business case for AMD management

3.1 The business case for AMD management

It is essential to improve the business case to convince decision-makers that pro-active AMD management is financial sensible. This requires collaboration across different work areas and disciplines and an improved cross-organisation understanding of specific practices, norms, and tools. For example, difficulties in identifying long-term environmental and social risks and quantifying those late costs using cost evaluation processes such as Net Present Value (NPV) tools, can lead to an inaccurate apportionment of cost over time and discourage timely AMD action. When financial risks are evaluated over a timeframe significantly different from those of the environmental and social-economic impacts, mine closure and AMD mitigation costs can be significantly underestimated; this makes it challenging to communicate convincing economic arguments favouring early and pro-active AMD management. Nevertheless, effective economic tools can be used to provide credibility to AMD risk analysis and can be presented in the business case. Quantifying the annual cost of process operations related to AMD pro-active management and comparing such operational scenarios with post-closure long-term treatment, is critical in a business plan to understand the cash-flow variability and prevent financial choking at closure stage. Furthermore, the shorter duration of staff roles in mine operation relative to the AMD risk timeframes leads to industry KPI practices that conflict with setting priorities to manage AMD from the early stages of the project. This practice, combined with the inadequate determination of long-term financial risk and its costs, disincentives the integration of AMD management into mine planning and operational procedures.

3.2 AMD risk management

The framework for assessing the feasibility of mining projects typically requires an emphasis on sustainability principles and mitigation of water management, stakeholder values and closure costs. In many countries, regulatory frameworks require mining companies to identify, evaluate and manage all significant AMD risks at early stages of the project evaluation. The assessment of risks is part of governance management processes and is presented in project development and closure plans (Lottermoser, 2015). However, the current risk assessment framework is fragmented, as consideration of different risks is done separately by different agencies. The lack of a consolidated regulatory structure that integrates the economic, social, and environmental impacts prevents the continuous evaluation of the impact of a mining project on a particular site and region (Roche & Judd, 2017). In the case of AMD risks, this can mean that the magnitude, severity and costs of long-term impacts from a particular mine are not accurately quantified. Therefore, despite regulatory compliance, adherence to permit conditions, and the development of required management plans, some projects can still result in long term and significant environmental, social and economical impacts.

Some of the challenges for current AMD management strategies relate to geochemical investigations and tests conducted during preliminary phases. These characterisations are often not extensive, and can be inadequate for a robust prediction of AMD formation, particularly if long term prediction is required. Insufficient or inappropriate characterisation of waste materials, drainage quality, inadequate segregation or encapsulation of waste/tailings and lack of long term monitoring data, have resulted in the ongoing oxidation of sulfide minerals and AMD formation during the operations phase (Richards et al., 2006). Similar issues have been found across numerous mine sites and highlight the need for thorough characterisation and constant re-assessment of AMD formation risks, from different mine materials exposed throughout the mine life cycle. Improved risk assessment programs comprising integrated screening and risk review protocols, covering all operations and activities posing an AMD risk, have been developed and implemented at some mines. These assessments include detailed technical aspects such as WRD management plan and 3D block modelling and facilitate improved closure planning, better management of resources and improved stakeholder expectations (Green & K, 2011).

Nevertheless, despite better understanding of AMD risks, advances in risk assessment frameworks, and the development of improved tests, protocols and processes, there is still a failure to systematically manage AMD adequately and mine incidents continue to occur (Commonwealth of Australia, 2019). Reported adverse events include the leakage of contaminated tailings water at the Ranger uranium mine, the inadequate sampling and waste rock mischaracterisation at the McArthur River Mine, and the saline, radioactive water, uranium and other metals seepage from the tailings storage facility at the Mary Kathleen uranium mine (Roche & Judd, 2017). These are examples of ongoing 'blind-spots' in the management and mitigation of AMD risks resulting in environmental and social-economic damage, unplanned remediation costs and reputational damage to the industry.

These blind spots have previously been related to a multitude of factors, ranging from industry cultural and organisational mindsets, geological variability and lack of deposit and repositories knowledge, inherent technical limitations of AMD testing, decision-making based on inadequate tools or insufficient monitoring, lack of internal accountability processes and ineffective engagement with the full range of stakeholders (Lottermoser, 2015). Nevertheless, there is practical evidence suggesting that company-wide awareness and multidisciplinary involvement in operational decision-making, backed up with regular auditing and technical reviews, is critical for successful AMD risk management (Miller et al., 2012).

3.3 Identified issue: challenges aligning science and operations for decision making

Workshop participants commented that currently it is challenging to align knowledge of site-based mineralogy and AMD geochemistry with management approaches to mine planning and operations. Participants highlighted that when combined with a risk-averse mindset, this reinforces the focus on AMD treatment at the end of the mine life, when fewer mitigation options are available. Companies frequently opt for treatment options that may not be the most environmentally and social-economically sustainable in the long term. Table 3 shows comments related to this Issue Theme.

Table 3: Sub-aspects raised in relation to Issue Theme: challenges aligning science and operations for decision-making.

ISSUE	SUB-ASPECTS RAISED BY PARTICIPANTS
I2. Challenges aligning science and operations for decision making (developing a business case)	How can we influence mine plans and operational practices to focus more on source control and AMD prevention? This is still not occurring despite the science/engineering behind AMD generation, prevention, mitigation and treatment being well understood and documented.
	Science of AMD source terms is well established, but problems continue to occur.
	Mining engineers at the moment understand little about geochemistry, they are too focused on geotechnical stability.
	How and where to better educate all disciplines about source control and closure challenges.
	There continue to be challenges with material characterisation, segregation and scheduling.
	Those responsible for AMD issues are likely to be different people, possibly in different organisations, and will likely change over time. Challenging to maintain momentum and coherence of approach.
	Approaches taken to implement solutions has been ad hoc, with lack of continuity in testing of methods of control and treatment; this can lead to issues persisting that should have been solved.
	Need to bring these initiatives back to cost valuation and identify what the value proposition is.
	Issues are increasing with more reverse osmosis, waste generation and disposal.
	Bactericide technology is not yet accepted in mainstream mining sector.

3.4 Identified issue: poor decision making due to unsuitable metrics/tools/models currently used

Workshop participants commented that the decision-making instruments used for long-term strategic assessments were still inadequate and their application was not integrated across disiplines. This resulted in improper evaluation of long-term risks and costs. Table 4 shows comments associated with this Issue Theme.

Table 4: Sub-aspects raised in relation to Issue Theme: poor decision-making due to unsuitable metrics/tools/models currently being used.

ISSUE	SUB-ASPECTS RAISED BY PARTICIPANTS
I5. Poor decision – making due to unsuitable metrics/tools/models currently used	At the start of an operation, companies rarely have sufficient clarity on future consequences and risk of AMD.
	Predictive modelling is never done over the next few hundred years (few models are capable). But this is exactly what is needed for prediction of AMD impacts.
	Current company cultures are often reactive instead of proactive. AMD management suffers because of this.
	Had a preventative approach been taken right from the beginning, people would feel responsible for AMD prevention.
	Important time horizons differ between different stakeholders.
	Residual risk is often not considered until closure is imminent and by then many options have closed. Those closed options may have been more effective and cheaper.
	The focus on short-term vs long term risks is determined by current values and norms. But those norms aren't the same across all stakeholders. Organisational culture and approaches to AMD issues are not standard.
	Local management may not implement a process that those the higher in corporate structure intended to achieve.
	To effectively deal with AMD, must understand both short and long-term economics.
	To stage-gate (approval stages – proof of concept>pre-feasibility->feasibility) a project must consider economic levers and operational reactivity at each stage. using this approach would ensure that AMD management is considered across each stage of the life of mine.
	Need to assess viability of all options and the consequences of all options.
	Using net present value (NPV) often drives poor environmental decision-making. Typically, supervisors suggest that investments in environmental management are deferred.
	Economics is a major problem around relinquishment – goals and KPIs are too short-term (decisions are inappropriately based on NPV).
	NPV is used as a KPI but AMD risk increases later in mine life, leading to greater costs in the long term. NPV is not a useful tool for environmental decision-making.
	NPV is useful for capturing known cost at a specific point of time,but does not measure non-financial costs.
	Costs of tailings reprocessing are high, so trials get stopped when business is bad.
	Currently most focus is on reprocessing of the tailings for economic recovery.
	Guidelines are being used as standards.

3.5 Identified opportunity: quantifying residual risk to improve the business case

Workshop participants commented that business plans should be required to include a risk analysis of different AMD impact scenarios, the associated management costs of each scenario, and the resultant annual cash flow during operation, closure and post-closure stages. Table 5 shows the comments associated with this Opportunity Theme.

Table 5: Sub-aspects raised in relation to Opportunity Theme: meeting the long-term objective – quantifying residual risk to improve the business case.

OPPORTUNITY	SUB-ASPECTS RAISED BY PARTICIPANTS
O5. Meeting the long term objective – quantifying the residual risk to improve the business case	Opportunity to quantify the impact of mine water quality on local fauna and flora – this is of key interest to communities.
	Long-term, vegetation establishment is crucial.
	Really need to improve monitoring programs (start monitoring even earlier).
	Engage community on which part of environment they value most, which part not so much, and adapt according to community preferences.
	Work with communities from the outset to set realistic expectations and responsibilities for relinquishment.
	Frame conversation in terms of ongoing management rather than relinquishment.
	Develop case studies on relinquishment.
	Make better use of post-closure management funds.
	Management for closure needs to happen at beginning of life of mine. It is essential to clarify the vision for closure – at the beginning.
	Use residual risk frameworks in planning for closure, to determine the cost scenarios.
	Use economic models with low and high uncertainty bounds for risk assessment.
	Require all investment decisions to quantify social and environmental risk, including after closure.
	How do we accurately include AMD costs into discounted cash flow analysis in estimates of net present value (NPV).
	Improve divestment due diligence and better apportion cost over time?
	Change manager KPIs to include long-term perspective.
	Develop KPIs around source control for mining managers.

3.6 Driving transitions in organisational culture for improved AMD management

When we focused on what needed to be done to improve the business case for AMD minimisation or at least improved AMD management, the following themes were identified:

- Key challenges exist aligning science and operations for decision-making.
  - Poor decision-making occurs due to unsuitable metrics/tools/models currently being used.
- The long-term objective must be kept front of mind by quantifying residual risk to improve the business case.

These points do not call for small incremental improvements in our knowledge about AMD; they call for culture shifts within organisations. The complexity of this problem reflects a multidisciplinary challenge and is embodied by consolidated operational practices that do not serve pro-active management and obstruct the required cultural shift. The multifaceted nature of the issue comprises a critical challenge in adequately defining the root cause of the problem and developing methods to understand it, let alone creating solutions.

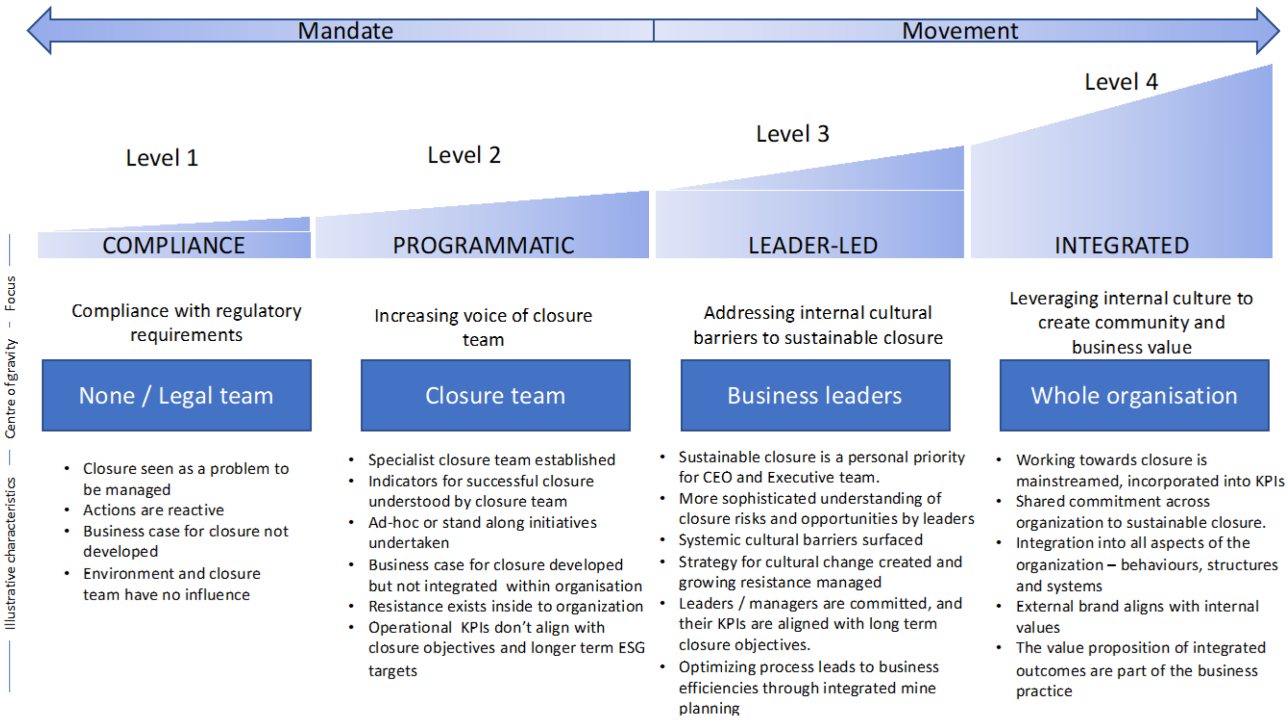

Figure 2: Organisational maturity relating to sustainable mine closure. Modified from Deloitte (2018), who undertook a similar anlaysis for organisation maturity relating to gender equity.

Transitioning an organisation from compliance with regulatory requirements for AMD management and closure, to integration of mine closure within the whole organisation culture and operations (Figure 2), is dependent on a shared understanding of several key points. All decision-making teams across a company must understand the risks of AMD, future uncertainties surrounding AMD and the lost opportunities if the risk is not mitigated. Utlimately, the internal business proposition for AMD management must be rigorously communicated and underpinned by this shared understanding. A key question then is how can CRC TiME support the required transitions in organisational maturity.

4 Engagement, communication and education

4.1 The interplay between communication, cross-disciplinary education and engagement

In recognising the importance of the social license to operate (SLO) to minimise reputational risks and costly social conflicts, and to build societal and community support for their projects, the mining sector has adopted sustainable principles and Corporate Social Responsibility (CSR) initiatives. This has increased stakeholder collaboration and community engagement in decision-making processes (Fraser, 2018). However, mining companies have not fully incorporated social-economic accountability and environmental success criteria into all decision-making processes and business models (Frederiksen, 2018). Poorly communicated internal values, lack of collaborative relationships between stakeholders and communication gaps between internal teams have all contributed to the situation. Developing and effectively implementing new accountability frameworks, establishing improved practices of cross-department dialogue and platforms that inform decision-making are required for improved accountability and better management outcomes in the mining industry (Kemp et al., 2012).

A sustained commitment to improved AMD management requires the involvement of multiple areas, such as finance, logistics, supply chain, engineering and economics, and a deep understanding of the long-term financial costs and risks of AMD, as well as environmental and social impacts that underly those risks and costs. Interdisciplinary collaboration combined with operational consideration of long-term risks is essential to create robust business plans for effective management of AMD impacts, reduce closure costs and improve environmental and societal outcomes. Thus, knowing how to communicate these aspects across teams is paramount to getting key messages across to people with different skills, capabilities and responsibilities. Inter-department collaboration practices are sometimes inefficient due to discipline-specific language and lack of formal cross-disciplinary communication tools, resulting in lost opportunities to promote awareness across different teams and influence hierarchies of decision-makers.

4.2 Identified issue: need for comprehensive stakeholder engagement and collaboration

Workshop participants commented that while much of the mining industry has been actively implementing CSR principles through its policies and practices, there is often a remaining misalignment between industry interests and community aspirations. As a result, mining operators may remain detached from the complexities of the environmental and social-economic realities in which they operate, and their business practices are often biased towards sharing 'selective' information with local communities. Based on the dialogue mapping, Table 6 shows comments associated with this theme.

Table 6: Sub-aspects raised in relation to Issue Theme: need for comprehensive stakeholder engagement and collaboration.

ISSUE	SUB-ASPECTS RAISED BY PARTICPANTS
I4. Need for comprehensive stakeholder engagement and collaboration	Are companies committed to helping communities understand risk of mining operations, or are they trying to steer communities in a specific direction to ensure get decisions over the line?
	How do we take a cumulative approach to risk and regulation, and look beyond our own company's own interest (in both space and time)?
	Residual risk is often not considered until closure and by then many options have closed.
	AMD issues with longer time horizons are harder to raise on the agenda with stakeholders, there are just so many issues to discuss.
	How can future custodians be better equipped to understand uncertainty in costs/risks?
	How can we better address community cultural concerns?
	Important to understand who in the community is interested and the different voices that need to be heard.
	We tend to talk to people In the same fields, but are less confident talking to people from different backgrounds and interests. This is common in communities where we have operations.
	The continually changing regulator and community expectations over the life of mine is a real challenge.
	We need a different approach altogether, need ongoing collaborative management. Need a three-way process between mining company, government and community from the outset, regarding AMD management in perpetuity.
	Majors don't sufficiently influence minors to approach AMD with similar integrated and comprehensive approaches.
	Sharing information (data and case studies) is really important. However, we only share the good stories; this creates a bias in perceptions.
	Are Social Responsibility Reports capturing the real issues and messages, or are they too general to be useful?

4.3 Identified opportunity: educate and inform professionals

Workshop participants commented that to be able to develop a rigorous business case and influence mine planning, technical staff need a better understanding of how technical risks can be materialised into financial risks and how to communicate effectively from a financial perspective. In addition, staff knowledge of specific contexts is of great value, however this knowledge remains less effective due to a lack of suitable communication channels and access key decision-making processes. There is a need for greater on-job training courses, targeting cross-pollination between disciplines whilst fostering more interdisciplinary collaboration and avoiding a silo culture. Based on the dialogue mapping, Table 7 shows participant comments associated with this theme.

Table 7: Sub-aspects raised in relation to Opportunity Theme: education and inform professionals.

OPPORTUNITY	SUB-ASPECTS RAISED BY PARTICPANTS
O2. Educate and inform professionals (internal focus)	Develop case studies on relinquishment and learn from best practice mining company case studies. Learn also from failures.
	Perform benchmarking using case studies – both good and bad examples.
	Scale up projects to reduce uncertainty in AMD predictions and share findings with others.
	Some of this work is being done with selenium research in South Australia.
	Develop demonstration sites to provide learning opportunities for practitioners.
	Compare models: identify key knowledge gaps and prioritise model development.
	Provide a safe forum for sharing failures as well as the good news stories.
	Learn from the 'safety journey'. How was safety incorporated into business models?
	Best to use toolbox approach and educate all stakeholders.
	Bridge between scientific and economic language is critical to engage company teams and help real understanding of AMD risks.
	We must bridge the gap between geochemical and financial risk language.

4.4 Identified opportunity: enhance communication and collaboration

Workshop participants commented that communication and collaboration with external stakeholders, particularly with local mining communities, is a significant and vital way to tackle concerns by companies, governments and societies, at both local and global levels. However, there is a need for improved structured communication and collaboration processes that create more comprehensive and holistic engagement with external stakeholders. Based on the dialogue mapping, Table 8 shows the comments associated with this theme.

Table 8: Sub-aspects raised in relation to Opportunity Theme: enhance communication and collaboration.

OPPORTUNITY	SUB-ASPECTS RAISED BY PARTICPANTS
O4. Enhance communication and collaboration (external focus)	Educate public around AMD in a similar way that has been done for climate change. Increase public awareness via education on AMD.
	Telling the water story is a way to engage ordinary folks.
	Link all of the issues and opportunities on this topic to responsible water stewardship.
	A key role for the CRC in improving mine water literacy for the public.
	Encourage major players to work <u>together</u> with ICMM to work on global standards, protocols and guidance.
	Investigate if cross-company partnerships have been successful. Has sharing of information and lessons leant been useful?
	Think in terms of enagement/collaboration rather than communication/consultation – consultation has a bad reputation, as it has been done poorly in the past.
	Work with communites from the outset to set realistic expectations and responsibilities for relinquishment.
	Engage with the community about which part of environment they value more, which part not so much and adapt closure options according to the community preferences.
	Improve effective communication via different language/messaging for different stakeholder groups, based on their concerns.
	Improve communication on the strategic importance of AMD issues, among different roles, disciplines and interests.
	Articulate (internally) the benefit of why mining companies should report their environmental/AMD management strategies and objectives at a mine site level, rather than at a global corporate level only.
	Find a way to share data.
	Opportunity to expand and invest in the area of the impact of mine water quality on local fauna and flora. Communities want to know this.

5 Standards and governance

5.1 A governance framework for AMD management

The mining industry governance regime is gradually becoming more complex, involving multiple entities representing the state, investors, NGOs, communities and civil society in general. The ongoing adverse global AMD environmental impacts have caused social disruption, local economic instability and led to a polarised public opinion on mining projects which has ultimately resulted in distrust of the motivations of mining companies (Mcintyre et al., 2018). Societal expectations of mining projects have changed and become more demanding regarding sustainable development, legal compliance with environmental regulations, greater transparency and more scrutiny from governments and regulators. Local communities, in particular, due to their proximity to projects and sensitivity to the adverse effects, are demanding a greater share of benefits and increased involvement in decision-making processes. However, the absence of formal documents reporting impacts at a site-scale undermines assurances provided to local communities, as it precludes them from accurately assessing potential social, cultural or economic risks posed by the operations and understanding legacy impacts once operations cease (Roche & Judd, 2017). These data-sharing aspects play an increasingly important role in conceding and validating SLO (Prno & Scott Slocombe, 2012). Despite implementing additional regulatory requirements for Social Impact Assessments to minimise these impacts, risks are often under-evaluated or not fully captured in risk assessments (Roche & Judd, 2017). There is a growing need for the creation of new business models with respect to AMD management that include stakeholder values and, in particular, increase collaboration with local communities. This requires a fundamental shift in industry mindset and a clearer understanding of the critical aspects that need to be incorporated in a new business model for sustainable AMD management across the whole life-of-mine.

5.2 Regulatory framework

The regulation of mining activities in Australia is complex with regulations relevant to environmental AMD impacts, fragmented across Commonwealth, State/Territory and Local Government jurisdictions (Table 9). Federal laws such as the National Environmental Protection Council Act 1994, the Environmental Protection and Biodiversity Conservation Act 1999 (EPBC Act), and the Commonwealth Water Act 2007 regulate environmental protection and, therefore, the actions likely to significantly impact water bodies ecosystems and biodiversity. However, federal regulation does not specifically address AMD risks, for example, the EPBC Act is not applicable to abandoned mines and, with the exception of uranium mining (Australian Government, 2016), it does not include the impact of mineral mines on water resources (Australian Senate Standing Committees on Environment and Communications, 2017; Commonwealth of Australia, 2019). As the ownership of minerals is vested in the state where extraction occurs, the state and territory governments manage mine operations and associated environmental impacts through their respective regulatory authorities, with a number of instruments used to regulate mining operations and closure (Table 8, Cunsolo & Mckenzie, 2019).

During pre-feasibility and operation phases, the primary means used by states to regulate environmental impacts is through the standard authorization processes required for a mining project (Simate & Ndlovu, 2021). In addition, statutory instruments including mining leases, Environmental Impact Assessments, construction approvals, environmental discharge, dewatering approvals governed through their respective Mining Acts, Water Quality Protections Guidelines etc, are used to assess the environmental risks and suitable corrective/mitigation measures (Australian Government, 2016). However, these documents do not explicitly regulate AMD nor the production and release of acidity. Similarly, there is no AMD-specific regulation during the closure and post-closure stages that limits the release of acidity to the environment, denoting a critical gap in the current regulatory regime.

Furthermore, a 'care and maintenance' stage can present significant AMD risks. Although operators are still required to meet certain environmental obligations during this stage, the responsibilities during 'care and maintenance' tend to focus on keeping the site safe and stable, rather than active management to mitigate AMD risk.

Table 9: Comparison of NSW, Queensland and WA state regulatory frameworks.

STATE	REGULATORY DOCUMENT	AUTHORITY
New South Wales	Mining Act Mining Regulation Environmental Planning and Assessment Act Mining Operations Plan (MOP) Guidelines	Department of Planning and Environment (DPE)
Queensland	Mineral Resources Act Mineral Resources Regulation Environmental Protection Act Environmental Protection Regulation Rehabilitation Requirements for Mining Resources Activities Guideline	Department of Natural Resources, Mines and Energy (DNRME) Department of Environment and Science (DES)
Western Australia	Mining Act Mining Regulations Mining Rehabilitation Fund Act Mining Rehabilitation Fund Regulations Environmental Protection Act Environmental Protection Regulation Guidelines for Preparing Mine Closure Plans	Department of Mines, Industry Regulation and Safety (DMIRS) Environmental Protection Authority (EPA) EPA/DMIRS

5.3 Regulation of abandoned sites

In Australia, 75% of Australian mines undergo premature or unplanned closure resulting in unsatisfactory closures, mines left in care and maintenance or simply abandoned; this creates a growing financial and environmental liability (Roche & Judd, 2017). Although AMD issues are present in many of these sites and can result in negative environmental and social impacts, neither federal nor state/territory environmental protection legislation specifically addresses the impacts from abandoned mines. As such, abandoned mines are not subject to enforcement of environmental remediation by the government (Commonwealth of Australia, 2019). Consequently, there is ambiguity about responsibilities, standards and processes to achieve adequate rehabilitation of such sites and each abandoned site is dealt with on a case-by-case basis (Australian Government, 2016).

Nevertheless, to prevent problematic mine closure, state governments have enacted various mine closure best practice programs specifically related to the rehabilitation of abandoned mine sites. However, not all programs allocate statutory responsibility, whilst others lack fresh water or biodiversity protection and specific rehabilitation and closure criteria in relation to existing land use and community expectations. This results in ongoing community vulnerability to mining legacies and the need for further regulatory improvement (Australian Senate Standing Committees on Environment and Communications, 2017). In some states (e.g. Western Australia), the rehabilitation of abandoned mines is funded through a levy-based approach to which mining operators are required to pay an annual fee. This fund is used for rehabilitation if the operator fails to meet rehabilitation obligations. For abandoned mines, rehabilitation is funded using the annual interest earned on the fund (Australian Government, 2016). Other states do not have a formal program for dealing with rehabilitation of abandoned mines (Commonwealth of Australia, 2019).

5.4 Identified issue: need for greater clarity around accountability and internal values

Workshop participants commented that internal organisational practices and accountabilities are intertwined with internal stakeholder interests and objectives. They highlighted tensions between short and long-term objectives, caused by different priorities being adopted across the organisation hierarchy. Based on the Dialogue Mapping, Table 10 shows the comments associated with this Issue Theme.

Table 10: Sub-aspects raised in relation to Issue Theme: need for greater clarity around accountability and internal values.

ISSUE	SUB-ASPECTS RAISED BY PARTICPANTS
I3. Need for greater clarity around accountability and internal values	Key AMD people in organisations need power, influence and tenacity to ensure AMD issues are properly considered within the organisation.
	The focus on short-term vs long-term risks is determined by current values and norms. Norms are not the same across all stakeholders. The organisational culture regarding AMD issues is not standard.
	There are a lot of challenges to effectively deal with AMD in relation to different jurisdictions, specifically around the chain of liability.
	If you want to impact people at deeper levels in the organisation e.g. team leads/supervisors, we have to start at the top to change values.
	Need for consistent KPIs for people with different roles in the mining process
	How to define an AMD site and define consistent KPIs to manage that site?
	AMD is much more challenging for sites with extensive legacy issues, which are then transferred via acquisition. Typically such sites require long-term maintenance in perpetuity.
	Is relinquishment is a valid goal? We need to ask this question.
	We have to shift relinquishment expectations that we will be able to 'walk away' at the end of the mine. There are nearly always going to be perpetual measures required and risk to public and regulator is too great.
	Companies must commit to helping communities understand risk of mining operations. But sometimes they are trying to steer communities in a specific direction to ensure get decisions over the line.
	AMD management is different to safety management, where everyone has responsibility.
	Need to tell the water story better, and regulators have an important role to play here.

5.5 Identified opportunity: standards, governance and regulation

Workshop participants commented that the regulatory framework around environmental impacts, particularly related to AMD, needs further consideration to understand aspects that may block, undermine or conflict with mining project goals, adequate post-closure management and long-term mine rehabilitation. Participants called for improved identification of regulatory gaps or loopholes that jeopardise the achievement of closure goals. Table 11 shows the comments associated with this Opportunity Theme.

Table 11: Sub-aspects raised in relation to Opportunity Theme: enhance standards, governance and regulation.

OPPORTUNITY	SUB-ASPECTS RAISED BY PARTICIPANTS
O3. Enhance standards, governance and regulation	Governments should be requiring adequate community engagement.
	Develop a code for AMD management like there is for cyanide.
	Organisational culture and accountabilities should include training, education, capacity building, benchmarking, assurance and governance standards.
	Use a stage gate approach – accountability is required.
	Develop a concept of requiring an 'Engineer of Record' signoff (assume by mining engineer) on AMD management.
	Sufficiently detailed checklist for AMD management might be helpful, organisations can use this to check off what they have put in place in their AMD management plan, what aspects are covered in the plan.
	Articulate the benefit of why mining companies should report their environmental/AMD management strategies and objectives at a mine site level, rather than at a corporate level only.
	Ensure there are management plans for AMD and build in conformance auditing with multidisciplinary input into all phases.
	Use an audit approach to recognise and reward those companies that have implemented best practices vs. enforcing (by law) the implementation of such practices.
	Better use of post-closure management funds.
	Opportunity to expand and invest in the area of impact of mine water quality on local fauna and flora – this is a key interested for the community.

6 Understanding the science of AMD

A focus on controlling operational costs and improving productivity drives the development and implementation of ever more efficient AMD mitigation processes. Nevertheless, despite the significant body of literature on alternative treatment processes, most studies have been confined to laboratory and pilot scale. Examples of large-scale application and industrial implementation are rare, due to high costs of scaling up technologies, as well as the complexity of integrating with site operations and the feasibility of deployment to geographically remote areas (Skousen et al., 2019).

The mining sector is capital intensive and cyclical in nature, characterised by declining ore grades and volatile commodity prices, and has a primary focus on daily operational productivity targets; together these constrain the sector's risk appetite. Uncertainty around deposit geochemical composition and how and when it translates to AMD formation also inhibits the commercialisation and implementation of AMD research and innovation (Ediriweera & Wiewiora, 2021). Industry culture and organisational structures also lead to limited cross-discipline collaboration and hesitancy in trusting external stakeholder knowledge, skills, and capabilities. This further creates obstacles in the diffusion of innovative solutions and effective collaborative partnerships with parties involved in developing those innovations (Gruenhagen & Parker, 2020).

6.1 Identified issue: need for improved scientific understanding or deposit knowledge

Workshop participants commented that knowledge of resource geological characterisation (i.e. mineralogy, microstructure, etc) in mining operations is often still incomplete, resulting in gaps in site-based prediction and remediation strategies of AMD. They highlighted a need for improved source control characterisation, i.e., site-based data collection, extensive minerals characterisation, and adequate segregation of materials based on their geochemical characteristics. They also commented that results from detailed characterisation can help identify and accurately quantify minerals and elements of concern for potential AMD impacts, and improve the integration of AMD management with mine planning processes and operational tools. Table 12 shows the comments related to this Issue Theme.

Table 12: Sub-aspects raised in relation to Issue Theme: need for improved scientific understanding or deposit knowledge.

ISSUE	SUB-ASPECTS RAISED BY PARTICIPANTS
I1. Need for improved scientific understanding or deposit knowledge (enhancing the biophysical science)	We still have unresolved questions that we had 30 years ago. But there are now additional challenges.
	At the start of an operation, there is rarely sufficient clarity on future consequences and risks of AMD.
	Predictive modelling is never done for the next few hundred years (few models are capable). But this is what is critically needed for AMD risk management.
	There are lots of questions and concerns about reprocessed materials.
	Challenges exist with AMD covers – how to access tailings for reprocessing.

6.2 Identified opportunity: improve knowledge of source control, remediation and value opportunities

Workshop participants commented that there is a critical need for improved practices and processes for AMD prevention, for the prediction of AMD formation and for the creation of economic value from mining wastes that could offset to some extent the cost of treatment. Table 13 shows the comments associated with this Opportunity Theme.

Table 13: Sub-aspects raised in relation to Opportunity Theme: improve knowledge of source control, remediation and value opoprtunites.

OPPORTUNITY	SUB-ASPECTS RAISED BY PARTICIPANTS
O1. Improve knowledge of source control, remediation and value opportunities	Why cant we transform AMD into a valued product>?
	Opportunities can be attached to AMD: e.g. reprocessing for social and economic potential.
	Reprocessing should be liability centric.
	Look for opportunities in reprocessing waste.
	Find market solutions that use the water as it is.
	Involve consumers that could use the water being produced/discharged.
	Using tailings to fill impacted mining voids.
	Explore potential options to control oxidation in situations such as construction of cells in WRDs for placement of acid forming waste.
	Explore possible applications in low-grade stockpiles, ROM pads, etc.
	Explore viability of placing waste rock into pits, flood with water and add carbon to create a bioreactor – could be implemented in coal pits.
	Recent research has shown successful use of milk as a bactericide. Also potential for use of brewery waste.
	Opportunities around closure of heap leaches.

7 Where to from here for CRC TiME

The five identified issues and five identified opportunities were next classified according the recommended actions for the CRC (Table 14). Three categories of actions have previously been used to identify appropriate processes to progress lines of inquiry within a wicked problem.

The three action categories are:

1. Commit and Implement

Based on the discussion in the workshop, there appeared to be reasonable agreement amongst the stakeholders present on what was needed as the next steps. With this agreement, commitment to undertake the project(s) is now the limiting factor. The line of enquiry could transition directly to scope a research concept for the CRC to consider.

2. Complicated

Based on the discussion in the workshop, there appeared to be reasonable agreement amongst the stakeholders on what aspects required further exploration and definition, to make progress. However, it was agreed that the exploration required an inter-disciplinary approach with multiple stakeholders. A consultative workshop is then recommended to better define the line of enquiry prior to transitioning to a scoping activity.

3. Complex

Based on the discussion in the workshop, aspects were contested amongst the stakeholders. While the issue may be clearly identified, differing values amongst the stakeholders and the need for an inter-disciplinary approach made the path forward less clear. The stakeholders have, in effect, identified another wicked problem embedded within the overarching wicked problem. The identified theme needs further clarification regarding its nature, potential causes, required stakeholders and implications of solutions.

Themes that are classified as 'Commit and implement' and 'Complicated' should be considered as potential activities for the CRC TiME in the short term. However, the CRC also has an opportunity to explore those themes identified as 'complex'; given the nine-year life of the CRC and the many engaged stakeholders, the opportunity should not be missed to progress the issues or opportunities identified as 'complex'.

This classification therefore helps define an action roadmap for the CRC and inform research priorities.

Table 14: Identified themes were classified into three action categories.

	THEMES	COMPLEX	COMPLICATED	COMMIT AND IMPLEMENT
ISSUES	I1. Need for improved scientific understanding or deposit knowledge (enhancing the biophysical science)			✓
	I2. Challenges aligning science and operations for decision making (internal focus)		✓	
	I3. Need for greater clarity around accountability and internal values	✓		
	I4. Need for comprehensive (including life of mine) stakeholder engagement and collaboration (external focus)		✓	
	I5. Poor decision making via unsuitable metrics/tools/models currently used	✓		
OPPORTUNITIES	O1. Improve knowledge of source control, remediation and value opportunities			✓
	O2. Educate and inform professionals (internal focus)		✓	
	O3. Enhance standards, governance and regulation	✓		
	O4. Enhance communication and collaboration (external focus)		✓	
	O5. Meeting the long-term objective – quantifying residual risk for improving the business case	✓		

Finally, we merged information from Tables 2 and 14 to demonstrate that themes with greater interconnectivity had a higher complexity level associated with their actions for progress (Figure 3). In contrast, themes classified as '*Commit and Implement'* had limited connectivity and their impacts spanned across only a couple of other themes.

We can also see that the Opportunity Theme O2 (Educate and inform professionals) showed the highest degree of interconnectivity due to its multi-disciplinary perspectives and involvement of different stakeholders. As such, its outcomes are likely to impact other themes and, therefore, should be given priority for execution and implementation. This is a key recommendation from our analysis of the discussion points of the workshop participants.

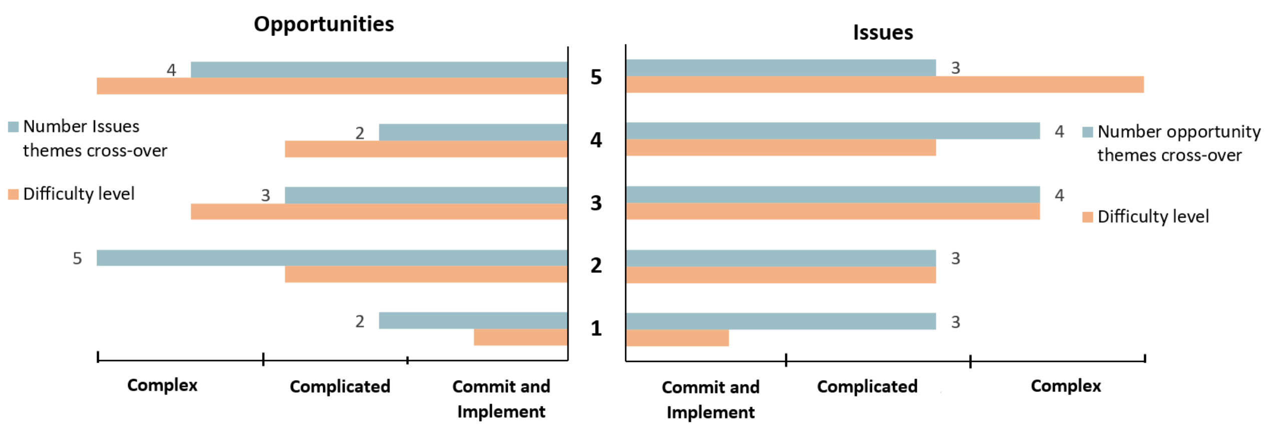

Figure 3: Issues (right) and Opportunities (left) and respective interconnectivity with other themes (grey bars and their associated number) and complexity levels (orange bars).

Based on the emergent themes, a roadmap was created (Table 15) to identify the areas where future CRC work could make the most impact in helping improve a business case to minimise AMD risk across the mining life cycle. The outlined scope for each theme is based on workshop discussion. In each case, we have highlighted the work to be done in the short and medium term.

Table 15: Suggested AMD research themes, summary of related scope and their timelines.

SHORT TERM (0–3 YEARS)	MEDIUM TERM (3–6 YEARS)
ENHANCING THE BUSINESS CASE FOR IMPROVED AMD MANAGEMENT	
Develop methodologies to support the required transitions in organisation maturity relating to mine closure generally, and AMD management specifically. Undertake a case study audit of KPIs and their timeframes, across the whole of business, identifying where conflicts arise for AMD management.	Improve frameworks to adequately quantify risks and opportunities throughout mine-of-life, particularly for mine closure planning and associated residual risks.
EDUCATE AND INFORM CROSS-DISCIPLINARY PROFESSIONAL TEAMS	
Identify skills needs and education required to capture closure challenges in the business case for improved AMD management.	Deliver educational resources for cross-disciplinary teams, to facilitate a shared understanding of AMD risks.
UNDERSTAND COMMUNITY ASPIRATIONS FOR AMD-AFFECTED LANDS	
Explore how to improve traditional owner and community awareness of AMD. Explore opportunities for two-way science with traditional owners of AMD-affected lands. Use traditional owner and community aspirations for the future use of AMD-affected lands, to drive AMD and closure research.	Develop effective AMD communication resources with adequate language and messages for different stakeholder groups, based on their concerns. Develop platforms to share (anonymised) operational data for benchmarking and to improve community and investor engagementSelect demonstration sites and develop case studies of both failures and success in AMD management and the relinquishment of AMD-affected land.
ENHANCE STANDARDS, GOVERNANCE AND REGULATION	
Develop approaches for governance of regional-scale AMD management, with consideration for cumulative impacts on regional economies. Assess operational and regulatory barriers that may limit social and environmental monitoring and reporting, and the associated liabilities.	Review and evaluate the decision-making processes that underlie the existing permitting conditions with respect to AMD (water pollution). Develop new regulatory approaches that can be used to improve outcomes, based on specific site-level environmental constraints.
IMPROVE KNOWLEDGE OF SOURCE CONTROL, REMEDIATION AND VALUE OPPORTUNITIES	
Improve our understanding of source control and materials handling through accurate forecasting of AMD. Through geochemical risk assessments, evaluate opportunities in reprocessing waste and converting AMD into a valued product.	Develop predictive models of current and future AMD risk, to support long-term AMD governance. Validate remediation and valued-added technology focused on scale-up studies.

8 References

Abandoned Mine Reclamation Clearinghouse (AMRC). (2021). *What is AMD?* http://www.amrclearinghouse.org/sub/amdbasics/whatisamd.htm.

Alissa, E. M., & Ferns, G. A. (2011). Heavy metal poisoning and cardiovascular disease. *Journal of Toxicology*, *2011*(September). https://doi.org/10.1155/2011/870125

Australian Government. (2016). Leading Practice Sustainable Development Program for the Mining Industry: Preventing Acid and Metalliferous Drainage (p. 221). Australian Government. Retrieved from Dfat.gov.au, Industry.gov.au

Australian Senate Standing Committees on Environment and Communications. (2017). *Rehabilitation of mining and resources projects as it relates to Commonwealth responsibilities*. Submission 39. https://www.aph.gov.au/Parliamentary_Business/Committees/Senate/Environment_and_Communications/MiningandResources

Beck, K. K., Mariani, M., Fletcher, M. S., Schneider, L., Aquino-López, M. A., Gadd, P. S., Heijnis, H., Saunders, K. M., & Zawadzki, A. (2020). The impacts of intensive mining on terrestrial and aquatic ecosystems: A case of sediment pollution and calcium decline in cool temperate Tasmania, Australia. *Environmental Pollution*, *265*. https://doi.org/10.1016/j.envpol.2020.114695

Bernal, M. P., & Martinez-Alcala, I. (2020). Environmental Impact of Metals, Metalloids, and Their Toxicity. In G. Deshmukh, T. Rupesh; K. Durgesh and Guerriero (Eds.), *Metalloids in Plants: Advances and Future Prospects* (First Edit, pp. 451–488). John Wiley & Sons Ltd.

Chen, L. X., Huang, L. N., Méndez-García, C., Kuang, J. L., Hua, Z. S., Liu, J., & Shu, W. S. (2016). Microbial communities, processes and functions in acid mine drainage ecosystems. *Current Opinion in Biotechnology*, *38*, 150–158. https://doi.org/10.1016/j.copbio.2016.01.013

Commonwealth of Australia. (2019). Senate Inquiry - Environment and Communications References Committee Rehabilitation of mining and resources projects and power station ash dams as it relates to Commonwealth responsibilities (pp. 123–146). (Issue March). Retrieved from www.aph.gov.au/senate_ec

Culmsee, P., & Awati, K. (2013). *The Heretic's guide to Best Practices: The Reality of Managing Complex Problems in Organisations*. Heretics Guide Press.

Cunsolo, A., & Mckenzie, B. (2019). Mining in Australia: Overview. In *Scientific American* (p. 15). https://uk.practicallaw.thomsonreuters.com/8–576–7530?transitionType=Default&contextData=(sc.Default)&firstPage=true

Ediriweera, A., & Wiewiora, A. (2021). Barriers and enablers of technology adoption in the mining industry. *Resources Policy*, *73*(December 2020), 102188. https://doi.org/10.1016/j.resourpol.2021.102188

Fraser, J. (2018). Mining companies and communities: Collaborative approaches to reduce social risk and advance sustainable development. *Resources Policy*, *September 2017*, 101144. https://doi.org/10.1016/j.resourpol.2018.02.003

Frederiksen, T. (2018). Corporate social responsibility, risk and development in the mining industry. *Resources Policy*, *59*(October), 495–505. https://doi.org/10.1016/j.resourpol.2018.09.004

Gammons, C. (2009). Subaqueous Oxidation of Pyrite in Pit Lakes. In D. Castendik & E. L. Eary (Eds.), *Mine Pit Lakes Characteristics, Predictive Modeling and Sustainability* (pp. 139–145). SME.

Gomo, M. (2018). Conceptual hydrogeochemical characteristics of a calcite and dolomite acid mine drainage neutralised circumneutral groundwater system. *Water Science*, *32*(2), 355–361. https://doi.org/10.1016/j.wsj.2018.05.004

Gorman, M. R., & Dzombak, D. A. (2018). A review of sustainable mining and resource management: Transitioning from the life cycle of the mine to the life cycle of the mineral. *Resources, Conservation and Recycling*, *137*(May), 281–291. https://doi.org/10.1016/j.resconrec.2018.06.001

Green, R., & K, R. (2011). Geochemical Risk Assessment Process for Rio Tinto's Pilbara Iron Ore Mines. *Integrated Waste Management – Volume I*, *August 2011*. https://doi.org/10.5772/20473

Gruenhagen, J. H., & Parker, R. (2020). Factors driving or impeding the diffusion and adoption of innovation in mining: A systematic review of the literature. *Resources Policy*, *65*(July 2019), 101540. https://doi.org/10.1016/j.resourpol.2019.101540

Habib, A., Bhatti, H. N., & Iqbal, M. (2020). Metallurgical Processing Strategies for Metals Recovery from Industrial Slags. *Zeitschrift Fur Physikalische Chemie*, *234*(2), pp. 201–231. https://doi.org/10.1515/zpch-2019–0001

Hadjipanagiotou, C., Christou, A., Zissimos, A. M., Chatzitheodoridis, E., & Varnavas, S. P. (2020). Contamination of stream waters, sediments, and agricultural soil in the surroundings of an abandoned copper mine by potentially toxic elements and associated environmental and potential human health–derived risks: a case study from Agrokipia, Cyprus. *Environmental Science and Pollution Research*, *27*(33), 41279–41298. https://doi.org/10.1007/s11356–020–10098–3

Hogsden, K. L., & Harding, J. S. (2012). Consequences of acid mine drainage for the structure and function of benthic stream communities: A review. *Freshwater Science*, *31*(1), 108–120. https://doi.org/10.1899/11–091.1

INAP. (2009). *The Global Acid Rock Drainage Guide (GARD Guide): Prediction, Prevention, Management*. http://www.gardguide.com

Jennings, S. R., Blicker, P. S., & Neuman, D. R. (2008). Acid mine drainage and effects on fish health and ecology: a review. *Reclamation Research Group*, *1*(1), 1–26.

Kemp, D., Owen, J. R., & Van De Graaff, S. (2012). Corporate social responsibility, mining and 'audit culture.' *Journal of Cleaner Production*, *24*, 1–10. https://doi.org/10.1016/j.jclepro.2011.11.002

Kocaman, A. T., Cemek, M., & Edwards, K. J. (2016). Kinetics of pyrite, pyrrhotite, and chalcopyrite dissolution by Acidithiobacillus ferrooxidans. *Canadian Journal of Microbiology*, *62*(8), 629–642. https://doi.org/10.1139/cjm-2016–0085

Küsel, K. (2003). Microbial Cycling of Iron and Sulfur in Acidic Coal Mining Lake Sediments. *Water, Air, and Soil Pollution*, *49*, pp. 67–90.

Lottermoser, B. (2015). *Predicting Acid Mine Drainage: Past, Present, Future Prognose von Acid Mine Drainage,* Mining Report. https://mining-report.de/english/predicting-acid-mine-drainage-past-present-future/

Masocha, M., Dube, T., Mambwe, M., & Mushore, T. D. (2019). Predicting pollutant concentrations in rivers exposed to alluvial gold mining in Mazowe Catchment, Zimbabwe. *Physics and Chemistry of the Earth*, *112*(February), 210–215. https://doi.org/10.1016/j.pce.2018.12.007

McIntyre, N., Angarita, M., Id, N. F., Camacho, L. A., Pearse, J., Id, C. H., Jaime, O., Baena, R., & Ossa-moreno, J. (2018). A Framework for Assessing the Impacts of Mining Development on Regional Water Resources in Colombia. *Water*, *10*(268), 1–18. https://doi.org/10.3390/w10030268

Miller, S., Rowles, T., Millgate, J., Pellicer, J., Morris, L., & Gaunt, J. (2012). Integrated Acid Rock Drainage Management At the Phu Kham Copper Gold Operation in Lao Pdr. *9th International Conference on Acid Rock Drainage*.

Monachese, M., Burton, J. P., & Reid, G. (2012). Bioremediation and tolerance of humans to heavy metals through microbial processes: A potential role for probiotics? *Applied and Environmental Microbiology*, *78*(18), 6397–6404. https://doi.org/10.1128/AEM.01665–12

Mpofu, C., Morodi, T. J., & Hattingh, J. P. (2018). Governance and socio-political issues in management of acid mine drainage in South Africa. *Water Policy*, *20*(1), pp. 77–89. https://doi.org/10.2166/wp.2017.068

Naidu, G., Ryu, S., Thiruvenkatachari, R., Choi, Y., Jeong, S., & Vigneswaran, S. (2019a). A critical review on remediation, reuse, and resource recovery from acid mine drainage. *Environmental Pollution*, *247*, 1110–1124. https://doi.org/10.1016/j.envpol.2019.01.085

Naidu, G., Ryu, S., Thiruvenkatachari, R., Choi, Y., Jeong, S., & Vigneswaran, S. (2019b). A critical review on remediation, reuse, and resource recovery from. *Environmental Pollution*, *247*, 1110–1124. https://doi.org/10.1016/j.envpol.2019.01.085

OECD. (2019). *Mining and Green Growth in the EECCA Region*.

Park, I., Tabelin, C. B., Jeon, S., Li, X., Seno, K., Ito, M., & Hiroyoshi, N. (2019). A review of recent strategies for acid mine drainage prevention and mine tailings recycling. *Chemosphere*, *219*, pp. 588–606. https://doi.org/10.1016/j.chemosphere.2018.11.053

Price, W. (2009). Prediction manual for drainage chemistry from sulphidic geologic materials. In *MEND Program* (Vol. 1, Issue 1).

Prno, J., & Scott Slocombe, D. (2012). Exploring the origins of 'social license to operate' in the mining sector: Perspectives from governance and sustainability theories. *Resources Policy*, *37*(3), pp. 346–357. https://doi.org/10.1016/j.resourpol.2012.04.002

Richards, D. G., Borden, R. K., Bennett, J. W., Blowes, D. W., Logsdon, M. J., Miller, S. D., Slater, S., Smith, L., & Wilson, G. W. (2006). Design and implementation of a strategic review of ard risk in Rio Tinto. *7th International Conference on Acid Rock Drainage 2006, ICARD – Also Serves as the 23rd Annual Meetings of the American Society of Mining and Reclamation*, *2*(January 2015), pp. 1657–1672. https://doi.org/10.21000/jasmr06021657

Roche, C., & Judd, S. (2017). *Ground Truths: Taking Responsibility for Australia's Mining Legacies*. http://www.mpi.org.au/wp-content/uploads/2016/06/Ground-Truths-2016-web.pdf

Sangita, Udayabhanu, G., & Prasad, B. (2010). Studies on environmental impact of acid mine drainage generation and its treatment: An appraisal. *Indian Journal of Environmental Protection*, *30*(11), 953–967.

Simate, G., & Ndlovu, S. (eds.) (2021). *Acid Mine Drainage from Waste to Resources*. CRC Press / Taylor & Francis Group (1st ed.).

Skousen, J. G., Ziemkiewicz, P. F., & McDonald, L. M. (2019). Acid mine drainage formation, control and treatment: Approaches and strategies. *Extractive Industries and Society*, *6*(1), 241–249. https://doi.org/10.1016/j.exis.2018.09.008

Tabelin, C., Sasaki, A., Igarashi, T., Tomiyama, S., Villacorte-Tabelin, M., & Ito, M. (2019). Prediction of acid mine drainage formation and zinc migration in the tailings dam of a closed mine, and possible countermeasures. *MATEC Web of Conferences. EDP Sciences.*, *06003*, 268.

Thisani, S. K., Von Kallon, D. V., & Byrne, P. (2021). Review of Remediation Solutions for Acid Mine Drainage Using the Modified Hill Framework. *Sustainability*, *13*, 8118.

Villa, M., Manjón, G., Hurtado, S., & García-Tenorio, R. (2011). Uranium pollution in an estuary affected by pyrite acid mine drainage and releases of naturally occurring radioactive materials. *Marine Pollution Bulletin*, *62*(7), pp. 1521–1529. https://doi.org/10.1016/j.marpolbul.2011.04.003

9 Acknowledgements

The authors are indebted to the project Industry Steering Group, the Science, Technology and Advisory Group and other industry representatives for their guidance and valuable input during early project work, the OST workshops themselves and our subsequent thematic analysis sessions. We also thank them for their constructive advice during the reviews of early versions of this report. These people include Anna Kaksonen (CSIRO), Jon Crosbie (MMG Australia Limited), Kristy Beckett (FMG), Mansour Edraki (UQ), Sarah Harmer (Flinders University), Rosalind Green and Santiago Barrera Ramirez (Rio Tinto), and Rynhard Kok (Newmont Mining Corporation).

Appendix: Collaborative stakeholder workshops

Open space technology

Unlike traditional seminar/workshop events, the OST process is not prescribed, and there is no pre-fixed agenda. Due to its highly participatory and flexible approach, participants voluntarily discuss any strategy for solving problems and the dialogue around a central theme is steered by each participant input. It is an instrumental methodology to conduct multi-discipline stakeholder participatory conversations who have much to gain from interacting with each other, but are segregated in their business areas (and life) and do not historically communicate well. In this context, the role of the facilitator is to explain how the OST process works and to make every participant a co-creator of the event.

Ethics and consent

The research team submitted an application for Human Research Ethics Approval at the University of Western Australia. We were subsequently informed that Human Research Ethics was not required, given that the event would be widely advertised online and people would volunteer to attend. We would not ask attendees their cultural background, nor whether they were indigenous. It was viewed that the online workshops were no different to other online meetings or workshops associated with voluntary attendance at industry conferences, where discussions were used to inform future possible avenues for research.

Despite the project not requiring Human Research Ethics approval, we continued to meet the usual ethics commitment to provide project information and asking for prior consent, with attendees asked on web-based registration whether they were happy for their names to be included as attendees. All transcripts of discussions were de-identified, and transcripts were distributed to attendees for feedback and a final opportunity to remove their name from the attendees list. The transcripts are not presented in their raw (de-identified) form in this report, and have been safely stored for future reference.

A large range of potential workshop participants were identified by the CRC TiME leadership group, and the steering committee for this project. Stakeholders from different areas and technical backgrounds, including industry practitioners, community groups, mining engineers, policy-makers, NGOs, major investors and researchers, were invited to attend the workshop via email. Separate invitations were sent to community leaders and indigenous representatives. Invitees were also asked to pass the invitation on to anyone who they thought would be interested. In this manner, the invitation was distributed to a large range of stakeholders across the world.

The workshop

The global stakeholders were brought together via an online video conference platform (*Qiqochat and Zoom*) to discuss the overarching questions for the workshop: *Why has acid and metalliferous drainage (AMD) been such an intractable issue and what can be done about it?* Ninety stakeholders from seventeen countries attended across two virtual interactive five-hour workshops. The demographics of attendees is shown in Table 16 and Figures 4 and 5.

Table 16: Number of workshop attendees and their home country.

COUNTRY	ATTENDEES
Australia	44
Canada	12
USA	7
Brazil	5
South Africa	5
NZ	2
Panama	2
Spain	2
Sweden	2
UK	2
Chile	1
Mongolia	1
Nigeria	1
Peru	1
Philippines	1
Russia	1
Turkey	1
TOTAL	**90**

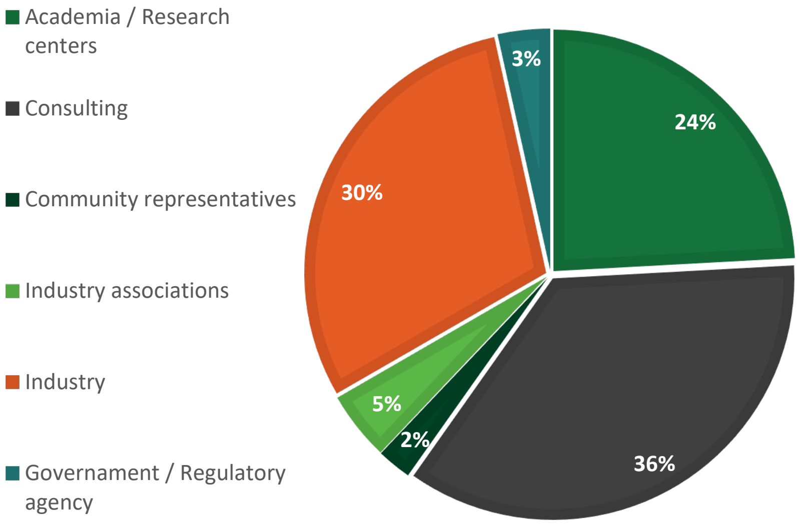

Figure 4: Range of workshop participants.

Figure 5: Locations represented at the workshops.

The workshop facilitators invited participants to propose discussion topics relevant to the overarching theme, an agenda wall was co-created, with parallel discussion groups scheduled across two sessions. Each participant then decided which discussion groups to join across the workshop, based on their personal interests.

Each discussion topic was allocated a *Zoom* breakout room, and participants were free to join the conversation in any breakout room, or move and join a different conversation. Each discussion group had one or more convenors who had proposed the topic, and all participants had real-time access to a google document that allowed them to collectively capture participant contributions in the form of notes, questions and comments.

A total of twelve topics were proposed and discussed at the event (across the two workshops). Twelve discussion groups were formed (Table 17), and the points raised in each discussion group were further analysed.

Table 17: Discussion topics and number of participants.

DISCUSSION GROUP	TOPIC	NUMBER OF PARTICIPANTS
1	Bactericide perceptions and your experiences	8
2	Improving source control in mine plans/operations	15
3	Standard or codes of practice as guidance for designs	6
4	Evaluating integrated treatment solutions	9
5	Novel technologies in reprocessing AMD for value recovery	3
6	Residual risk and economic frameworks: Are they successful in final closure and do they meet stakeholder and community needs?	20
7	How can we better integrate designs between mining, processing and waste management to proactively avoid or control AMD?	8
8	Which values/norms do organisations hold re AMD issues and responsibilities?	10
9	How can the challenges (and opportunities) of addressing AMD be communicated in a way that engages diverse stakeholders, especially community stakeholders with limited knowledge of mining or science?	10
10	What have we learned in the last 30 years that could help the way we approach the AMD issue?	7
11	How can market forces be harnessed to address AMD from legacy mine sites?	26
12	How do AMD sites achieve relinquishment?	8

After the workshop, participant contributions (i.e. the google documents) to each discussion group, were collated for structured thematic analysis.

Using dialogue mapping to identify issues and opportunities

A small working group undertook the subsequent thematic analysis of the workshop conversations. We used Dialogue Mapping™ (www.cognexus.org) as an interactive technique to visualise the group thinking and build a shared understanding of the AMD problem, based on the workshop dialogues. Dialogue Mapping allowed us to identify common themes running across different workshop discussion groups, and gain insights into the perceptions of the workshop participants. Dialogue Mapping is particularly useful when solutions to strongly interdependent issues are embedded in different areas and require the engagement of a diverse (and often large) group; this is a characteristic of AMD management challenges.

A Dialogue Map i.e. a diagram of the developing thinking process, was interactively created, starting from the initial problem definition or question, through identfication of common themes, issues and opportunities, to a decision-making process about outcomes. Dialogue Mapping uses the graphic language IBIS to capture the group knowledge as key questions, ideas, comments and arguments arise and structures them in a graphical diagram to visualise and detect new thematic issues and questions (Culmsee & Awati, 2013). This approach aims to obtain a deeper definition of the problem (issues) and an understanding of the space where the solution(s) (opportunities) lie.

Learnings from using OST

Using AMD as a case study, we have used explored areas related to mining industry processes and methods, cultural behaviours and organisational practices that cascade into inefficient management and decision-making processes. This study adopted a participatory dialogue with global stakeholders based on Open Space Technology, to discuss the different components of AMD intractability, and scope out a collaborative view on critical areas where attention is required to reduce AMD risks across the mine life cycle. The workshops replicated the informal, face to face and rich conversations occurring during breakout periods at plenary sessions where the evaluation of complex ideas is more engaging and efficient. This interdisciplinary collaboration amongst stakeholders from different areas of expertise, to cooperate in deliberations that impact them, despite having different interpretations and goals, is increasingly recognised as an essential process to expand on complex aspects; underlying issues and opportunities are identified. This represents an efficient participatory approach to decision-making processes.

Contrary to traditional approaches to problem-solving where the problem is clearly defined before solutions are considered, the dialogue mapping analysis explored the problem and its possible solutions in parallel. This 'opportunity-driven' method identified ten themes as the critical areas where further research is required to adequately address the AMD problem (five issues themes) and its potential solutions (five opportunities themes). The clarity of the themes that emerged from capturing workshop conversations and mapping them graphically, demonstrates the methodology's ability to unveil collective tacit knowledge and explicitly detect underlying issues and associated new questions (opportunities).

The participants commented that they had thoroughly enjoyed the workshop; various reasons were cited:

- The workshop format and digital platform supported collegial discussions with global colleagues.
- Many had rarely been asked before to tackle the big question of why AMD is not better managed.
- A deep discussion on residual risk occurred that rarely takes places outside of risk specialists.
- The frank nature of the discussions was appreciated and considered constructive for moving the conversations forward. It was commented that such frank discussions rarely occur.
- There was a shared sense that what was being discussed started to tackle the root cause of the problem, rather than 'low hanging fruit' that were typically not so affective.

These commented highlighted the usefulness of both the Open Space Technology format and the the digital platform to connect stakeholders from across the globe, to have a critically important conversation.