Giant Mine Oversight Board

GIANT MINE STATE OF KNOWLEDGE REVIEW

Arsenic Dust Management Strategies

August 2017

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Prepared for:

Giant Mine Oversight Board

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ACRONYMS AND ABBREVIATIONS

AANDC	Aboriginal Affairs and Northern Development Canada
As	Arsenic
As_2O_5	Arsenic pentoxide
As_2O_3	Arsenic trioxide
ASTDR	Agency for Toxic Substances and Disease Registry
bgs	below ground surface
CAD	Canadian Dollar
CO_2	Carbon dioxide
ºC	Degrees Celsius
DST	Dundee Sustainable Technologies
DIAND	Department of Indian Affairs and Northern Development
Fe(0)	Elemental Iron
EA	Environmental Assessment
Fe(III)	Ferric iron
Fe(II)	Ferrous iron
FB	Frozen Block
FBA	Frozen Block Alternative
GMOB	Giant Mine Oversight Board
GNWT	Government of the Northwest Territories
H&S	Health and Safety
HBHM	Hydraulic Borehole Mining
INAC	Indigenous and Northern Affairs Canada
kg	kilogram(s)
km	kilometre(s)
MVEIRB	Mackenzie Valley Environmental Impact Review Board
m	metre(s)
nZVI	nano-Zero Valent Iron
OMM	Operation, Maintenance and Monitoring
ppm	parts per million
PRB	Permeable Reactive Barriers
QA/QC	Quality Assurance and Quality Control
SENES	SENES Consultants Limited
SRK	SRK Consulting Inc.
SOK	State of Knowledge
SRB	Sulphate Reducing Bacteria
TCLP	Toxicity Characteristic Leaching Procedure
USD	United States Dollar

EXECUTIVE SUMMARY

Arcadis Canada Inc. (Arcadis) was retained by the Giant Mine Oversight Board (GMOB) to complete a State of Knowledge (SOK) Review to provide an assessment of technologies, methods, or integrated combinations of technologies and methods that are potentially relevant to arsenic trioxide management at the Giant Mine site, with a specific focus on underground arsenic trioxide. This report provides a summary of the results of this SOK Review.

BACKGROUND

The former Giant Mine is located approximately 5 kilometres (km) north of the City of Yellowknife, in the Northwest Territories. It began producing gold in 1948 and operated until 1999 when the property went into receivership and Indigenous and Northern Affairs Canada (INAC) and the Government of the Northwest Territories (GNWT) assumed responsibility for the management of the site, including pre-existing environmental liabilities.

The gold ore at the Giant Mine is collocated with arsenopyrite, an arsenic-bearing mineral. During processing of the ore, an arsenic trioxide dust mixture was generated, precipitated and collected in baghouses. Beginning in 1951, the dust was stored on-site in purpose-built vaults, or in previously mined-out chambers (stopes). Over approximately fifty years of operation, 237,000 tonnes of arsenic trioxide dust were generated and stored on site. The dust is, on average, approximately 60% arsenic by weight. Arsenic trioxide is water soluble and therefore poses a risk to both people and the environment through transport to local water bodies such as Baker Creek and the Great Slave Lake.

INAC retained a Technical Advisor in 2000 to assess the different remedial options for managing the arsenic trioxide dust at the Giant Mine. The evaluation of methods was conducted in two phases. Initially, over fifty technologies were identified as potentially applicable as part of complete alternatives for long-term management of the arsenic trioxide dust. The second phase reviewed 'representative alternatives' involving a limited number of these technologies.

The Mackenzie Valley Environmental Impact Review Board (MVEIRB) issued its Report of Environmental Assessment and Reasons for Decision on the Giant Mine Remediation project in 2013. The Frozen Block Alternative for the arsenic trioxide dust was judged to be the most appropriate management approach currently available, and is considered an interim solution for a maximum of 100 years. Measures were identified in the MVEIRB's report to assist in identifying a better long-term management solution, including the periodic review of arsenic management technologies, and the allocation of funds to support arsenic management research. In June 2015, the GMOB was established as an independent entity to ensure that these measures are implemented and that remediation at the Giant Mine site is carried out in a way that is environmentally sound, socially responsible, and culturally appropriate (GMOB, 2017). In 2016, the GMOB awarded a contract to Arcadis to conduct the first periodic review of arsenic management methods.

ASSESSMENT OF METHODS

All previous methods and new methods identified were initially evaluated against threshold criteria to determine if there had been any technological advances since the 2002 review and to gauge technical maturity and risk. In the second stage of the assessment, methods which passed the initial screening were evaluated against a complete set of criteria and given an overall ranking.

The methods evaluated were divided into four categories and are outlined below:

- In Situ Management
  - Frozen Block was evaluated as a baseline for other methods. It was assumed that ground freezing will be completed using both active and passive thermosyphons.
  - Nano-Scale Zero-Valent Iron would function as a reactive barrier/shell around the dust storage areas.
- Dust Extraction
  - Remote Mechanical Mining Methods would consist of a combination of mining technologies to extract at least 98% of the dust prior to treatment, including boxhole boring, hydraulic borehole mining and raise boring.
  - Hydraulic Borehole Mining was also evaluated as a standalone dust extraction technology and would use pressurized water in an enclosed system to extract at least 98% of the arsenic trioxide dust.
- Ex Situ Waste Stabilization/Processing
  - Cement Stabilization provides both physical encapsulation of the dust with cement and chemical stabilization through the formation of calcium arsenate minerals.
  - Cement Paste Backfill is a variation of cement stabilization wherein a high fine grained material concentration reduces friction and allows mixtures containing the treated arsenic paste to be pumped.
  - Vitrification would stabilize the dust through the formation of arsenical glass in a high temperature furnace.
  - Mineral Precipitation creates a precipitate of crystalline scorodite and ferric arsenate under ambient pressure and temperature from dissolved arsenite (requires dissolution and oxidation as part of process).
  - Biologically-Mediated Reductive Arsenic Precipitation uses large scale bio-reactors to generate hydrogen sulphide, which reacts with solubilized arsenite to produce precipitated reduced-phased minerals (orpiment and realgar) (requires dissolution and oxidation as part of process).
  - Biologically-Mediated Oxidative Arsenic Precipitation produces scorodite through the use of large scale bio-reactors (requires dissolution and oxidation as part of process).
- Physical Isolation and Disposal
  - Sand-Shell Purpose-Built Vault is a potential subsurface storage solution where the treated dust would be relocated to new subsurface concrete vaults surrounded by sand and/or gravel for increased stability.

Sensitivity analyses were conducted to determine the impact that the weighting of certain scoring criteria would have on the overall scores. The weightings of four critical scoring criteria (Effectiveness, Operation, Maintenance and Monitoring Requirements, Short-Term/Health & Safety and Cost) were varied. These were considered critical criteria due to their impact on the long-term project outcome. It was determined that the changes in weighting of these four criteria had minimal impact on the overall ranking of the methods.

Arcadis also reviewed vendor proposals which were provided by the GMOB. These proposals were presented to GMOB both before and during the SOK review. Several of the technologies proposed may have application to other aspects of the Giant Mine remediation effort (e.g., treatment of pumped groundwater or surface water), but the review focussed on their applicability to arsenic dust treatment specifically.

INTEGRATED ALTERNATIVES

Long term management of the arsenic dust located at Giant Mine is complex due to its large quantity (237,000 tonnes), physical characteristics (dust-like), and current storage condition (subsurface chambers and stopes). Because of this complexity, a number of different technologies, or methods, will likely need to be integrated to provide effective treatment. A series of combined methods is defined as an integrated alternative within the body of this document. Nearly all of the methods evaluated need to be integrated with other methods in order to be a successful remedy. Ex situ remedies must include an extraction method, treatment method, and a plan for final storage. In situ remedies do not require dust extraction, but must require a level of treatment (as with nZVI) or physical encapsulation (as with the Frozen Block Method) to ensure acceptable arsenic flux. All integrated remedial alternatives must also have a form of long-term water treatment to capture any remaining arsenic that is not treated by the method implemented.

Alternatives that were evaluated include: the Frozen Block Alternative; Vitrification with Extraction, Gold Processing and Storage; Cement Stabilization and Cement Paste Backfill with Extraction and Storage; and Mineral Precipitation with Extraction and Storage.

Gold recovery would be possible with any of the ex situ stabilization processes evaluated although it was specifically included in the vitrification alternative. The market value of gold has increased significantly since 2002 (about four times), making re-evaluation of previous technologies that include gold extraction worthwhile.

Long-term storage of the treated arsenic would be required for all ex situ methods. Long-term storage options could include: placing the treated product back underground in the mine within the chambers/stopes or purpose-built vaults; off-site disposal at an existing landfill; construction of an on-site landfill; or above ground storage in silos or other permanent containment structures.

CONCLUSIONS AND RECOMMENDATIONS

This study has identified a number of areas in which significant technical advancements have been made since the initial assessment of options for arsenic trioxide dust management at the Giant Mine (cement stabilization, vitrification). In addition, novel methods that were not included in 2002 were evaluated (nano-ZVI and the sand shell method).

The highest-ranking extraction method was hydraulic borehole mining (HBHM), and the highest-ranking treatment method was vitrification. As discussed, these individual highly ranked methods were combined into potential integrated remedial alternatives. Any of these promising alternatives would benefit from additional, deeper technical and financial evaluation if they are to be considered for full-scale implementation.

Based on the results of this study, it is evident that there have been significant advances in hydraulic borehole mining. It performed well on all of the performance criteria and it appears, based on expert reviews and research, that dust extraction could be performed effectively and safely. It is also technically mature.

The top-ranked dust stabilization and processing method was vitrification. Based on the potential for long-term stability of the resulting glass, moderate overall costs, and potential for gold recovery, it is recommended that future research on arsenic dust treatment involve further evalaution of vitrification-based technologies.

This review focused primarily on the technical aspects of the methods and the purpose of the evaluations within this report is prioritizing research efforts. The methods identified as most promising via the ranking process can be further prioritized for research efforts by using specific criteria; the Technical Maturity and Pilot Testing/Design/Pre-Installation Requirements criteria are likely the most relevant for this purpose.

As additional methods are identified or proposed, the same scoring process could be used to compare them to methods evaluated in this report. More novel or proprietary methods may be more challenging to evaluate but using the same criteria as a basis for analysis should ensure that such analyses have similar level of technical rigour applied.

This evaluation presents a high-level review of technology developments. It is assumed that significant additional evaluation of community impacts, verification of feasibility, and development of detailed cost estimates would be required for any of the methods to move forward to field implementation.

1 INTRODUCTION

The former Giant Mine is located approximately 5 kilometres (km) north of the City of Yellowknife, in the Northwest Territories. It began producing gold in 1948 and operated until 1999 when the property went into receivership and Indigenous and Northern Affairs Canada (INAC) and the Government of the Northwest Territories (GNWT) assumed responsibility for the management of the site, including pre-existing environmental liabilities.

The gold ore at the Giant Mine is collocated with arsenopyrite, an arsenic-bearing mineral. During processing of the ore, an arsenic trioxide dust mixture was generated, precipitated and collected in baghouses. Beginning in 1951, the dust was stored on-site in purpose-built vaults, or in previously mined-out chambers (stopes). Over approximately fifty years of operation, 237,000 tonnes of arsenic trioxide dust were generated and stored on site. The dust is, on average, approximately 60% arsenic by weight. Arsenic trioxide is water soluble and therefore poses a risk to both people and the environment through transport to local water bodies such as Baker Creek and the Great Slave Lake.

In 2000, INAC contracted a Technical Advisor to review potential alternatives for arsenic dust management. After extensive evaluations, input from an Independent Peer Review Panel, and numerous recommendations gathered through public workshops and other information sources, it was determined that the Frozen Block Alternative was the best available treatment process for the arsenic dust. A comprehensive Remediation Plan was developed for the site (SRK, 2007). Due to the nature of the project and the potential for the project to have a significant adverse impact on the environment, the City of Yellowknife requested an Environmental Assessment (EA) be completed. The EA was performed between 2008 and 2013 to evaluate these concerns.

The Mackenzie Valley Environmental Impact Review Board (MVEIRB) issued its Report of Environmental Assessment and Reasons for Decision on the Giant Mine Remediation project in 2013. After this review, the Frozen Block Alternative was allowed to proceed to the regulatory phase for approvals; however, concerns for the process were voiced, including the need for perpetual care. Specifically, the Frozen Block Alternative would require indefinite active maintenance and replacement of key components. As a contingency for approval, measures required to facilitate the identification of a better long-term management solution included:

- Limiting the project to a maximum of 100 years;
- Requiring periodic review of the project every 20 years; and
- Facilitating ongoing research in emerging technologies towards finding a permanent solution (MVEIRB, 2013).

The Giant Mine Oversight Board (GMOB) was established as an independent oversight body for the Giant Mine remediation project through a legally-binding agreement to meet the mandates of the EA (Canada, GNWT, Yellowknives Dene First Nation, City of Yellowknife, Alternatives North, North Slave Métis Alliance, 2015; GMOB, 2016). This State of Knowledge (SOK) Review is one of the first steps in moving forward with the development of a research program to fulfill the requirements of the EA. This report provides an assessment of technologies, methods, or integrated combinations of technologies and methods that have developed since the 2002 review that may be relevant to arsenic trioxide management at the Giant Mine site, with a specific focus on underground arsenic trioxide.

1.1 Summary of Previous Assessment

As mentioned above, INAC retained a Technical Advisor in 2000 to assess the different remedial options for managing the arsenic trioxide dust at the Giant Mine. The Technical Advisor team was lead by SRK Consulting Inc. (SRK) and included SENES Consultants Limited (SENES), Lakefield Research Ltd. and HG Engineering Ltd. To address the concerns posed by the presence of the arsenic on the site, an assessment was conducted to evaluate remedial methods that could stabilize and minimize the risk of arsenic release into the environment. The evaluation of methods was conducted in two phases. During the initial review, over fifty technologies were identified as potentially applicable as part of complete alternatives for long-term management of the arsenic trioxide dust (Table 1). The results of this Phase 1 assessment were presented in June 2001. The second phase, presented in December 2002, reviewed 'representative alternatives' involving a limited number of these technologies. A human health and ecological risk assessment was also completed to evaluate current and possible future levels of arsenic release from the site.

During the studies, a consistent nomenclature was defined differentiating an individual component of a remedial solution from an integrated, complete remedial solution. A "method" was defined as an individual step in the management of arsenic trioxide dust and an "alternative" was defined as the group of methods that would produce a complete remedial solution. These definitions have been maintained in this document.

Table 1. Methods initially Considered for Management of Arsenic Trioxide Dust (SRK, 2002)

In Situ Management	Removal of Dust	Re-Processing to Recover Gold and/or Arsenic Value	Waste Stabilization and Disposal
Pump and treat methods • Status quo pump and treat • Flow segregation • Partial flood • Inflow reduction Isolation methods • Hydraulic cage • Grout curtain • Diversion of Baker Creek • Surface cover • Ground freezing In situ modifications • Engineered dilution • Dust freezing • Biological treatment Relocation underground • Move deeper underground • Move above water table • New engineered/ purpose built vaults	Bulk Mining Methods • Open pit mining • Re-stoping of dust • Freezing and re-stoping of frozen dust • Remote mechanical mining • Clamshell excavation (from top of chamber) Methods of Retrieving Dust in a Pipe • Wet vacuum • Dry vacuum • Fluidization from base • Flooding and pumps • Wet reverse circulation • Dry reverse circulation • Hydraulic borehole mining • Dredging Other Mining Methods • Solution mining Volatilization	Direct shipment of crude dust Production and shipment of refined dust • Fuming (selective sublimation) • Leaching & recrystallization (Hot water, caustic, etc.) Arsenic metal production Manufacture of added value products • Copper Chromated Arsenate • Lumber treated with CCA Stabilization of As_2O_3 and preparation of refractory gold values for recovery • Pressure oxidation • Biological treatments Cyanidation and gold recovery Water treatment • Water treatment for arsenic removal • Cyanide destruction	Isolation and Containment • Conventional landfill • Lined basins • Concrete/steel vaults (permanent) • Concrete/steel structures or containers (temporary) • Underground disposal Physical stabilization • Bitumen encapsulation • Cement encapsulation • Zeolite or clay additive • Vitrification • Vibrasonic Chemical stabilization • Precipitation with iron • Precipitation with calcium • Slag disposal • Polysilicates

A report was prepared by SRK in 2001 summarizing the results of the initial evaluations. Following public consultation, detailed analysis of twelve selected remedial alternatives was then carried out (SRK, 2002). Three public workshops and presentations to interested community groups were held to discuss the results of the 2002 report.

The twelve remedial alternatives presented in the 2002 report are listed below (Table 2).

Table 2. Remedial Alternatives presented in 2002 Arsenic Trioxide Management Alternatives Final Report (SRK, 2002)

Category	Alternative	Description
Long-Term Water Collection and Treatment	A1	Water Collection and Treatment with Minimum Control
	A2	Water Collection and Treatment with Continued Dewatering
	A3	Water Collection and Treatment with Seepage Control
Dust Isolation by Ground Freezing	B1	Re-Establish Natural Permafrost
	B2	Frozen Shell
	B3	Frozen Block
Removal and Deep Disposal	C	Removal and Deep Disposal
Removal and Off-Site Disposal	D	Removal and Off-Site Disposal
Removal, Gold Recovery and Arsenic Trioxide Purification	E	Removal, Gold Recovery and Arsenic Trioxide Purification
Removal, Gold Recovery and Arsenic Stabilization	F	Removal, Gold Recovery and Arsenic Stabilization
Removal and Encapsulation	G1	Removal and Cement Encapsulation
	G2	Removal and Bitumen Stabilization

It was concluded that nine of the twelve alternatives would be able to achieve arsenic releases below 2,000 kilograms(kg)/year. The sale of a purified arsenic trioxide product was no longer a viable option for the mine due to regulatory changes since this alternative was originally proposed in the 1980s and further assessment of this alternative was not carried out (SRK, 2002).

The probability of arsenic release was evaluated for each alternative over the short term and the long term. Worker health and safety risks were also evaluated. Cost estimates were prepared for each of the feasible alternatives. The overall risk and cost estimates presented by SRK are summarized in Table 3.

Table 3. Summary of Cost Ranges (in $ Millions) and Risks for Alternatives Reviewed Previously (SRK, 2002)

Alternative	Overall Risk	Dominant Risk Category	Net Cost Range (2002) $Million
A1. Water Treatment with Minimum Control	High	Long-term	30-70
A2. Water Treatment with Drawdown	Moderate	Long-term	80-110
A3. Water Treatment with Seepage Control	Moderate	Long-term	80-120
B2. Frozen Shell	Low	Long-term	90-110
B3. Frozen Block	Low	Long-term	90-120
C. Deep Disposal	Moderate	Worker H&S	190-230
D. Removal & Surface Disposal	High	Short-term	600-1000
F. Removal, Gold Recovery & Arsenic Stabilization	Moderate	Worker H&S	400-500
G1. Removal & Cement Encapsulation	Moderate	Worker H&S	230-280

The Technical Advisor presented recommendations for the preferred in situ and ex situ alternatives to be further assessed through public consultation. Some stakeholders preferred to leave the dust in place to minimize risks associated with dust extraction while other stakeholders preferred the ex situ options as this would result in a lower long-term risk (INAC and GNWT, 2010). The Frozen Block Alternative was recommended as the best in situ alternative due to the low overall risk and dust extraction and cement encapsulation was recommended as the best ex situ alternative. It was also noted that bitumen encapsulation should be further considered if this alternative could be applied at full scale (SRK, 2002).

Water treatment would be required prior to and during implementation of any of the alternatives and following remediation in the medium and long term. It was noted that long-term water management of some form would be required for all the proposed remedial alternatives. It was assumed that residual untreated dust would remain after extraction or ground freezing and even 1-2% of the dust remaining could cause extensive groundwater contamination (SRK, 2002). A groundwater treatment system has been implemented at the Giant Mine to address multiple sources of groundwater impacts at the mine, including seepage from the dust chambers and stopes, soils, bedrock, mine walls, tailings pond seepage, waste rock backfill and tailings backfill. The majority of the arsenic contamination in groundwater has been attributed to the arsenic dust storage areas. The groundwater at the mine is currently treated by the addition of ferric sulphate and lime slurry followed by a settling pond and polishing pond (INAC and GNWT, 2010).

As stated in MVEIRB's Reasons for Decision (MVEIRB, 2013), the Frozen Block Alternative is considered a 100-year interim solution for the site. It is briefly described in the following section (Section 1.2). As mentioned above, the EA decision requires that technology reviews be completed periodically to evaluate the state of knowledge surrounding arsenic dust treatment (GMOB, 2016; MVEIRB, 2013). This State of

Knowledge (SOK) Review is the first of these reviews and identifies and evaluates technological advances in remedial methods since the previous review was completed in 2002.

1.2 Frozen Block Alternative

The Frozen Block Alternative was selected as the remedial option for the Giant Mine as it was concluded to have a lower risk to workers, lower risk of short-term arsenic release and lower risk of long-term arsenic release compared to other alternatives identified at that time.

Pilot and Optimization studies were conducted on Chamber 10 at the site between 2013 and 2015 to verify the remedial alternative's feasibility and to evaluate optimization parameters. The results of the pilot test are being used to optimize design of full-scale freezing. Chamber 10 was frozen with the use of 38 freeze pipes and thermosyphons and freezing data was collected over a period of four years. During freezing, the ground temperature and efficiency of each pipe were monitored. It was determined that freezing could be implemented more quickly than expected and that active and hybrid freezing systems were both effective. It was determined that both active and passive freezing systems would be implemented on site (INAC, SRK Consulting, 2016).

Over the long term, the goal would be to maintain the temperature of the ground 10 metres around and below the dust at or below -5ºC. It was determined that a dry frozen block would freeze three to seven years faster than if the dust was wetted so the dry freezing method is currently planned for the remaining dust chambers (SRK, 2016).

The Frozen Block method was evaluated as part of this State of Knowledge Review to provide a baseline for evaluation of the other methods. The evaluation results are provided in Section 3.1. As ground freezing has already been initiated, it has been assumed that any other remedial option selected in the future would be implemented starting with frozen ground conditions. This assumption was used when evaluating other remedial methods for the site. If a different remedial method is considered in the future, the incremental increase in effectiveness of the new method relative to the effectiveness of the Frozen Block at that time, will need to be weighed against the full capital cost of implementing the new method, and the anticipated future expenditures to maintain the Frozen Block.

2 RESEARCH PLAN METHODOLOGY

The process that was followed to evaluate the current state of knowledge regarding arsenic dust remediation is described below. At the start of the SOK review, a work plan was submitted to the GMOB. During the course of the evaluation, slight changes to the work plan and methodology were made. This section presents a description of the work as it was performed during the review. The original work plan as submitted to the GMOB is provided in Appendix A for reference. The GMOB comments and responses to the work plan are also included in this appendix.

2.1 Initial Method Review

Scoring was conducted in two stages: the first stage evaluated all previous methods and new methods against threshold criteria; and the second stage evaluated methods that passed the first stage against the complete set of criteria.

The threshold criteria used in the initial evaluation were:

- Technical Maturity and Risk; and
- Incremental development since 2002 (when the SRK *Arsenic Trioxide Management Alternatives – Final Report* was produced)

The results of the threshold criteria evaluation are presented in Tables 4 through 7. The complete set of second stage scoring criteria are presented in Section 2.4: Technical Assessment of Methods. In addition, permanence of a given method was examined as part of the Technical Maturity and Risk criteria. Any method that was not considered permanent was excluded from further evaluation.

To preserve continuity from the 2002 SRK evaluation (see Section 1.1, above), methods that had previously been evaluated were revisited to investigate whether significant technical advancement had occurred. Surveys (Appendix B) were sent out to relevant members of the project team and external technical experts. Based on survey responses, the following method subject areas from the 2002 SRK report were re-evaluated during the 2016 SOK review:

- **In Situ Management**
  - Biological Treatment
  - In situ stabilization
- **Waste Stabilization and Disposal**
  - Cement encapsulation
  - Cement Paste Backfill
  - Vitrification
  - Precipitation with iron/calcium or other additives
  - Ex situ biological precipitation (oxidative and reductive)
- **Removal of Dust**
  - Remote mechanical mining
  - Hydraulic borehole mining (HBHM)
- **Emplacement/Final Storage**
  - New engineered/purpose built vaults (sand shell method)

In addition to the methods mentioned above, specific proposals sent to the Giant Mine Oversight Board were evaluated during the review of the relevant methods. These proposals were not reviewed using the full process applied to the technologies selected initially. They were instead reviewed for general technical soundness and feasibility for use at Giant mine. These proposals were:

- DGF New Tech Canada/ Nanotek
  - Nano-Scale Zero Valent Iron with polymer encapsulating material
- βio- βol Techology
  - Gallium Arsenide Semi-conductor wafer manufacturing
- ecoStrategic Group
  - pH manipulation for arsenic and selenium removal from surface water sources
  - Assessment, enchancement, and development of *Polaromonas* bacterium as bioremediation tool
- Dundee Sustainable Technologies
  - Extraction of gold from arsenic dust via chlorination process
  - Vitrification of arsenic dust to form stable glass by-product

Table 4. Stage 1 Evaluation Results and Rationale- In Situ Management Methods

In Situ Management			
	Threshold Criteria		
	Technical maturity and risk	**Incremental development since 2002**	**Rationale for Inclusion/Exclusion**
Groundwater Management Methods:			
Typical pump and treat. (Existing water treatment method uses ferric sulphate, lime slurry and settling and polishing ponds)	No	No	Groundwater management methods do not deal specifically with the dust, they were not evaluated during this review.
Passive water treatment methods for long-term reduced OMM	No	No	
Segregation of groundwater flow	No	No	
Partial flooding of mine	No	No	
Inflow reduction	No	No	
Isolation Methods:			
Hydraulic cage	No	No	Not considered permanent.
Grout curtain	No	No	Does not treat source and therefore not permanent.
Diversion of overlying surface water bodies	No	No	Not considered permanent.
Ground freezing	Yes	Yes	Current planned remedy.
In situ Modifications:			
Engineered dilution	No	No	High risk (eventual failure)
Dust freezing	Yes	Yes	Current planned remedy.
Biological treatment	Yes	Yes	Development in both oxidative and reductive methods for stabilization, could be applied in in situ.
In situ stabilization (cement, nano-scale iron, or other additives)	Yes	Yes	Application of chemical admixtures to stabilize dust has developed.

Note: Bold indicates methods that advanced to second phase of review.

Table 5. Stage 1 Evaluation Results and Rationale- Methods for Re-Processing to Recover Gold

Re-Processing to Recover Gold			
	Threshold Criteria **Technical maturity and risk**	**Incremental development since 2002**	**Rationale for Inclusion/Exclusion**
Direct Shipment of Crude Dust			
Production and shipment of refined dust	No	No	High risk (safety)
Fuming (selective sublimation)	No	No	High risk (safety)
Leaching and recrystallization (hot water, caustic, etc.)	No	No	High risk (safety)
Arsenic Metal Production			
Arsenic metal production	No	No	High risk (safety and financial)
Stabilization of As2O3 and Preparation of Refractory Gold Values for Recovery			
Pressure oxidation	No	Yes	Re-evaluation of gold revenue necessary due to increase in gold market value since 2002.
Biological treatments	No	Yes	
Water Treatment (as needed for processing/ pre-processing):			
Water treatment for arsenic removal (existing water treatment method uses ferric sulphate, lime slurry and settling and polishing ponds)	No	No	Groundwater management methods do not deal specifically with the dust, they were not evaluated during this review.
Passive water treatment methods for long-term reduced OMM	No	No	

Note: Bold indicates methods that advanced to the second phase of review.
Gold recovery is briefly reviewed in Section 4.5 but did not go through the scored evaluation.

Table 6. Stage 1 Evaluation Results and Rationale- Dust Removal Methods

Removal of Dust			
	Threshold Criteria		Rationale for Inclusion/Exclusion
	Technical maturity and risk	Incremental development since 2002	
Bulk Mining Methods:			
Open pit mining (for use in one area of stopes)	No	No	Minimal development since 2002.
Re-stoping of dust	Yes	Yes	Evaluated as part of Paste Backfill and Hydraulic Borehole Mining.
Freezing and re-stoping of frozen dust	No	No	Not considered permanent.
Remote mechanical mining	Yes	Yes	Development in remote mining methods decreases risk for dust extraction.
Clamshell excavation	No	No	Minimal development since 2002.
Backfilling chambers and stopes	Yes	Yes	Evaluated as part of Paste Backfill and Hydraulic Borehole Mining.
Paste technology	Yes	Yes	Research in rheology of paste has expanded uses and increase efficiency and was evaluated in Paste Backfill.
Retrieving Dust in a Pipe:			
Wet vacuum	No	No	Hydraulic Borehole Mining review encompasses the many developments that have been made in ore extraction and processing that were specifically identified in this category.
Dry vacuum	No	No	
Fluidization from base	No	No	
Flooding and pumps	No	No	
Wet reverse circulation	No	No	
Dry reverse circulation	No	No	
Hydraulic Borehole Mining	Yes	Yes	
Dredging	No	No	
Other Mining Methods:			
Solution mining	No	Yes	High risk (safety)
Volatilization	No	No	High risk (safety)
Relocation Underground:			
Move dust deeper underground	No	No	Not considered permanent.
Move above water table	No	No	Not considered permanent.
New engineered/ purpose built vaults	No	No	Sand shell method was evaluated.

Note: Bold indicates methods which advanced to second phase of review.

Table 7. Stage 1 Evaluation Results and Rationale Waste Stabilization and Disposal Methods

Waste Stabilization and Disposal			
	Threshold Criteria		Rationale for Inclusion/Exclusion
	Technical maturity and risk	**Incremental development since 2002**	
Physical Stabilization:			
Bitumen/asphalt encapsulation	Yes	No	Minimal development since 2009 and narrow remediation application window (primarily petroleum).
Cement encapsulation/ stabilization	Yes	Yes	Cement stabilization with additives like lime have performed very well in recent laboratory studies.
Zeolite or clay additives for stabilization	Yes	No	Minimal development since 2002.
Vitrification	Yes	Yes	A pilot scale vitrification plant for arsenical dust is operational.
Vibrasonic	No	No	Does not treat source.
Chemical Stabilization:			
Precipitation with iron/calcium or other additives	Yes	Yes	Advancements have been made in ambient temperature and pressure scorodite formation, calcium arsenate/arsenite formation and apatite-type arsenical minerals.
Slag disposal	No	No	Minimal development.
Polysilicates	No	Yes	Developments have not reached sufficient technical maturity.
Isolation and Containment:			
Concrete/steel vaults	No	No	Minimal development since 2002.
Lined basins	No	No	Minimal development since 2002.

Note: Bold indicates methods that advanced to the second phase of review.
Bitumen/asphalt encapsulation is briefly reviewed in section 3.4.6 but did not go through the scored evaluation.

2.2 Information Sources

Data was collected across disciplines, including drilling and mining companies, laboratories, academia, and both governmental and non-governmental organizations. The list of entities and individuals who were approached for updated information is presented below. A list of the technical experts who reviewed specific methods or provided input and their expertise are included as Appendix C.

- Drilling firms
  - Boart Longyear (Real Brazeau)
  - Big Country Drilling
  - Layne Christensen
  - Kinley Exploration LLC (Colin Kinley, CEO)
- Additional Industry Firms
  - Global Foundries
    - Semi-conductors/ Gallium Arsenide Research (Gary Patton, Ph.D.)
  - Paques BV
    - Biological wastewater and gas treatment vendor
    - Biological arsenic precipitation (Paula González Contreras, Ph.D.)
  - SGS Canada Inc.
    - Gold extraction (John Geldart)
    - Cementation (Rob Caldwell)
  - Times Limited (Sheridan WY, USA)
    - Cement Stabilization (Terry Mudder, Ph.D.)
- Academia
  - Colorado School of Mines (Brian Asbury, Ph.D; Mark Kuchta, Ph.D)
  - University College London (Julia Stegemann, Ph.D.)
  - Imperial College London (Christopher Cheeseman, Ph.D)
  - Queens University (Heather Jamieson, Ph.D.)
  - University of Quebec (Mostafa Benzaazoua, Ph.D.)
  - New Jersey Institute of Technology (Jay Meegoda, Ph.D.)
- Government entities
  - US Mine Safety and Health Administration (MSHA)

  - Natural Resources Canada (CanmetMINING)
  - National Risk Management Research Laboratory (NRMRL)
  - US Environmental Protection Agency (EPA)
- Research organizations with Industry Participation
  - Interstate Technology and Regulatory Council (ITRC)
  - International Network for Acid Prevention (INAP)
  - Mineralogical Association of Canada (MAC)
  - International Council on Mining and Metals (IMMM)
  - Waterjet Technology Association (WJTA)
  - The Mining Association of Canada
- Mining Companies
  - AngloAmerican PLC
  - Cameco (Scott Bishop, Steven Wuschke, James Hatley)
  - BHP Billiton Ltd.

During the review, the project team polled reviewing experts regarding their knowledge of specific projects where arsenic stability was evaluated (e.g., McLean Lake Mine Environmental Impact Study, Saskatchewan). Their responses were used to support the review process.

2.3 Data Gathering (literature reviews, technical workshops, etc.)

A literature review was conducted in a focused manner to evaluate both technical changes for previously identified methods and novel technologies developed since the original assessment. Recent review articles, where available, were used as a primary means to assess the state of the art in areas of interest. Literature was gathered from a variety of sources including conference proceedings, scholarly journals, vendor white papers/ technical sheets; and interviews with internal and external experts. Articles and reviews that were particularly useful during the review are referenced within the method review summary, otherwise all references are cited at the end of this document in the Reference section (Section 6).

2.4 Technical Assessment of Methods

The second stage of scoring was completed by a group of two to four people with the technical expertise to assess the methods using their pre-existing knowledge, who were provided with information collected during the data gathering phase of the project. A semi-quantitative system of performance/assessment/ ranking criteria (ranking criteria) was used to evaluate the methods. The ratings for each method were recorded in a spreadsheet-based tool/scoring sheet (discussed below) that automatically converted the qualitative ratings into a numerical score. This scoring sheet, as well as a summary of the literature search, was provided to the experts prior to the call. A copy of the final scoring sheet is included in Appendix D.

The spreadsheet-based tool that was developed for this project is a semi-quantitative system that can be used to rank and sort methods based on evaluation criteria. A very high, high, moderate, low, or very low score was used for each criterion/characteristic being evaluated. These qualitative scores were assigned a numerical value (5, 4, 3, 2, 1 for very high, high, moderate, low, and very low, respectively). These scores were then multiplied by a weighting factor using a similar system (i.e., priority= 10, high = 5, medium = 3, low =1). The weighted scores for each criterion were totaled, allowing for a uniform means of comparison over a wide range of methods. At the end of the review, during data analysis, weighting factors were adjusted to perform a sensitivity analyses. The sensitivity analysis process and results are presented in Section 4.3.

During method evaluations, each review team participated in a conference call meeting to evaluate a single method. Each scoring session included a facilitator to direct the flow of the call and record the results in the spreadsheet tool. In addition, either or both the project manager or project director were present to help ensure consistency between groups, probe key technical areas, and assist with placing the reviews in the appropriate context of a larger remedy. The results each expert gave for each scoring criterion were discussed and a consensus score for each criterion was reached. The scoring criteria are discussed further in the next section (Section 2.5).

The results of each method were compiled into a single spreadsheet that summarized the results of all other methods. This complete list of evaluated methods also ranked the technologies according to their total weighted scores (sum of the products of the score and weight for each category). After all methods were reviewed, the scores were reviewed and adjusted by the technical director and staff to ensure consistent rankings across technologies. Any changes to the scores were sent back out to the experts to ensure their concurrence with the revised ranking(s).

2.5 Setting of Performance/Assessment/Ranking Criteria

As stated above, a semi-quantitative system of ranking criteria was used to evaluate the methods. The selection of the ranking criteria defines the important characteristics of the desired handling/treatment/processing/isolation methods. The criteria used are inclusive of those used in the original assessment, with some modification, (SRK, 2002) and incorporated other ranking criteria developed by Arcadis and requested by the GMOB. During the original SRK assessment, the following criteria were used to evaluate technologies:

- Technical viability;
- Field experience;
- Available and adequate evaluation data;
- Robustness— (long-term solution);
- Implementation- including environmental acceptability; and
- Performance monitoring of method.

Working with these initial criteria, Arcadis developed modified criteria to evaluate promising methods. Promising methods were those which had passed through the initial screening showing high level of technical maturity, relatively low level of health and safety risks, and identifiable development since 2002. These criteria and descriptions were sent out to each expert as part of the method rating sheet. During the course of the evaluations, a clearer concept of some of these criteria developed. Both the initial definition, and the modified/final (if applicable) definitions are given below. The low versus high ranking indicates how a given method scored for that ranking with high being desirable and low being less desirable so that a low score equates to a high risk or high cost, for example.

- **Technical Maturity**
  - Initial: Probability of becoming a practical, useful technology, likely time required to develop a technology to the point of being implementable, availability of data for evaluation, fundamental soundness of technology.
    - Low = implementation > 10 years out, Moderate = implementable within < 10 years, High = immediately implementable.
  - Final: No changes

- **Effectiveness (Long-term Stability/Permanence)**
  - Initial: How material of an impact will the method have compared to the currently implemented remedial strategy (performance evaluation defined as arsenic flux). Does the method have a high probability of a being a permanent solution?
    - Low = long-term stability unknown or unproven, Moderate = moderate long-term stability (100 years), High = long-term stability likely.
  - Final: No changes

- **Technical Independence**
  - Initial: Does the method provide benefit if it is the only change made, or, does it require additional technical changes or invention during implementation?
    - Low = requires additional unproven, expensive, or high risk methods to be effective, Moderate = requires some modification of existing condition using established methods, High = can be implemented effectively, essentially independent of other methods used at the site.
  - Final: How many additional levels and steps are required within the integrated treatment process for the complete remedy? Are these additional methods unproven, expensive or high risk?
    - Low = requires many additional unproven, expensive, or high risk methods to be effective, Moderate = requires moderate interim processing steps using established methods, High = standalone process.

- **Confidence in Predictive Models**
  - Initial: Low = lack of or poor predictive models and/or the absence of long-term performance data for technology, Moderate = accepted predictive models available or field data for 5-10 years of performance available, High = Field data for >10 years, and/or well validated predictive models exist for analogous systems.
  - Final: No changes

- **Pilot Testing/Design/Pre-Installation Requirements**
  - Initial: Low = requires extensive pilot/field/design work before implementation, Moderate = requires a modest level of pilot/field/design effort prior to implementation, High = requires minimal or no pilot testing, low-moderate level of design effort required.
  - Final: No changes

- **Operation, Maintenance and Monitoring (OMM) Requirements**
  - Initial: How much active management will be required
    - Low = requires active (OMM) quarterly or more frequently, Moderate = requires annual OMM, High = passive remedy, requires only monitoring for compliance purposes.
  - Final: How much active maintenance and system operation would be required after the implementation of the remedial alternative?
    - Low = requires active OMM quarterly or more frequently, Moderate = requires annual OMM, High = passive remedy, requires only monitoring for compliance purposes after remedial alternative is implemented.

- **Risk – Short-term Risk, Worker Health and Safety (H&S)**
  - Initial: In order to make an effective comparison against previously evaluated methods, short-term and worker health and safety risk categories, as defined in supporting document (SD) 18 of the 2002 SRK Report were used. Long-term stability, i.e., permanence, a priority in this review, is evaluated within the effectiveness category. These risk categories are described in more detail within SD 18 (SRK, 2002d); however, a brief description is given below. Risk type will be divided into two categories:
    - **Short-term risk –** The risk that a quantity of arsenic sufficient to affect ecological or human health could be released to the receiving environment during the preparation or implementation phase of each alternative and;
    - **Worker health and safety risks –** The conventional safety risks and the arsenic related health risks that would be faced by workers active in the preparation, implementation, and post-implementation activities.
      - Worker health and safety risk will be evaluated based on individual activities. Low, medium, and high-risk qualifiers will be used.
        - Drilling and installation of wells and/or freezing systems
        - Dust extraction and transport
        - Dust processing
        - Water treatment
        - Residue disposal.
  - Final: Short-term risk and worker H&S were evaluated during the method reviews by the Arcadis team and the expert reviewers. As stated above, the low versus high ranking indicates how a given method scored for that ranking with high being desirable and low being less desirable. In the case of risk, a low score equates to a high risk. Scores assigned were low, medium and high. The H&S scores were reviewed by an Environmental Health and Safety specialist on the project team before finalizing.

- **Practicality of Contingency Measures in Case of Failure**
  - Initial: Low = Difficult to apply an alternative method if the selected method is used, Moderate = the choice of a secondary back-up method is somewhat constrained in choice due to the primary method, High= secondary methods easy to implement.
  - Final: No Changes

- **Time Required for Implementation**
    - Lead/development and implementation time required, in the context of conversion from the FB method. As with other criteria, the low versus high ranking indicates how a given method scored for that ranking with high being desirable and low being less desirable. A low score in this case would take longer for implementation.
        - Initial: Low = Would require more than 20 years to implement, Moderate = would require 10-20 years to implement, High = would require less than 10 years to implement.
        - Final: No changes

- **Ease of Implementation**
    - Initial: Compatibility with the currently implemented remedial alternative.
        - The process of switching from the Frozen Block Alternative to a new long-term approach will be a concern during implementation of any new remedy. Issues such as accommodation of thaw times, site conditions post-frozen block remedy, saturation of the dust, and site accessibility and stability will be discussed and evaluated.
        - Low = complicated and difficult transition from frozen block alternative, Moderate = moderately complex transition from frozen block alternative, High = easy transition from frozen block alternative.
    - Final: No changes

- **Compatibility with Future Land Uses in Giant Mine Area**
    - Initial: Low = final remedial alternative does not add any benefit to future land use, Moderate = final remedial alternative adds some benefit to future land use, High = final remedial alternative adds significant benefit to future land use.
    - Final: Focus on treatment 'footprint'. Very Low/Low = final remedial alternative significantly disrupts or could impact present or future development of land, Moderate = implementation of final remedial alternative will impact current or future development of land, and some long-term impacts may be anticipated, High = final remedial alternative may impact short term use, but minimally disrupts future development of land, Very High = final remedial alternative causes minimal disruption both in the short-term during implementation and in long term.

- **Cost – Initial and Total Lifecycle Cost**
    - As with other criteria, the low versus high ranking indicates how a given method scored for that ranking with high being desirable and low being less desirable.
    - Initial: Low = cost more than 25% greater than current remedy, Moderate = cost within 25% of current remedy, High = cost less than or equal to 75% of the cost of the current remedy
    - Final: The estimated cost range for the frozen block, assuming 2% annual increase since the 2002 SRK report, is $120-160 million dollars. Cost scores were selected based on the following categories:
        - Very Low = $200M+, Low = $160-200M, Moderate = $120-$160M, High = $80-$140M, Very High = <$40-$80M

- **Compatibility with Cold Climates**
  - Arsenic- and site-specific challenges are superimposed on general remediation challenges associated with northern environments. There are numerous examples where technologies developed for southern projects have been unsuccessful when applied to the northern context. Typical challenges include: equipment/geotechnical failures, low efficiency of chemical/biological processes and low human productivity in cold-weather environments. The risks of neglecting to consider the effectiveness of technologies in northern environments are significant and can include: major cost overruns, schedule delays, health and safety risks and complete project failure.
    - Initial: Low = major issues arise from implementing technology in cold climates, Moderate = moderate or unknown issues in implementing technology, High = technology is already successfully used in cold climates.
    - Final: No changes

2.6 Weighting Criteria Selection

The individual weight for each evaluation criteria was selected prior to the review and are presented in Table 4, and graphically in Figure 1. Because of the desire to find a permanent remedial option for the arsenic, priority weighting (a multiplier of 10) was given to the effectiveness criterion, which evaluates a method's long-term permanence in the absence of maintenance. A high weight (multiplier of 5) was given to the OMM requirements, short-term/worker health and safety risk criteria as these were identified by the GMOB to be of particular importance in considering a final solution. Collectively, effectiveness, OMM and short-term/health and safety criteria make up 52% of the entire score for each method.

The criteria given a medium weight (technical maturity, practicality of contingency measures, cost, and compatibility with future uses), are also important factors to be considered in selecting a method. However, these categories are not as significant to the specific technical goal of this review.

Lower weighting (versus the above) was assigned to compatibility with cold climates, technical independence, confidence in predictive models, pilot testing, time required for completion and ease of implementation criteria. Because of their relatively low weight, these criteria do not contribute as significantly to the score. However, including them in the evaluation yielded a more complete evaluation and may be useful in assisting with any future evaluations.

Table 8. Scoring Criteria Weight Contribution by Percent

Evaluation Criteria	Weight	Percent Contribution to Total Score	Numeric Weighting (maximum value)
Effectiveness (Long Term Risk/Permanence)	Priority	26.3%	50
OMM Requirements	High	13.2%	25
Short-term/ H&S Risk	High	13.2%	25
Technical Maturity	Medium	7.9%	15
Practicality of Contingency Measures in Case of Failure	Medium	7.9%	15
Cost	Medium	7.9%	15
Compatibility with Future Uses	Medium	7.9%	15
Compatibility with Cold Climates	Low	2.6%	15

Technical Independence	Low	2.6%	5
Confidence in Predictive Models	Low	2.6%	5
Pilot Testing/Design/Pre-Installation Requirements	Low	2.6%	5
Time Required for Completion	Low	2.6%	5
Ease of Implementation	Low	2.6%	5
		TOTAL	**190**

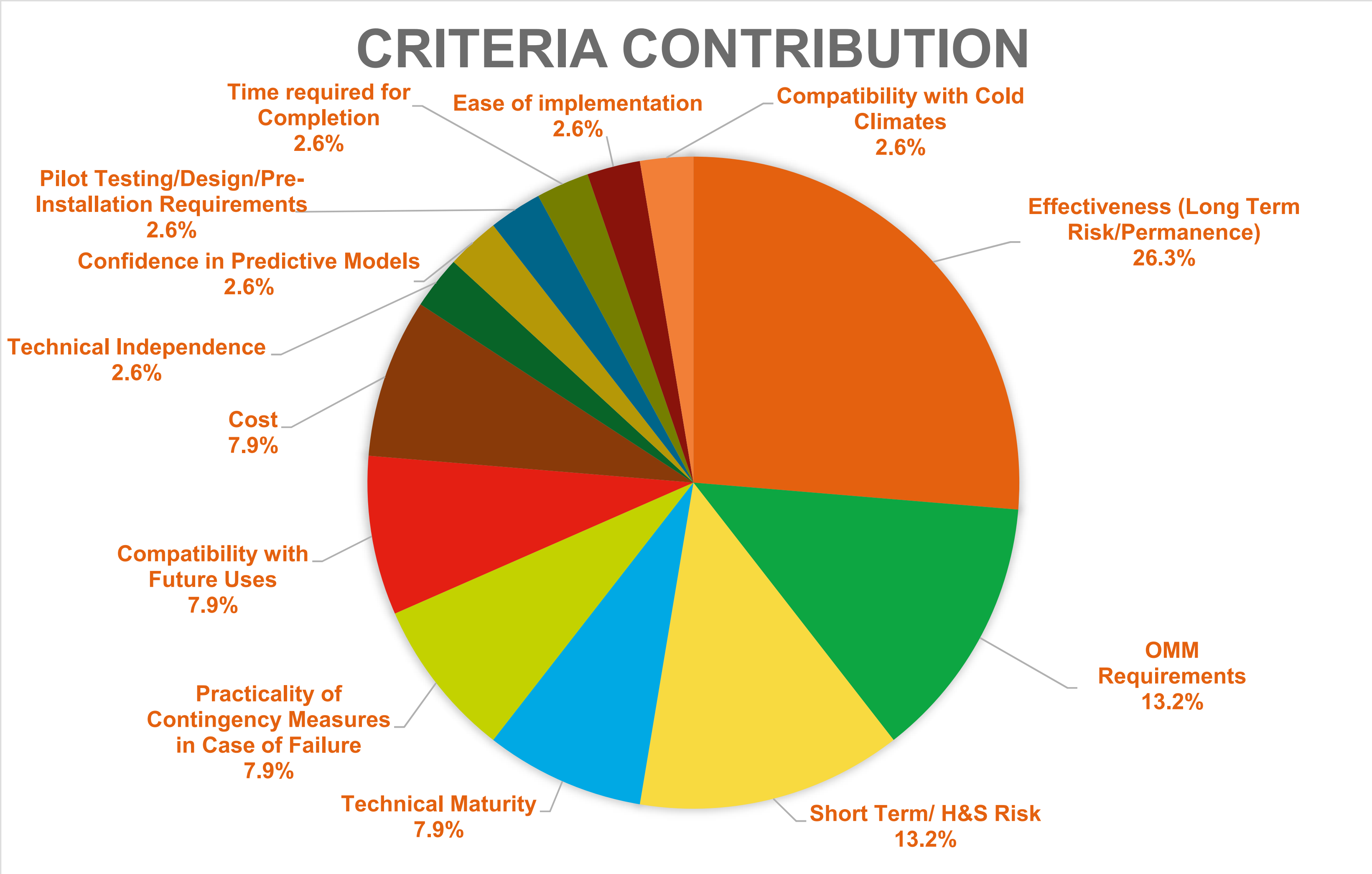

Figure 1. Criteria Contribution to Final Score Based Upon Weight

2.7 Quality Assurance of Technology Ranking

In order to assess the reproducibility of the rating system, one of the treatment methods, ambient pressure and temperature scorodite mineral precipitation was evaluated by two separate expert teams. The ratings from the primary and the secondary group were compared and assessed for comparability. The results of this comparison are discussed in Section 4.2.

2.8 Sensitivity Analysis

Sensitivity analyses were conducted to evaluate the impact of changing effectiveness (long-term risk/permanence), OMM requirements, short-term/ H&S risk which were given priority and high weight, and cost, which was given a medium weight, but depending on stakeholder interest, could play a larger role in the evaluation. The sensitivity analysis is discussed in further detail in Section 4.3

3 RESULTS - ARSENIC TRIOXIDE DUST MANAGEMENT METHODS

This section presents the results of the evaluation. In order to establish a baseline for comparison to the other methods, the results of the Frozen Block method are presented first, followed by the In Situ Management methods (nano-Zero Valent Iron [nZVI], In Situ Biological Precipitation), Dust Extraction/Mining (Remote Mechanical Mining and Hydraulic Borehole Mining), Waste Stabilization and Processing (Cement Stabilization, Cement Paste Backfill, Vitrification, Mineral Precipitation (Scorodite), and Ex Situ Biological Precipitation (Oxidative and Reductive). Bitumen/Asphalt stabilization is briefly discussed. Finally, Physical Isolation and Disposal methods (Sand Shell Storage Chambers) are evaluated.

3.1 Frozen Block (FB) Method

The Frozen Block (FB) Method was evaluated on January 9, 2017 by Rich Royer, Ph.D. and Kathryn Farris, M.S. of Arcadis as a baseline evaluation.

The FB method is the remedial method currently being implemented at the Giant Mine, and is considered the "100-year interim solution" for the arsenic dust. Ground freezing technology is robust and has been in use at the industrial scale for decades. The process as it relates to the Giant Mine is summarized below.

The FB method stabilizes the dust by freezing the ground surrounding the dust chambers and stopes. Water in contact with the frozen ground will freeze, creating a capsule that limits groundwater exposure to the waste. These frozen conditions would be implemented initially as a hybrid active/passive system. Active freezing is accomplished by circulating a cold liquid through pipes installed in the ground. Passive freezing uses thermosyphons which syphon heat from the ground and disperse it into cold air at the surface. This process, unlike active freezing, requires no additional energy input after initial installation. Pilot studies were conducted at the Giant Mine between 2013 and 2015 to evaluate potential trade-offs and optimization parameters. The frozen block method is described in significant detail in the Giant Mine Remediation Project - Developer's Assessment Report completed in October 2010 (INAC and GNWT, 2010).

The scores for the Frozen Block method according to the review criteria are summarized below (Table 9) and are described in more detail in the sections following.

Table 9. Evaluation Results: Frozen Block

Evaluation Criteria	**Frozen Block**
Technical Maturity	High
Effectiveness (Long-term Risk/Permanence)	Moderate
Technical Independence	Very High
Confidence in Predictive Models	High
Pilot Testing/Design/Pre-Installation Requirements	Moderate
OMM Requirements	Moderate
Short-term/ H&S Risk	High (indicating low risk)

Evaluation Criteria	Frozen Block
Practicality of Contingency Measures in Case of Failure	Moderate
Time required for Completion	Moderate
Ease of Implementation	Very High
Compatibility with Future Uses	Moderate
Cost	Moderate
Compatibility with Cold Climates	Very High

3.1.1 Technical Maturity: High

Both active and passive freezing have been implemented for decades and are technically mature. Active freezing is the most common method and has been in use to freeze the ground around tunnels and shafts for over 120 years. It has also been implemented by the mining industry to create frozen underground walls that prevent water from entering mines and as a ground stabilizer for invasive activities.

Passive ground freezing strategies such as thermosyphons have been used for decades to maintain permafrost at shallow depths, and have recently been applied to create frozen walls around shallow contamination. Previous studies at the Giant Mine have tested thermosyphons to preserve and cool areas of thawed permafrost over the depths typical of the arsenic trioxide chambers and stopes since 2002. The data collected during these studies have indicated that the thermosyphons can develop frozen ground to depths of 100 m. As the chambers have total depths in the range of 47-90 m bgs, the studies support the feasibility of freezing the ground across the entire chamber depths.

In addition, the successful implementation of pilot optimization and trade-off studies further support the rating of high technical maturity.

3.1.2 Effectiveness (Long-term Risk/Permanence): Moderate

Assuming the thermosyphons are maintained indefinitely, there is a very high likelihood of long-term stability of the arsenic. The estimated post-implementation arsenic release for this method is 190 kg/year from other sources at the site (i.e. not from the arsenic trioxide dust stored in vaults and chambers) to Baker Creek (INAC, GNWT, 2010), which is well below the required threshold of 2,000 kg/year.

However, because the arsenic is not stabilized chemically or removed from the area, it is inherently soluble and could result in a release if left unmaintained and the frozen block thaws. In the 2010 Developers Assessment Report, thawing and climate change were discussed. In the event of failure of all thermosyphons, it would take approximately ten years before the arsenic dust would warm to -5°C. It was estimated that it would take twenty to fifty years after full failure of the FB system before the integrity of the remedial alternative was compromised. A prolonged lapse in regular maintenance on the thermosyphon network could result in the potential for ground thawing and release of the arsenic. Because of this, FB is scored moderate for effectiveness.

3.1.3 Technical Independence: Very High

The Frozen Block method is a comparatively simple remedial alternative, requiring primarily the installation of active and passive freeze pipes, and a temperature monitoring system. No additional novel or invasive technologies are needed to implement this method; therefore, it scores very high for technical independence. The dust does not need to be extracted in order to implement the Frozen Block method.

3.1.4 Confidence in Predictive Models: High

This scoring criterion does not rate the effectiveness of the technology itself, but rather rates the confidence in the ability to predict the performance of the technology in the field based on developed models. In 2006, SRK reported on a series of thermal modeling simulations of the long-term temperatures in the frozen blocks. The models included information on placement of thermosyphons, thawing and climate change simulations, and evaluations of heat flux. The results from this study indicated that the ground could remain frozen for extended periods of time with limited maintenance and monitoring. The results from the Freeze Optimization Study provided additional information to revise the predictive models including the development of site specific estimates of the thermal properties of the bedrock and calibrated equations to estimate the rate of heat removal by thermosyphons (SRK, 2012). Because of the extensive modeling conducted to date, FB scores high in the confidence in predictive models criterion.

3.1.5 Pilot Testing/Design/Pre-Installation Requirements: Moderate

A series of pilot tests and optimization studies have been conducted to support application of the FB method. This has included optimization of the thermosyphon distribution scheme and the development of more robust parameters for freeze simulations. These studies have taken place over the past five years, and constitute a moderate level of effort for pilot testing.

3.1.6 OMM Requirements: Moderate

Monitoring and maintenance of the thermosyphons in perpetuity is anticipated. Maintenance would include annual inspections of the thermosyphon network and at minimum annual groundwater monitoring after the initial start-up process. Because OMM would be required in-perpetuity, FB ranks moderate in this criterion.

3.1.7 Short-term/ H&S Risk: High (indicating low level of risk)

As with other criteria, the low versus high ranking indicates how a given method scored for that ranking with high being desirable and low being less desirable. Based upon the document *Risk Assessment of Phase 2 Alternatives*, both passive and active ground freezing scored an overall “very low” risk in short-term risk for significant arsenic release and a “low” risk for worker health and safety. This would translate to a high ranking in the scoring matrix, indicating a low level of overall short-term and worker health and safety risk.

3.1.8 Practicality of Contingency Measures in Case of Failure: Moderate

Because this method does not significantly modify the dust characteristics and does not add bulk to the dust formation, any number of other treatment options remain open if the frozen block proves inadequate for long-term arsenic stabilization. The only major concern would be the potential for arsenic release if the dust was thawed prior to additional processing, as it is our understanding there is no contingency measure in place to capture arsenic potentially released during the thaw process. Therefore, FB scores moderate for practicality of contingency measures.

3.1.9 Time Required for Completion: Moderate

During the pilot studies, a range of active and passive systems were evaluated. These studies determined that an aggressive, active approach could have full freezing in approximately 10 years. A less aggressive approach using entirely passive thermosyphons would freeze the dust in approximately 15 years. Based on this evaluation, this method scores moderate for time required for completion.

3.1.10 Ease of Implementation: Very High

This rating criterion evaluates the complexity of a transition from frozen block to a new technology. Therefore, evaluating this criterion to the Frozen Block specifically is difficult. In general, the implementation of the Frozen Block method is moderately complex, requiring a thorough understanding of the thermal properties of both the dust and surrounding rock, development of a freeze pipe design and layout, and implementation. Because there would be no need to transition from FB to another method, FB scores very high in this category.

3.1.11 Compatibility with Future Uses: Moderate

The areas around the freezing infrastructure will be limited from further development. It is understood that the frozen chambers and stopes will be fenced to prevent access (INAC, GNWT, 2010).

3.1.12 Cost: Moderate

In the 2002 SRK Report, costs were given for each method and technology assessed. The Frozen Block method cost was estimated as a net cost of $90-120 million. Assuming a 2% increase in price per annum, the cost for this process in 2017 dollars is an approximate range of $120-160 million. This revised cost range was used as a comparison for the remaining technologies.

3.1.13 Compatibility with Cold Climates: Very high

As the method takes advantage of the site's cold climate, it ranks very high in the compatibility with cold climates scoring criterion.

3.2 In Situ Management

In situ management of the dust at the site could encompass treating the dust itself in-place to render the arsenic immobile, or forming an in situ barrier which would prevent dissolved phase arsenic leaving the storage areas in groundwater. In the latter context, permeable reactive barriers (PRBs), considered a green engineering approach, have been used at full scale for inorganics, including arsenic since the early 2000s to remediate contaminated groundwater.

The EPA defines PRBs as "*An emplacement of reactive media in the subsurface designed to intercept a contaminant plume, provide a flow path through the reactive media, and transform the contaminant(s) into environmentally acceptable forms to attain remediation concentration goals down-gradient of the barrier.*" (Bronstein, 2005).

PRB treatment methods can be divided into two main categories: abiotic and biotic. Abiotic reactive processes result in either oxidation, reduction or precipitation of contaminants through chemical reactions in the subsurface. This can be through emplacement of zero valent iron, furnace slag, sodium dithionite or other materials. Biotic reactive processes harness the metabolic processes of native or augmented microbes to control precipitation or degradation of contaminants. Growth is usually stimulated through either injection or emplacement of liquid or gaseous amendments to facilitate the growth and activities of appropriate microorganisms.

The use of in situ chemical precipitation by nano-zero valent iron (nZVI) was reviewed as part of the evaluation process. Zero valent iron is used commonly as a remediation media for arsenic and other contaminants, and nZVI allows for enhanced injection and higher reactive surface area.

A consensus was reached by the team that nZVI could not be used in situ to stabilize the arsenic trioxide dust en masse as it would be very difficult to ensure sufficient mixing of the nZVI with all of the dust and the significant increase in molar volume resulting from the reaction could pose problems underground. Instead, this technology was reviewed as a secondary component, functioning as a reactive barrier/shell around the dust storage areas. The shell would be created by emplacing the nano-scale ZVI via fracturing into the bedrock around the dust storage areas.

In situ biological PRBs were discussed during the ex situ biological precipitation reviews, but it was determined that that method did not warrant a review due to the significant difficulties in implementation at the site such as difficulties in establishing continuous reactive zones in fractured rock around the arsenic dust deposits, the need for subsequent mobilizations for addition of amendments to maintain proper biological environment, and the potential for less than optimal microbial activity due to temperature and arsenic concentrations.

3.2.1 In Situ Chemical Precipitation/Stabilization (nano-Zero Valent Iron)

Nano-Iron/Zero Valent Iron (nZVI) technologies were evaluated on January 10, 2017. Reviewers were John Vogan M.Sc., David Vance, Ph.D., and Rich Royer, Ph.D., all of Arcadis

The nZVI treatment technology mechanism is a function of arsenic adsorption and co-precipitation reactions with iron oxides. As noted above, coarser grain (often sand-sized) zero-valent iron has been used in permeable reactive barriers for over 20 years, and has been used to treat a variety of contaminants of concern including chlorinated solvents, metals, and metalloids. In aqueous solution, iron oxides are generated through the spontaneous oxidation of Fe (0) to Fe(II), and Fe(III). Arsenic, and other metals are then incorporated into mineral phases, or adsorbed to the surface of the oxides. However, the large particle size of traditional ZVI limits its emplacement (via injection) in fractured subsurface environments such as the Giant Mine. Nano-scale ZVI (nZVI), more recently introduced as a remedial alternative, has a much smaller particle size which enables its distribution via injection methods, and larger surface area which gives it a greater reactivity relative to coarser-grained ZVI.

Application of nZVI and ZVI, and similar treatments are active areas of research. Over the past 10 years, ZVI research has focused on expanding the breadth of application and counteracting the limitations of the technology. Application of magnetic fields, ultrasound, UV-Visible light activation, coupling with other materials such as zeolites or clays, and the addition of other chemical additives, such as surfactants (e.g., EDTA) and polymers have been investigated to enhance activity, injection radius, and stability of nZVI. ZVI technology is well reviewed in the recent paper: *The limitations of applying zero-valent iron technology in contaminant sequestration and the corresponding countermeasures: the development in zero-valent iron technology in the last two decades (1994-2014)* (Li, et al., 2015).

Other metals are also being researched as potential additives for arsenic sequestration/removal. For example, Wu et al. 2016 investigated the capacity of copper powder to remove aqueous arsenic in a hydrochloric acid solution.

This technology could potentially be applied in conjunction with other source-control measures such as the Frozen Block. Application of this technology as a reactive shell could involve two complimentary processes: 1) the adsorption and stabilization of the arsenic onto the iron oxides and 2) the formation of these mineral oxides which would block fractures and impede flow from the storage areas into the surrounding rock. Over the course of several injections, water flow egressing the arsenic trioxide chambers and stopes would be limited and low in arsenic concentration. This could serve as a secondary control in case of less than optimal performance of a primary stabilization method.

The results of the evaluation of treatment with nano-scale ZVI are summarized below (Table 10) and are described in more detail in the sections following.

Table 10. Evaluation Results: Nano Iron/ZVI

Evaluation Criteria	**Nano Iron/ZVI**
Technical Maturity	Low
Effectiveness (Long-term Risk/Permanence)	Very Low
Technical Independence	High
Confidence in Predictive Models	Moderate
Pilot Testing/Design/Pre-Installation Requirements	Very Low
OMM Requirements	Low
Short-term/ H&S Risk	High (indicating low risk)
Practicality of Contingency Measures in Case of Failure	Moderate
Time required for Completion	Moderate
Ease of implementation	Low
Compatibility with Future Uses	High
Cost	Low (indicating high cost)
Compatibility with Cold Climates	High

3.2.1.1 Technical Maturity: Low

ZVI has been implemented at many sites as an amendment in permeable reactive barriers. Numerous laboratory studies have shown that arsenic immobilization can be achieved with ZVI, and the technical underpinnings of the technology are well understood. Both arsenite and arsenate can be removed from solution via these reactions, with arsenate removal usually more effective. However, field scale implementability in bedrock environments is less common (Arcadis has performed a demonstration at a chlorinated solvent bedrock site); nZVI is a newer technology with less long-term field data relative to standard ZVI and other remediation technologies (Bronstein, 2005). To the best of our knowledge, neither ZVI nor nZVI has been applied at the scale required at the Giant Mine site.

3.2.1.2 Effectiveness (Long-Term Risk/Permanence): Very Low

Multiple levels of stability are possible depending on the arsenic speciation and stabilization method. Stabilization with nZVI/ZVI occurs through multiple pathways (adsorption or ferric oxide co-precipitation), and it is difficult to control the stabilization pathways in situ. Therefore, it must be assumed that long-term stability will be a function of both competitive adsorption of arsenite and arsenate to the surface of ferric oxides as well as its incorporation in mineral phases. It is not technically/economically feasible to inject enough nZVI to stabilize the entirety of the stored arsenic trioxide, as the reaction capacity of the nZVI is limited. Because this technology would not eliminate the source of arsenic, its effectiveness as a long-term solution is very low.

3.2.1.3 Technical Independence: High

This scoring criteria evaluates the interdependence of this method with the development of other methods. This technology is highly independent as it could be implemented without necessitating changes to other planned remedial strategies on site. It would have a minimal above-ground footprint. As applied as a shell or barrier, it could be implemented in conjunction with, or after the implementation of the frozen block method.

3.2.1.4 Confidence in Predictive Models: Moderate

This scoring criterion does not rate the effectiveness of the technology itself, but rather rates the confidence in the ability to predict the performance of the technology in the field based on developed models. ZVI and nZVI chemistry is fairly-well understood. Uncertainty exists in its large-scale application in the field, as performance is contingent on accessing all flow pathways. Performance could be assessed during implementation through evaluation of hydraulic head changes and changes in water chemistry in the subsurface. However, identifying, successfully injecting into, and monitoring of fractures that represent conduits between the arsenic dust mass and the external environment is a fundamental challenge with this type of technology.

3.2.1.5 Pilot Testing/design/pre-installation Requirements: Very Low

The dominant arsenic species dissolving from the dust will be arsenite, which may gradually convert to arsenate over time and/or as groundwater enters more oxic environments. Extensive pilot testing of candidate nZVI formulations with respect to arsenite and arsenate removal would need to be conducted. In addition, methodologies for the in situ pre-oxidation of arsenite would need to be investigated, as this step may enhance subsequent arsenic removal when groundwater contacts nZVI.

A major field effort would be required in order to map the subsurface fracture network to design an injection-based remedial system based around this technology.

3.2.1.6 OMM Requirements: Low (indicating high level of OMM)

Due to consumption of the nZVI which 'drives' these reactions, the sorption capacity of the reactive shell would be used up after a period, and at least partial replenishment of reactive nZVI would be necessary. In addition, the potential exists for the identification of additional groundwater flow pathways that had not yet been sealed, requiring additional injections.

Monitoring would need to confirm the reduction of arsenic flux from the storage areas to the surrounding environment. At a minimum, quarterly or annual monitoring programs would have to be implemented initially, as it would be necessary to evaluate the degree of 'shell completion' after initial injections. Depending on the results of the initial monitoring, less frequent monitoring events (e.g., once every 5-10 years) could be implemented.

3.2.1.7 Short-term/ H&S Risk: High (indicating low level of risk)

Because the design for a remedial alternative incorporating nZVI would include Injection points outside of the footprint of the arsenic dust, health and safety risks for both workers and the short-term release of contaminants is low. Extraction of the dust is not included in this remedy, which significantly reduces the risk of a short-term environmental exposure. Due to these considerations, this method scores highly in the short-term health and safety risks because of the minimal risk during injections and low risk of exposure to the dust.

3.2.1.8 Practicality of Contingency Measures in Case of Failure: Moderate

This treatment method would involve an iterative process for identifying flow pathways and remedying them with additional injections. Because this technology would not modify the dust, other potential remedial alternatives could be employed if this technology failed to effectively encapsulate the dust in the long term.

3.2.1.9 Time Required for Completion: Moderate

Anticipated time for implementation is expected to be between 10 and 20 years, including pilot studies. Therefore, it scores "moderate" in the time required for implementation.

3.2.1.10 Ease of Implementation: Low

A transition from Frozen block to this technology would be complex due to the injection process necessary to implement this technology. An initial extensive bedrock investigation would be necessary

to design the emplacement system and multiple injections would likely be needed to ensure complete coverage. However, due to the fact that frozen water will exist in much of preferential flow pathways near the chambers, injection of nZVI would be necessary either outside of the influence of the frozen block, or the chambers would need to be thawed prior to injection, both of these methods would have major impacts on schedule and costs. Additional injection pathways would be required. In addition, any remaining flow pathways initially sealed by the ground freezing may open up during a transfer of technologies, requiring further injections.

3.2.1.11 Compatibility with Future Uses: High

As a standalone technology, impact to future local land use is governed only by the need to access injection locations in virtual perpetuity. However, the potential does exist for some invasive site activity through re-injection of nZVI.

This method could also be combined with additional processes to treat the arsenic dust, which may have larger impact on future uses.

3.2.1.12 Cost: Low (indicating high cost)

Due to the inherent uncertainty in the injection process, and the potential necessity for additional injection events, a wide range of potential costs is possible. In addition, since this technology would only provide a reactive barrier/shell around the dust and could not be applied as the primary treatment method, additional costs would be necessary to stabilize the source material. Therefore, this criterion is scored low, indicating higher costs.

3.2.1.13 Compatibility with Cold Climates: High

nZVI is designed to operate at groundwater temperatures, and the proposed in-field ZVI concentration can be lab tested at the site temperatures to confirm whether the reaction rate at low temperatures is sufficient to accommodate the reduction of anticipated arsenic concentrations in groundwater entering the nZVI zone (i.e., residence time in the reaction zone). A potentially more significant concern is potential loss of reactivity over time as the ZVI surfaces become coated with reaction products.

3.2.2 In Situ Biological Precipitation/Stabilization (Oxidative and Reductive)

In situ biological precipitation is increasingly being used as a passive method to reduce acid rock drainage at mines. Typically at shallower overburden sites, this type of PRB would be composed of organic material, such as mulch or compost and gravel. Alternatively, injections of electron donors such as lactate or ethanol can be directly injected into the subsurface to establish sulphate reducing conditions, modifying subsurface conditions to facilitate metals precipitation and water neutralization. This would likely be the case in bedrock sites like the Giant Mine. Design parameters such as background sulphate concentration, pH, redox potential, and soil type can significantly impact performance of in situ biological precipitation (Mial, Brusseau, Carroll, Carreon-Diazconti, & Johnson, 2012).

Studies on in situ biological precipitation of arsenic have had mixed results due to the toxicity of the arsenic and the potential to form soluble thio-arsenates in sulphate-rich environments (Sun, Quicksaill, Chillrud, Mailloux, & Bostick, 2016). There is also an inherent risk that changing the redox conditions of the groundwater systems to a more anaerobic (reducing) environment can dissolve some iron and arsenic containing minerals. This could result in the mobilization of additional arsenic and other trace metals, an undesirable consequence (Sun, Quicksaill, Chillrud, Mailloux, & Bostick, 2016). The most likely difficulty faced with an in situ process would be the hydrophobicity of the arsenic trioxide dust, itself. The ability to distribute organic carbon as the dust wets and develops and effectively lower permeability will significantly limit the amount of reductant distribution if trying to deliver reagents into the dust. Without aqueous penetration, treatment through an in situ approach injection would be limited. Because of these complications, in situ biological precipitation and stabilization were not evaluated further and no scoring sheets were completed. Ex situ microbial precipitation methods were evaluated and are presented in Sections 3.4.5.1 and 3.4.5.2.

3.3 Dust Extraction/Mining

For a majority of the arsenic dust treatment methods being evaluated in this assessment, dust extraction is a pre-requisite. Mining, in general, requires the integration of several different extraction and transportation methods to effectively extract material from the subsurface. Over the past 15 years, there have not been many new developments in the mechanics of hard rock mining process but there has been significant improvement in the process control and integration of the mining operations. Remote mining has become far more feasible, limiting man-hours involved in direct mining activity and limiting worker exposure to hazardous environments.

Due to the inherent risks present in the mining industry, and in response to an adapting workforce, there has been an industry shift towards automation for several years (Jamasmie, 2010). For example, in 2008, Rio Tinto launched a program called “Mine of the Future™” whose purpose is to find advanced ways to extract minerals deep in the subsurface while minimizing environmental impacts and reducing safety risks. Through this program, they have implemented autonomous haulage systems, automated drilling systems, and automated long-haul railway systems, which are currently in place in a number of mines in western Australia. These mines can now be operated remotely in cities such as Perth at large operations centers (Rio Tinto, n.d.; Jamasmie, 2010). BHP Biliton has also implemented similar technologies at their mines. In Canada, remote mining of hazardous minerals such as high-grade uranium ore at McArthur River and Cigar Lake by Cameco is being conducted. This has established Canadian permitting processes for automated mining equipment, which could reduce permitting time at Giant Mine if these methods are implemented. Health and safety requirements and the exposure risks at McArthur River and Cigar Lake could be considered comparable to the risks posed by mining the arsenic trioxide dust at Giant.

During early implementation, one of the complications of remote mining was signaling and communications. There was a high risk for mining equipment to not sense another piece of equipment, resulting in a high risk of subsurface accidents. Developments in sensors and autonomous vehicle logic are two main advancements that have made it possible to safely direct equipment in the subsurface and allowed autonomous subsurface and surface mining to become a reality (Maekawa, Noda, Tamura, Ozaki, & Machida, 2010; Roberts & Corke). Sophisticated communication networks are present at mines that utilize remote mechanical mining. These frequently integrate radio frequency with optical fiber, allowing for better communication between operators and equipment. In addition, devices which are connected to internet networks aid in equipment deployment, reduce subsurface congestion, and increase efficiency (Siegrist & Gibson, 2017; Schneider, Melkumyan, Murphy, & Nettleton, 2012).

One consideration that influences the choice of an extractive remedial alternative is the commodities market and its effect on mining equipment and labour costs. Significant cost savings could be obtained by carefully choosing the timeline for project initiation. During slower periods in the mining market, the potential exists for significantly lower costs to employ drillers and miners on site because of a lack of potential other opportunities. During upswings in the mining industry, multiple potential opportunities might be available to drillers, who would be less inclined to take on a project such as the Giant Mine, due to its relative health and safety hazards and job complexity.

It is understood that the stability of the crown pillars above the stopes is a concern (INAC and GNWT, 2010). The mining methods used to extract the dust could impact the stability and increase the likelihood of failure. This would need to be taken into consideration when planning and designing any mining activities at the site. The potential for and timing of backfilling of stopes with grout and/or treated materials would be considered as part of this analysis.

3.3.1 Remote Mechanical Mining

Remote Mechanical Mining technologies were evaluated on March 6, 2017 by Scott Bishop, P.Eng., Steven Wuschke, P.Eng. and James Hatley from Cameco Corporation and Rob Whipple, M.Eng., P.Eng. from Rob Whipple Engineering, Inc.

Due to the complexity of the stopes and chambers, it is likely that several different mining methods will be required to effectively remove the arsenic trioxide dust from the subsurface. Underlying mechanisms of mining have remained largely unchanged since 2002, but the automation of many mining tasks, and the ability to remotely mine in potentially hazardous areas has been a major advancement. (Minalliance, 2012). These advancements reduce the health and safety risk to workers, which was identified as one of the main disadvantages to dust extraction during the 2002 evaluation. A summary of these developments is given below.

This review re-evaluated dust extraction assuming a combination of mining methods, including boxhole boring, hydraulic borehole mining and raise boring, would be used. Hydraulic Borehole Mining is also evaluated as a standalone technology as part of this State of Knowledge Review because of its potential to be used on a significant portion of the project, and advancements in this technology since 2002. The remote mechanical mining methods were reviewed with the assumption that the subsurface would already be frozen due to the application of the Frozen Block method.

The 2002 review stated that wet borehole mining would be used to extract 85% of the dust and underground mining (remote mechanical mining methods) or open pit mining would be used for the remainder, depending on which stope or chamber was being mined. Layne Christensen Canada Limited prepared a plan of execution and cost estimate to mine out the dust. They proposed a combination of airlift drilling along with borehole mining with variable elevation monodirectional jetting. They indicated that airlift bulk sampling allows for drilling through very unstable ground without casing. It was proposed to start drilling using airlift bulk sampling technology followed by hydraulic borehole mining when the moisture content became too high for air drilling (SRK, 2002a).

Brief summaries of select remote mechanical mining methods are provided below:

Boxhole Boring

Boxhole boring is a method of mining from below the targeted area (in this case the chambers and stopes containing arsenic trioxide dust). The drill machine would be located in a purpose-built chamber below the chambers/stopes. The drill machine drills a series of overlapping holes into the chambers/stopes then collects the falling dust through a chute that leads to an extraction chamber, also located below the chambers/stopes (Cameco Corporation). Each borehole would be filled with concrete upon completion. For this mining method, the drill and extraction chambers would need to be built for these purposes unless suitable chambers already exist in the mine.

Raise Boring

Raise boring is similar to boxhole boring except that the drill machine would be located in a purpose-built chamber above the dust storage areas. A series of holes ("raise bores") would be drilled into the chambers/stopes and the dust would be collected from above using remote controlled scoop trams located at the bottom of the raise bores. Once each raise bore is complete, it would be filled with concrete (Cameco Corporation).

Hydraulic Borehole Mining

Hydraulic Borehole Mining consists of boring through rock using a high-pressure jet of water. The rock is often frozen in advance of boring to stabilize the area (SRK, 2002a). A pilot hole would first be drilled into the chambers/stopes and the dust would be flushed up the pilot hole. The dust would be pumped to the surface in a slurry form (Cameco Corporation).

A more detailed description and evaluation of Hydraulic Borehole Mining technology as a standalone method is provided in Section 3.3.2.

Airlift Technology

Airlift technology uses the difference in air pressure inside the drill column and on the annulus of the drill column to drill through very unstable ground without casing. Low volume, high pressure air is injected into the drilling string at a certain elevation to lower the pressure and density of the drilling fluid. The air then travels back up to surface while increasing in volume and accelerating the movement of fluid within the drill string. This creates a vacuum below the injection point and suction is developed across the bit face at the bottom of the drill string. High volumes of solids can be transported up the drill string to a solids handling system at surface (SRK, 2002). Air drilling is effective when the moisture content of the rock is not too high. If moisture content of the rock is elevated, the dust that is generated becomes moist and impacts removal and transport. At that point, a wet boring system would need to be used. Due to the hazards of the arsenic dust at Giant Mine, a wet boring system is preferred in order to limit dust generation.

The results of the evaluation of remote mechanical mining methods are summarized below (Table 11) and are described in more detail in the sections following.

Table 11. Evaluation Results: Remote Mechanical Mining

Evaluation Criteria	**Remote Mechanical Mining**
Technical Maturity	Moderate
Effectiveness (Long-term Risk/Permanence)	High
Technical Independence	Low
Confidence in Predictive Models	Moderate
Pilot Testing/Design/Pre-Installation Requirements	Moderate

Evaluation Criteria	Remote Mechanical Mining
OMM Requirements	High
Short-term/ H&S Risk	Low (indicating high risk)
Practicality of Contingency Measures in Case of Failure	High
Time required for Completion	Moderate
Ease of implementation	Moderate
Compatibility with Future Uses	High
Cost	Low (indicating high cost)
Compatibility with Cold Climates	High

3.3.1.1 Technical Maturity: Moderate

The mining equipment used today is generally the same equipment as was used 20 to 30 years ago; however, the reliability and automation of the equipment has increased. The mining methods discussed in Supporting Document 7 of the 2002 SRK report (SRK, 2002a) would likely limit the recovery to 98% or less in some stopes using a combination of methods. The use of additional mining methods such as boxhole, raise bore or hydraulic borehole mining, etc. would increase the dust recovery. Cameco currently uses remote mining methods to mine uranium ore (Cameco Corporation). Their equipment is web and wifi-based so that it can be controlled from many kilometres away. Rio Tinto has increased safety and productivity at their mines using autonomous machinery and drills operated from remote operation centres (Rio Tinto).

Any mining equipment to be used at the Giant Mine would need to be adapted to suit this particular site. The reviewers from Cameco indicated that it took them over five years to automate the equipment they currently use, in part due to the permitting process to allow remote equipment operation. It was anticipated by the reviewers that less time would be required for similar automation at the Giant Mine.

3.3.1.2 Effectiveness (Long-term Risk/Permanence): High

A combination of remote mechanical mining methods could effectively be used to mine out almost all of the arsenic trioxide dust. It would be possible to achieve 98% or more removal; however, the cost would increase significantly from 98% to 99% and from 99% to 99.5%, etc.

3.3.1.3 Technical Independence: Low

A family of remote mining methods were evaluated in combination, and it was determined that the remote mechanical mining methods should be able to remove at least 98% of the arsenic trioxide dust. A higher level of extraction would be possible, but with added costs. It was assumed that the majority of the material mined would be in the form of a wet slurry or paste. Wet borehole mining would be used to extract most of the dust while a combination of other methods would be used for the remainder of the dust.

While a combination of remote mechanical mining methods would be effective at extracting the dust, the dust would still need to be processed, moved and stored after extraction. Extraction alone would not be a sufficient treatment alternative for the arsenic trioxide dust.

3.3.1.4 Confidence in Predictive Models: Moderate

Remote mechanical mining methods have been used effectively in mines throughout the world. A combination of mining methods should be able to extract at least 98% of the dust. The ranking is restricted to the assumed use of geotechnical, geomechanical, hydrological and ground freezing models. The cost and productivity models for this application of remote mechanical mining methods are not robust.

3.3.1.5 Pilot Testing/Design/Pre-Installation Requirements: Moderate

A significant amount of design work would be required to ensure the health and safety of workers on the site to prevent exposure to the dust. Validation testing would be needed for PPE, equipment, ventilation, water management and arsenic containment. No extraordinary testing of the mechanized equipment would be required. The design and testing protocols that are standard for a new mine site would be sufficient. Assessing crown pillar stability during extraction (and possible backfilling) would also be required.

3.3.1.6 OMM Requirements: High (indicating low level of OMM)

Most monitoring needed during mining operations could be done remotely but there would be no long-term maintenance or monitoring requirements related to the remote mechanical mining methods themselves. There would still be a need for long-term groundwater monitoring on the site. Because of the complex nature of the suite of mining methods that would need to be employed, operations and process monitoring during the mining process would be involved. However, as long-term maintenance and monitoring requirements on the site would be minimal, a high score was given to Operation Maintenance and Monitoring.

3.3.1.7 Short-term/ H&S Risk: Low (Indicating high level of risk)

Since 2002, the expansion of remote mechanical mining has lowered the risk to worker health and safety, but mining the dust would still post a high level of risk. PPE requirements for any workers potentially exposed to the dust would be significant. Any work done near the stopes and chambers would require appropriate PPE due to the risk of airborne arsenic trioxide. Appropriate PPE to control potential exposure to dust containing arsenic trioxide would include respiratory protection, protective clothing, gloves and eye protection. The United States National Institute for Occupational Safety and Health (NIOSH) provides requirements for the type of respiratory protective equipment recommended for inorganic arsenic exposure (except for the arsenic compounds with significant vapour pressure) based on the airborne concentration of the arsenic compound. Ingestion is considered to represent the most important route of acute exposure of arsenic trioxide (ATSDR,2000). Strict application of safe work practices, including decontamination measures designed to minimize potential exposure via ingestion would therefore be an important part of exposure control. In addition to the risks posed by the arsenic dust, silica dust generation could also be a concern.

The use of PPE would also limit the length of time that each worker could spend underground. A well-designed ventilation system would help to mitigate some of the risks. The use of automated equipment would assist in reducing the risk of dust exposure to workers but it is likely that workers would still be potentially exposed to dust underground or aboveground.

In addition, workers would likely be working in confined spaces, which poses additional risks and health and safety requirements.

Each stope and chamber is different so there will be unique health and safety challenges with each one; however, the processing of the dust would be fairly consistent for the lifetime of the dust extraction operations.

Constructing purpose-built chambers for boxhole boring could present significant health and safety risks depending on the locations of these chambers relative to the dust chambers/vaults.

3.3.1.8 Practicality of Contingency Measures in Case of Failure: High

Multiple mining methods would be used to extract the dust so it would be easier to adapt to a different method during operation.

3.3.1.9 Time Required for Completion: Moderate

The dust would likely be mined from only two to three chambers at a time so full dust extraction would be completed in about 10 to 20 years. The rate of mining is proportional to the budget available; however, the choice of treatment/stabilization technology chosen for the dust could limit the rate at which the dust could be handled at surface. There are likely to be difficulties during mining operations that would temporarily slow extraction.

3.3.1.10 Ease of Implementation: Moderate

All of the proposed remote mechanical mining methods are already in use in other mines throughout the world so it would be a matter of modifying existing equipment to suit the Giant Mine site. Most of the mining methods discussed work well in frozen ground. Cameco and others already mine in frozen ground, where freezing the rock often needs to be done in advance of mining, (Cameco Corporation) so it would be possible to begin mining without unfreezing the dust and surrounding rock.

3.3.1.11 Compatibility with Future Uses: High

The footprint during dust extraction would likely be very small as most of the activity would be underground. Most of the surface disruption would be dependent on how the dust is processed at surface after it is extracted. It is assumed that dust extraction would be coordinated with treatment to avoid the need to store any quantities of untreated dust at surface.

3.3.1.12 Cost: Low

The cost would be significantly affected by what percentage of dust removal is required at the site. The cost to remove 98% of the dust would be exponentially less than the cost to remove 99% or 99.5%. The cost of mining would likely be well over $1,000/tonne with added health and safety issues associated with the dust. The duration of mining activities would also affect the cost of dust removal. Although it is anticipated that the dust could be extracted in 10 to 20 years, this timeline could be sped up by operating additional mining equipment at different chambers and stopes concurrently (more than two to three chambers/stopes at one time), which would increase the yearly project costs.

3.3.1.13 Compatibility with Cold Climates: High

Mining operations in cold weather would be possible but likely slower due to more equipment malfunctions. The mining could be run seasonally but there would then be issues associated with laying off and retraining staff every season.

3.3.2 Hydraulic Borehole Mining

Hydraulic Borehole Mining (HBHM) was reviewed as a standalone method on March 16, 2017 by Colin Kinley from Kinley Exploration LLC and Rob Whipple, M.Eng., P.Eng. from Rob Whipple Engineering, Inc. Kinley Exploration LLC provides engineering advisory services and supplies and operates hydraulic borehole mining equipment. Mr. Kinley was involved with the previous evaluation of drilling and dust extraction methods (SRK, 2002a). HBHM was reviewed as a standalone method since it is now considered possible to extract all (or the vast majority) of the dust with this method alone. Further details on the advances in this technology since 2002 are discussed below.

Hydraulic Borehole Mining is defined as a remote method of mining through strategically located boreholes by means of high pressure fluid jets. The resulting slurry of rock and water is then pumped to the surface for further processing (Cameco Corporation, n.d.). There are several advantages associated with borehole mining relative to conventional mining, including: increased safety, the ability to work in remote or hazardous areas, a reduction in adverse environmental impacts due to smaller footprint, increased mobility, increased selectivity in complex geologic environments, lower capital cost, improved system simplicity, and the ability to operate in a variety of ground conditions and hazardous operating conditions (Wiley & Abramov, 2004). HBHM may also provide a method for stabilized dust emplacement; putting the stabilized arsenic dust back underground via injection.

The 2002 SRK review stated that HBHM would be used to extract 85% of the dust and underground mining (remote mechanical mining methods) or open pit mining would be used for the remainder, depending on which stope or chamber was being mined. At the time of the 2002 review, Layne Christensen Canada Limited prepared a plan of execution and cost estimate to mine out the dust. A combination of hydraulic airlift bulk sampling along with borehole mining with variable elevation monodirectional jetting was proposed. The hydraulic airlift bulk sampling would allow for drilling through very unstable ground without casing. Hydraulic airlift bulk sampling technology would be would be followed by hydraulic borehole mining when the moisture content became too high for air drilling (SRK, 2002).

Since 2002, the major advancements in Hydraulic Borehole Mining technology include the extension of reach and the ability to model both jetting operations and structural stability of the mined-out areas. One of the main drawbacks to HBHM in 2002 was the large motors and high energy requirements necessary to generate an appropriate level of laminar (i.e., cutting) flow. The large machinery footprint reduced maneuverability and limited application. Hydraulic modeling for flow management has advanced, optimizing flow parameters and streamlining the mining process. HBHM is now applicable in a wider area of applications, including difficult mining conditions such as thin-seam coal deposits (Akbarzadeh & Miller, 2015).

In addition, a variety of polymers have been used to extend the radius of reach for the cutting fluid and increase the range of materials that can be successfully cut using water jet cutting (Oglesby, Padsalgikar, & Mohan, 2015).

HBHM technology was reviewed with the assumption that the subsurface would already be frozen. This presents several advantages as HBHM often works better in frozen ground. There would be less mixing of the remaining dust in the bottom of the stopes and chambers as well as during placement of the backfill. There would also be less dust generated during re-stoping. Transportation of the mined material (rock and dust) would result in less airborne arsenic trioxide than working with unfrozen material; however, freezing may not reduce the airborne arsenic trioxide generated from the dry dust (SRK, 2002a). One disadvantage associated with freezing would be the preclusion of the use of wet (slurry) recovery methods for any of the dust remaining after wet borehole mining, as the mass would already be frozen (SRK, 2002a).

The results of the evaluation of hydraulic borehole mining are summarized below (Table 12) and are described in more detail in the sections following.

Table 12. Evaluation Results: Hydraulic Borehole Mining

Evaluation Criteria	**Hydraulic Borehole Mining**
Technical Maturity	Very High
Effectiveness (Long-term Risk/Permanence)	High
Technical Independence	Low
Confidence in Predictive Models	Very High
Pilot Testing/Design/Pre-Installation Requirements	High
OMM Requirements	Very High
Short-term/ H&S Risk	High (indicating low risk)
Practicality of Contingency Measures in Case of Failure	High
Time required for Completion	Moderate
Ease of implementation	Moderate
Compatibility with Future Uses	Very High
Cost	Very High (indicating very low cost)
Compatibility with Cold Climates	High

3.3.2.1 Technical Maturity: Very High

HBHM technology has been in practice for over 100 years and is used in mines throughout the world, Including at mines in northern Canada. This method ranked higher than Remote Mechanical Mining as HBHM alone would not require significant adaptation for the site. In addition, some of the mining technologies included in Remote Mechanical Mining are less technologically mature than HBHM alone.

3.3.2.2 Effectiveness (Long-Term Risk/Permanence): High

HBHM is commonly used for both vertical and horizontal drilling and extraction. It would be possible to achieve 98% or more removal of the dust; however, the cost would increase significantly from 98% to 99%

and from 99% to 99.5%, etc. It was estimated during the call that 20% of the budget would be used to extract the last 5% of the dust.

It was also noted that hydraulic HBHM would be more effective than pneumatic boring as the use of high pressure air could cause major dust and health and issue concerns.

The possible presence of unknown foreign materials (e.g., debris, abandoned equipment) other than dust in the stopes and chambers could present a problem for HBHM.

This technology is very effective at removing the material; however, effectiveness as evaluated through an entire remedial alternative (extraction, stabilization, emplacement) is contingent on the effectiveness of the stabilization and emplacement methods selected.

The reviewers for both HBHM and remote mechanical mining methods thought that it would be possible to remove 98% of the arsenic trioxide dust using HBHM.

3.3.2.3 Technical Independence: Low

A HBHM system could be designed and built specifically for the Giant Mine using proven technology able to remove at least 98% of the arsenic trioxide dust. However, this method scores poorly in technical independence because subsequent processing that would be required after extraction. It is not a standalone process and would need to be integrated with a larger scale treatment alternative including dust processing, final emplacement and storage.

3.3.2.4 Confidence in Predictive Models: Very High

HBHM technology has been proven to work in mines throughout the world and HBHM equipment has improved since 2002, as described in the section 3.3.2.

3.3.2.5 Pilot Testing/Design/Pre-Installation Requirements: High

Some modification of existing equipment/systems would be required, as is usually completed to accommodate site specific conditions. There would be minimal requirements for pilot testing. Testing of the HBHM equipment would be done on a full scale at the site, most likely in one of the smaller chambers. Crown pillar stability during extraction (and possible backfilling) would also need to be evaluated.

3.3.2.6 OMM Requirements: Very High (indicating low level of OMM)

There would be no long-term maintenance or monitoring requirements related to HBHM. Maintenance required during HBHM would mainly consist of replacement of hydraulics on steel parts. The equipment would be sealed at ground surface so everything should be contained; however, if there was a leak it would be in liquid form. The seals would need to be monitored and maintained.

Since HBHM is a single technology, monitoring and operating the process is far less complicated than the remote mechanical mining methods, therefore a very high score was given to Operation Maintenance and Monitoring.

3.3.2.7 Short-term/ H&S Risk: High (indicating low level of risk)

Since 2002, HBHM has become significantly more versatile and its implementation as a closed system has decreased the level of worker health and safety risks when working with this method. Workers would be isolated from the dust due to seals around the equipment at ground surface and any potential health and safety concerns could be substantially lowered through the use of PPE. There would be some health and safety risk associated with HBHM equipment, relative to risks from arsenic and silica dust exposure; however, the health and safety risk is lower than that of conventional drilling and mining methods.

3.3.2.8 Practicality of Contingency Measures in Case of Failure: High

HBHM, like other mining methods, allows for flexibility during implementation to ensure that extraction can be completed. This contingency score reflects that it would be possible to move from HBHM extraction methods to another. For example, alternate lifting options could be implemented as part of the main HBHM system if one is identified as being insufficient or inadequate for a particular stope. Therefore, the practicality of contingency measures in case of implementation failure is high.

3.3.2.9 Time Required for Completion: Moderate

It was estimated that full dust extraction would be completed in within 10 years. Most of the time spent HBHM would be attributed to the odd geometries within the stopes and mobilization and demobilization at each chamber. It is likely that set up and tear down of the HBHM infrastructure would take longer than the mining itself. Once initiated, it is expected that HBHM would be able to keep up with the chosen dust processing method. Total project completion would be anticipated to occur within 10-20 years.

3.3.2.10 Ease of Implementation: Moderate

In order to get optimal dust removal, some cutting of rock and exterior portions of the surrounding chamber will be necessary, which is feasible with newer HBHM technologies. HBHM through the frozen ground surrounding the dust would likely decrease production and increase horsepower requirements (and therefore extraction costs), relative to more suitable bedrock environments, however it is commonly used in these conditions. Dust extraction rates could be varied to match the production rates of the chosen treatment technology. Cameco use ground freezing in areas such as Cigar Lake, where water-bearing sandstone is present. Without freezing, inflows and flooding could occur resulting in significant environmental and safety consequences (Cameco Corporation). Cameco freezes the overlying (300 metres or so) of water-bearing sandstone in mines such as Cigar Lake to reduce the risk of inflows and flooding that could cause significant impacts to health and safety and the environment. Excavations at McArthur River and other mines are also completed in frozen ground. It would not be necessary to wait until the stopes and chambers thawed before excavation could begin.

3.3.2.11 Compatibility with Future Uses: Very High

The footprint during dust extraction would likely be very small as most of the activity would be underground. Most of the surface disruption would be dependent on how the dust is processed at surface after it is extracted. It is expected that the surface disruption caused by hydraulic borehole mining would be less than if using a combination of remote mechanical mining methods as there would be less mining equipment operating in tandem.

It is assumed that dust extraction would be coordinated with treatment to avoid the need to store any quantities of untreated dust at surface.

3.3.2.12 Cost: Very High

During the discussions with experts, costs to extract the dust using HBHM were estimated at $40-60 million, which is less than the 2002 estimate for a combination of mining methods including open pit mining but more than the estimate for wet borehole mining of about $28 million (to mine 85% if the dust) (SRK, 2002). However, the cost is significantly affected by what percentage of dust removal is required at the site. Significant costs could be incurred in achieving increasing incremental removal rates as the amount of dust remaining in the stopes decreases. The cost of using HBHM alone was considered to be significantly less than using a combination of methods such as open pit mining and boxhole boring along with HBHM.

3.3.2.13 Compatibility with Cold Climates: High

HBHM equipment would be completely self-contained and work conducted indoors. The risks of pipes freezing because of low temperatures are mitigated by installing HBHM system pumps that are individually unitized and redundantly heated. Many mines using HBHM technology are currently operating successfully in Arctic conditions, such as Canadian diamond mines.

3.4 Ex Situ Dust Stabilization and Processing

This section includes the novel and/or advanced methods that relate to the dust stabilization and processing methods, such as isolation and containment, physical stabilization and chemical stabilization. Identified dust stabilization and disposal methods reviewed included: Cement Stabilization, Cement Paste Backfill, Vitrification, and Chemical Stabilization-Precipitation with iron/calcium or other additives. The dust would need to be extracted before implementing any of these stabilization methods.

3.4.1 Cement Stabilization

Cement Stabilization and Solidification (S/S) technology was evaluated on February 3, 2017 by Rich Royer, Ph.D. from Arcadis and Rob Caldwell from SGS.

Cement S/S technology is a widely-used stabilization technique for hazardous waste. Its application to the Giant Mine Arsenic Dust was initially reviewed as part of the *Giant Mine Arsenic Trioxide Management Alternatives Final Report* (SRK, 2002) and was selected as the preferred ex situ treatment method. This method was ultimately discarded due to the data gaps regarding long-term stability of the processed cement monoliths, uncertainties in cement and arsenic stabilization chemistry, and health and safety concerns surrounding arsenic dust extraction and processing. With any ex situ remedial method, dust extraction is still a valid concern. However, numerous recent studies have been completed characterizing the chemical behaviour of arsenic stabilized by cement and the arsenic stabilization mechanism is much better understood, yielding additional insight into the behaviour of the arsenic dust in cement the cement matrix.

Cement stabilization treatment combines both physical encapsulation of the dust with a chemical stabilization through the formation of calcium arsenate minerals. These minerals are stable under a variety of conditions, however high pore-water pH and oxidative conditions are preferred for long-term stability (Bothe & Brown, 1999a; Zhu, Zhang, Xie, Wang, & Cheng, 2006). Physical encapsulation lowers the hydraulic conductivity of the produced monoliths, reducing or virtually eliminating advective transport and limiting arsenic transport to diffusion. This significantly reduces the arsenic flux across the monolith surface and into the environment. The highest risk for arsenic release from the stabilized monolith would occur during curing and the “first wash,” an initial spike in arsenic concentrations due to the release of non-stabilized material present on the surface of the stabilized monolith as water encounters the monolith. Over that time, any surficial arsenic at the surface of the monolith can potentially be mobilized. This initial release could be controlled via capture of all impacted water. Once a monolith has fully cured and the initial arsenic flush has been captured and treated, the arsenic leaching potential is greatly diminished. Long-term weathering will cause some release of arsenic through carbonation at the surface of the monolith, however, this mineralization process builds a barrier or shell on the monolith surface which is more resistant to subsequent weathering. Therefore, carbonation becomes a self-limiting alteration process (Swash & Monhemius, 1995).

Since 2002, cement stabilization and solidification research has focused on evaluating stabilization admixtures as well as understanding underlying chemical principles associated with the stabilization process. Examples of admixtures that studies have focused on include Portland cement with and without iron, lime, fly ash, and slag (Singh & Pant, 2006; Leist, Casey, & Caridi, 2003). Results of these studies have shown that the stabilization and solidification process of arsenic is a combination of both chemical and physical processes and that leaching capacity is highly dependent on the buffering capacity and pH of the stabilized matrix. This highlights the need for testing of candidate treatment mixtures with the dust to be treated (Sullivan, Tyrer, Cheesman, & Graham, 2010). A cement stabilization treatability study on arsenic dust similar in composition to that present at the Giant Mine found that it is possible to effectively stabilize high arsenic containing dust by cement stabilization and solidification (Arcadis, 2016).

For the purpose of this evaluation, it was assumed that the dust would be mined, brought to the surface, and stabilized in a mixing plant on site for either surface disposal in a lined landfill (as proposed previously by Terriplan Consultants in their July 2003 report), deposited by re-stoping, or transported off site (Terriplan Consultants, 2003).

The results of the evaluation of cement stabilization are summarized below and are described in more detail in the sections following.

Table 13. Evaluation Results: Cement Stabilization

Evaluation Criteria	Cement Stabilization
Technical Maturity	High
Effectiveness (Long-term Risk/Permanence)	High
Technical Independence	Moderate
Confidence in Predictive Models	Moderate
Pilot Testing/Design/Pre-Installation Requirements	Moderate
OMM Requirements	High

Evaluation Criteria	Cement Stabilization
Short-term/ H&S Risk	Low (indicating high risk)
Practicality of Contingency Measures in Case of Failure	Very Low
Time required for Completion	Moderate
Ease of implementation	High
Compatibility with Future Uses	High
Cost	Very Low (indicating very high cost)
Compatibility with Cold Climates	High

3.4.1.1 Technical Maturity: High

Cement stabilization and solidification as a treatment technology is in use widely in the mining and remediation industries. There is a small body of research pertaining to cement stabilization with high-arsenic containing waste media. For example, Palfy et al. 1999 evaluated the stabilization of an arsenic sludge from carbon dioxide scrubbing. The waste mixture consisted of 163,000 ppm (16.3%) arsenic. A S/S admixture with Portland cement, ferric sulphate and lime effectively stabilized the waste, reducing arsenic in leachate from 6,340 ppm to 0.02 ppm (Palfy, Vircikova, & Molnar, 1999). Treatment of an approximately 40% arsenic by weight baghouse dust using cement and lime mixture was also shown to be effective in one study (Arcadis, 2016); however, optimization of process parameters through significant bench scale and pilot scale testing would be required.

3.4.1.2 Effectiveness (Long-term Risk/Permanence): High

Arsenic stabilization in calcium/lime-rich cement matrices has proven chemical stability through both mineral incorporation as well as arsenic fixation onto hydrate minerals. The structural stability and limitation of water contact with the dust due to the cementitious matrix provides an additional level of arsenic immobilization. Assuming that flow through the monolith is limited due to reduced hydraulic conductivity compared to the surrounding rock, the stability of the treated dust would be very high. During the method review, one expert indicated that he had worked with cement stabilized uranium waste and evaluated the integrity of the stabilized monolith 15 years post-stabilization. Very little change or degradation of the stabilized matrix was observed.

3.4.1.3 Technical Independence: Moderate

Any ex situ treatment method is highly dependent on the development of mining methods that are able to extract the arsenic dust safely: minimizing risk for arsenic release to the atmosphere, worker exposure, and maximizing dust recovery.

However, this technology does not require complete arsenic dust dissolution, or additional residuals management as would be necessary with methods such as mineral precipitation. Therefore, it scores moderate in technical independence.

3.4.1.4 Confidence in Predictive Models: Moderate

Long-term performance of cement stabilized waste forms has been shown to have a high level of stability once the early curing period is completed. After the initial wash of arsenic off the surface of the monolith, during which enhanced treatment of the water would be necessary, release would be limited to diffusion which can be measured and modeled to calculate the contaminant release rate from the matrix into the environment.

Similar to cement paste backfill, one area of cement stabilization behaviour that has not yet been fully modeled at this magnitude is the “first wash” - an initial spike in arsenic concentrations due to the release of non-stabilized material present on the surface of the stabilized monolith as water initially encounters the monolith.

This first wash would have to be monitored and measures would have to be taken to ensure adequate capture of the arsenic impacted water was achieved by the mine’s pump and treat systeoum. This would be applicable only if the dust were emplaced in the existing stopes or chambers after stabilization.

3.4.1.5 Pilot testing/design/pre-installation requirements: Moderate

The focus of the pilot testing and design phase would be on the formulation of the cement admixture. Because of the significant differences in arsenic dust characteristics between chambers B230, B233 and B234 and the remaining dust storage areas, bench scale tests for each different type of dust would need to be performed. Once the formulation(s) was developed, the field application would be similar to other stabilization/solidification projects. Pilot testing would include a small test cell to ensure that full-scale application does not have a negative impact on the cured matrix. Evaluation of heat evolution during mixing would also need to be evaluated in scale-up procedures.

3.4.1.6 OMM Requirements: High (indicating low level of OMM)

As with all treatment methods where the dust would be stabilized and stored on-site, compliance monitoring in-perpetuity would be needed. After initial implementation, quarterly sampling would be required to monitor the first wash and ensure that contaminated water is being captured and treated and not migrating off-site. After this initial period of monitoring and water treatment, the monolith would be essentially inert and would require no additional maintenance, unless compliance sampling identified resolubilization of arsenic.

3.4.1.7 Short-term/ H&S Risk: Low (indicating high level of risk)

As with any ex situ process, there is a high risk of a short-term release and worker health and safety exposure. This risk can be mitigated through wetting the arsenic dust, and establishing health and safety protocols prior to initiating the remedial program. In addition, heat evolution during mixing of large quantities of cement must be monitored and presents an additional risk.

Mixing large quantities of cement would be expected to generate airborne silica. Appropriate measures would need to be undertaken to minimize occupational exposure (NIOSH, 2014).

3.4.1.8 Practicality of Contingency Measures in Case of Failure: Very Low

The result of this treatment method is a large number of monoliths that have a high structural integrity. Assuming that the desired stability can be reached with a 17% dust loading, a loading achieved in a previous study, approximately 1.4 million tonnes of the stabilized arsenic mass will be generated (Arcadis, 2016). If the stabilized mass fails to achieve the designed level of stability, feasible contingency methods are minimal. It is, effectively, a “one shot operation.” Pump and treat could potentially be the only practical contingency method available.

3.4.1.9 Time Required for Completion: Moderate

Similar to Cement Paste Backfill, rates for cement stabilization processing vary and are based on desired design and performance parameters. Higher processing and emplacement rates can be achieved at higher costs Processing the dust could be done reasonably fast, depending on budget and available space for operations. A recent study on a similar waste designed a processing plant that operated at approximately 1,000 tonnes per month, translating to approximately 20 years of operation given the mass of dust at the Giant site. However, this was a small project, and faster rates could be achieved with a larger operation.

3.4.1.10 Ease of Implementation: High

A transition from the frozen block method to cement stabilization method would be moderately complex, driven primarily by the ability to remove the material from the ground. If an extraction process such as hydraulic borehole mining was involved, the mixture being brought up would be a slurry mix of both frozen and unfrozen dust with varying levels of saturation. Processing of the dust would have to include agitation to ensure that the dust is homogeneously distributed within the process mix. But this process is much less complicated than ensuring dissolution of arsenic, as is required by methods such as mineral precipitation.

After curing, the dust could either be transported off-site or transported back to the subsurface. Both options, however, incur costs beyond that required for extraction and stabilization. An alternative could be storage in lined areas at the surface of the mine site, which could impact future uses of the mine area (see below). This is a trade-off that would need to be evaluated.

3.4.1.11 Compatibility with Future Uses: High

Final storage would have an impact on future uses of the local area. The impact to future use would be less if the stabilized monoliths were stored underground or transported off-site to a lined landfill as there would be little to no long-term footprint on the site. Transportation of the stabilized monoliths into the subsurface would increase the total costs of the remediation project, as would transportation off-site to a lined landfill. Subsurface deposition would also be contingent on verification that the material could be stable within the subsurface and maintain an arsenic flux rate below the threshold of 2,000 kg/year. As surface storage would involve a significant area of land dedicated to housing the stabilized dust, future use of that land would be limited. The ranking of this category has only considered the impact to future use on the Giant Mine site and not to future use of an off-site storage facility. Possible storage options are discussed further in Section 4.4.5.

An additional concern would be the footprint of the processing equipment. Assuming the dust is processed at surface, disturbance of site development would occur while implementing the remedial alternative. While the storage of monoliths as described above would need to be considered, because of the trade offs in short-term site disturbance for long-term stability, this method ranks high in the compatibility with future uses at the site.

3.4.1.12 Cost: Very Low (indicating very high cost)

Cement and binders are typically the most significant costs of a cement stabilization project. Tests with similar material have shown possible loadings of up to 21% arsenic dust. Before costs estimates can be given, treatability tests would have to be conducted. Assuming 17% dust loading, $412 CAD/tonne for lime and $250 CAD/tonne for cement, reagent costs to treat the dust would be approximately $165 million CAD. Capital costs for mixers, pugmill, material shipment and site preparation and health and safety, as well as extraction and final emplacement or removal are expected to exceed $200 million, and therefore this technology receives a very low score.

3.4.1.13 Compatibility with Cold Climates: High

One major consideration with cement stabilization processes is the large amount of heat that is evolved during the cementation reaction. During large volume cement processing, the cement/water mixture can quickly reach boiling, and a major design consideration concerns how to regulate temperature and prevent the evaporation of water for hydration. The cold northern climate assists in regulating the temperature and a lower temperature could be a benefit, as less temperature regulation and cooling time would be required during the cooler months.

3.4.2 Cement Paste Backfill

Cement Paste Backfill (CPB) technology was evaluated on February 3, 2017 by Professor Mostafa Benzaazoua, Ph.D. from the University of Quebec and Patsy Moran, Ph.D. from Arcadis.

Paste backfilling technology is a disposal technique for mine tailings that has gained popularity within the mining industry to provide structural support in underground mines, eliminate or reduce surface storage of tailings, and reduce the overall environmental footprint of mining operations. Paste is defined as dewatered tailings with a high concentration of fine particles (recommended at least 15-20% solids finer than 20 µm). The high fines concentration reduces friction and allows high-solids-containing mixtures to be pumped with minimal production of bleed water, which is water in the cement that rises to the surface of the freshly placed material. Cement paste includes low concentrations of hydraulic binder (commonly 3-7% total weight of the solid). In addition to the benefits listed above, research has identified CPB as a method to control or limit the development of acid rock drainage and the migration of metals and other contaminants (Mehling Environmental Management Inc., 2006; Hamberg, Maurice, & Alakangas, 2015).

CPB stabilization performs similarly to that of cement stabilization, combining both physical encapsulation of the dust and chemical stabilization through calcium arsenate formation and arsenic sorption onto calcium-silicate-hydrates (CSH) (Hamberg, Maurice, & Alakangas, 2015; Coussy, Benzaazoua, Blank, Moszkowidz, & Bussiere, 2011). Similar to cement stabilization, physical encapsulation lowers the hydraulic conductivity of the monolith, reducing or eliminating advective transport and limiting arsenic release to diffusion. This significantly reduces the arsenic flux across the monolith surface and into the environment. The highest risk for arsenic release from the stabilized monolith would occur during curing and the “first wash," which is an initial spike in arsenic concentrations due to the release of non-stabilized material present on the surface of the stabilized monolith as water encounters the monolith. Over that time, surficial arsenic associated with the monolith can mobilize. This initial release would be mitigated through pump and treat measures.

The primary difference between cement stabilization and CPB is the strength of the produced monolith. In CPB, a high strength monolith is not the design priority and the unconfined compressive strength (UCS) for these mixtures is often less than 500 kPA after 28 days of curing (Fall, Benzaazoua, & Ouellet, 2004). Cement stabilized dust monoliths, on the other hand, are designed to withstand significant loading and have UCS that range from 4 MPa to greater than 15 MPa. This results in a material that is far less susceptible to crumbling, which would increase the surface area exposed to water and could result in greater arsenic release. This is a concern that will need to be addressed if CPB is to be implemented.

For additional information on CPB, including characterization and testing requirements, data gaps, and an evaluation on its performance in cold climates, the review by Lena Alakangas, Denis Dagly and Sven Knutsson is highly recommended (Alakangas, Dagli, & Knutsson, 2013).

For the purpose of this evaluation, it was assumed that the dust would be re-mined, brought to the surface, and stabilized in a mixing plant on site for before being pumped back into the subsurface for final disposal.

The results of the evaluation of cement paste backfill technology are summarized below and are described in more detail in the sections following.

Table 14. Evaluation Results: Cement Paste Backfill

Evaluation Criteria	**Cement Paste Backfill**
Technical Maturity	Moderate
Effectiveness (Long-term Risk/Permanence)	Moderate
Technical Independence	Moderate
Confidence in Predictive Models	Low
Pilot Testing/Design/Pre-Installation Requirements	Low
OMM Requirements	Moderate
Short-term/ H&S Risk	Low (indicating high risk)
Practicality of Contingency Measures in Case of Failure	Very Low
Time required for Completion	High
Ease of implementation	Moderate
Compatibility with Future Uses	High
Cost	Moderate
Compatibility with Cold Climates	Moderate

3.4.2.1 Technical Maturity: Moderate

CPB technology as it applies to providing stope stability is mature. Pumping requirements and material characterization and design are also well understood (Fall, Benzaazoua, & Ouellet, 2004); however, its application to arsenic stabilization is not. Research has been conducted investigating the stabilization effects of CPB on arsenic (Coussy, Benzaazoua, Blanc, Moszkowicz, & Bussiere, 2012; Coussy, Benzaazoua, Blank, Moszkowidz, & Bussiere, 2011; Benzaazoua, Marion, Picquet, & Bussiere, 2004; Hamberg, Maurice, & Alakangas, 2015). Additional bench scale studies would need to be performed with the Giant Mine dust in order to establish whether the technology as it is currently applied could be implemented at the site.

3.4.2.2 Effectiveness (Long-Term Risk/Permanence): Moderate

Arsenic stabilization in calcium/lime-rich cemented backfill has proven chemical stability through both mineral incorporation as well as arsenic fixation onto hydrates (Coussy, Benzaazoua, Blanc, Moszkowicz, & Bussiere, 2012; Coussy, Paktunc, Rose, & Benzaazoua, 2012). After an initial flush of non-incorporated arsenic, the long-term release of arsenic is expected to be controlled by diffusion. However, this evaluation has been limited to bench scale studies, and uncertainty still exists over the long-term geochemical stability (Alakangas, Dagli, & Knutsson, 2013).

3.4.2.3 Technical Independence: Moderate

Any ex situ stabilization method requires safe and effective mining methods for the arsenic dust. Because of this requirement, cement paste backfill's technical independence, has been given a moderate rating. It cannot be implemented unless additional technologies have reached a maturity level such that they could also be implemented on the site.

3.4.2.4 Confidence in Predictive Models: Low

Arsenic stabilization by lime and cement additives has been demonstrated on both bench and field scales. However, field scale implementation has been limited to low concentration arsenic media in soils (United States Environmental Protection Agency, 2001). Limited modeling or studies have been completed to date studying CPB combined with high arsenic content dust and long-term evaluations on geochemical stability are limited (Alakangas, Dagli, & Knutsson, 2013). Significant bench testing would be required to develop accurate source terms and parameters to establish accurate predictive models.

One area of cement paste backfill behaviour that has not yet been fully modeled is the "first wash"- an initial spike in arsenic concentrations due to the release of non-stabilized material present on the surface of the stabilized monolith as water encounters the monolith. As stated in the technology application section, this first wash would have to be monitored and measures would have to be taken to ensure adequate capture of the arsenic impacted water was achieved by the mine's pump and treat system.

3.4.2.5 Pilot Testing/Design/Pre-Installation Requirements: Low

In order to evaluate the effectiveness of arsenic stabilization by CPB, significant bench scale testing would be required prior to final acceptance of the technology. This would include varying a range of binders, evaluating temperature dependency on curing time and stability during freeze/thaw cycles, and examining geochemical parameters and leaching potential of the stabilized mixtures which could include a number of different leaching tests (e.g., tiered approach, ASTM 1308). Very-fine particle sizes of tailings and especially of the dust can hinder the workability of the material, which can result in an increase in the required amount of superplasticizer required to obtain desired workability. (Kim, Jang, Park, Han, & Kim, 2016).

An additional complication to the design is the heterogeneity of the arsenic dust. Because of changes in tailings processing and roasting in the 1950s, significant differences exist in the dust geochemistry. Concentrations of arsenic in the dust contained in chambers B230, B233 and B234, commissioned prior to 1957 contain significantly lower arsenic concentrations (range 36.1%-45.3% arsenic by weight) compared to the chambers and stopes commissioned after 1958 (average 64.2% by weight). This presents design challenges and additional pilot testing would be required in order to take this variability into consideration.

3.4.2.6 OMM Requirements: Moderate

As with treatment methods where the dust would be stabilized and stored on-site, monitoring would be required. After initial implementation, quarterly sampling would be required to monitor the first wash and ensure that the “first wash” water is being effectively captured and treated. Quarterly monitoring could then likely be reduced to annual monitoring. It is recommended that annual monitoring be continued in perpetuity if possible.

Limited to no maintenance would be required once the stabilized CPB was emplaced and the mine flooded unless annual monitoring indicated potential for release.

3.4.2.7 Short-term/ H&S Risk: Low (indicating high level of risk)

As with any ex situ process, there is a high risk of a short-term release and worker health and safety exposure. This risk can be mitigated through wetting the arsenic dust, and establishing health and safety protocols prior to initiating the remedial program. Much of the risk involved in this method is contingent on the mining and dust extraction methods.

Once extracted, dust processing will have additional safety issues, such as the potential for high heat evolution during mixing.

Mixing large quantities of cement would be expected to generate airborne silica. Occupational exposures to respirable crystalline silica are associated with the development of silicosis, lung cancer and airways diseases (NIOSH, 2014).

3.4.2.8 Practicality of Contingency Measures in Case of Failure: Very Low

Similar to cement stabilization, the result of this treatment method is several cement masses, with a total volume much larger than the initial mass of arsenic dust. Assuming a 1.3% dust loading, based on formulations derived from Coussy, Benzaazoua, Blanc, Moszkowicz, & Bussiere, 2012, a total of 18.5 million tonnes of stabilized CPB would be generated. This would amount to the generation of approximately 10.2 million m^3 of treated dust, assuming a bulk density of 1.8 tonnes/m^3. If it is discovered that the CPB mixture is unable to effectively stabilize the arsenic trioxide dust after full implementation, there would be few contingency measures available. Pump and treat could potentially be the only practical contingency method available.

3.4.2.9 Time Required for Completion: High

Rates for CPB emplacement vary and are based on desired design and performance parameters. Higher processing and emplacement rates can be achieved at higher costs. It is therefore likely that the rate of cement processing would be limited by the rate of dust extraction. Theoretically it would be feasible to process all of the dust in less than 10 years using this method, but would be dependent on budget and available space for operations.

3.4.2.10 Ease of Implementation: Moderate

A transition from the frozen block method to cement stabilization method would be moderately complex, driven primarily by the ability to remove the material from the ground. If an extraction process such as hydraulic borehole mining was involved, the mixture being brought up would be a slurry mix of both frozen and unfrozen dust with varying levels of saturation. Processing of the dust would have to include agitation to ensure that the dust is distributed homogeneously in the process mix.

Once the dust is out of the ground, processing is straightforward and uses methods that are already at scale and being implemented in mines globally.

3.4.2.11 Compatibility with Future Uses: High

The long-term footprint is expected to be minimal since the stabilized dust would be stored primarily in the subsurface, assuming a high enough arsenic loading could be achieved with satisfactory stabilization, and the stopes and underground mine workings have not otherwise been backfilled. This allows for unhindered surface development and high compatibility with future uses. However, during implementation of this remedial method, a larger processing footprint will be required which may interrupt land use during the processing interim.

Because of the trade-offs in short-term site disturbance for long-term stability, this method ranks high in the compatibility with future uses at the site. A very high rating would be minimally invasive both in the short-term during implementation and in the long term.

3.4.2.12 Cost: Moderate

Cost is driven primarily by the chosen admixture and therefore cannot be fully evaluated prior to bench scale testing. A high level cost estimate was developed based on previous CPB efforts completed by the project team using a high cement containing mixture (15% cement). A 20% health and safety contingency was applied to account for the increased health and safety concerns dealing with the arsenic dust. Costs to treat the arsenic dust by CPB would be approximately $95 million without the health and safety contingency and $120 million with the health and safety contingency added. This places CPB in the moderate range for cost.

3.4.2.13 Compatibility with Cold Climates: Moderate

Dissimilarly to the cement stabilization, where cooler temperatures aid in controlling heat evolved during cement curing, cold temperatures may negatively impact the hardening of the paste, and lengthen the curing time required prior to full stabilization. Pilot tests can yield valuable information on the temperature effects on curing time.

A recent literature review was conducted on the potential geochemical and geotechnical effects of adopting paste technology in cold climate conditions (Alakangas, Dagli, & Knutsson, 2013). In that report, several data gaps were identified regarding CPB's application in cold climates. They noted that "although application of paste technology for normal temperatures is relatively well documented, discussions, case studies, and assessments from a geotechnical point of view based on a scientific grounding were noted to be lacking for cold climate conditions." The report also stressed that each site was unique, and a complete geotechnical characterization of the paste type would be crucial.

3.4.3 Vitrification

Vitrification technology was evaluated on February 10, 2017 by Donald Carpenter, Ph.D. and Jeff Gillow, Ph.D. from Arcadis.

Vitrification has been performed at sites both in situ and ex situ. In situ vitrification is conducted by inserting electrodes into soil to carry high currents to melt the soil and convert it to a chemically durable and leaching resistant vitreous mass (Derghazarian, 2010). It has been shown to stabilize arsenic in soil under the right conditions but only to a depth of about 6.1 m (U.S. EPA, 1991). As the depth of the dust in the chambers and stopes is greater than 6.1 m, it is unlikely that all the arsenic could be converted into a stable glass via in situ vitrification. Successful in situ vitrification also requires the presence of suitable glass forming constituents that are missing within the arsenic trioxide dusts. Therefore, vitrification is considered as an ex situ method for the Giant site.

Ex situ processing of the arsenic dust would be possible by adding the dust to a glass mixture. Ex situ vitrification would be carried out by combining the dust with glassmaking materials in a high temperature furnace (Ionescu, T.R., & Barr, 1997). Ex situ vitrification has been used to stabilize ashes resulting from incineration of municipal solid waste and sewage sludge (Bingham & Hand, 2006). Vitrification is also commonly used in the radioactive waste industry and such waste is predicted to remain stable for thousands of years (World Nuclear Association, 2016); however, waste loading in those applications are much lower, and requires Joule-heated-type ceramic melters. A commercial vendor, Dundee Sustainable Technologies (DST), has had success with this process at a pilot stage and is in the process of scaling it up (Dundee Sustainable Technologies, 2016a).

Research has been conducted to determine what quantities of contaminants can be held within the glass. Managing the composition of the feed is critical as different components can affect the process (Bingham & Hand, 2006). Large quantities of silica typically need to be added to create the glass (Ionescu, T.R., & Barr, 1997). DST has created a vitrified product containing up to 20% arsenic, but higher loadings are possible (Dundee Sustainable Technologies, 2016b).

Contaminants can volatilize during vitrification so treatment of the off-gases is required. Processing also includes a period of cooling (U.S. EPA, 1991), which would need to be accommodated in the design. There is also a low added value for re-use of vitrified products (Bingham & Hand, 2006). The glass product would likely need to be either stored on-site (above ground or in the mine) or taken to a landfill for off-site disposal.

Vitrification is an energy intensive process (U.S. EPA, 1991) whether completed in situ or ex situ. Energy consumption is also highly dependent on the water content of the arsenic-bearing dusts. An elevated water content will greatly constrain glass production due to the endothermic requirement of water boiling. Subsequent condensation or maintaining a high-water content within the off-gas treatment system will also pose potential water treatment demands or additional energy consumption requirements.

The results of the evaluation of vitrification are summarized below and are described in more detail in the sections following.

Table 15. Evaluation Results: Vitrification

Evaluation Criteria	Vitrification
Technical Maturity	Moderate
Effectiveness (Long-term Risk/Permanence)	Very High
Technical Independence	Low
Confidence in Predictive Models	High
Pilot Testing/Design/Pre-Installation Requirements	Low
OMM Requirements	Very High
Short-term/ H&S Risk	Low (indicating high risk)
Practicality of Contingency Measures in Case of Failure	Low
Time required for Completion	Low
Ease of implementation	Low
Compatibility with Future Uses	High
Cost	Moderate
Compatibility with Cold Climates	Low

3.4.3.1 Technical Maturity: Moderate

Vitrification is a well-established technology that has been proven to be effective in stabilizing many types of waste (e.g., uranium, ash from municipal solid waste/sewage sludge). It has also been used effectively in treating contaminated soil in situ (U.S. EPA, 1997). It has also been successfully implemented at pilot scale with an arsenic dust with a similar chemical profile. Managing the composition of the dust is crucial to prevent crystallization and ensure the formation of a stable glass solid (Bingham & Hand, 2006). If implemented, a major challenge would be handling a non-uniform feedstock while maintaining continuous production of uniform non-crystalline glass as the composition of the dust in each of the chambers and stopes is variable. Crystal formation destabilizes the glass and could result in higher arsenic leaching capacity. DST has had success stabilizing similar arsenic dust at a pilot scale level at the Thetford Mines in Quebec. DST's proposal is reviewed in more detail later in this section.

3.4.3.2 Effectiveness (Long-term Risk/Permanence): Very High

Vitrification has been used to stabilize metals and high level radioactive waste for decades. If the quality of the glass can be maintained throughout production, meaning that the leachability of the glass continues to meet TCLP requirements, the arsenic will be stabilized for geological time periods (Bacon & McGrail, 2005). Vitrification of an arsenic dust with an arsenic loading of 23.5% was able to pass TCLP with final leachate concentrations ranging from 0.007 mg/L - 1.8 mg/L (United States Environmental Protection Agency, 2002).

As noted above, long-term control of arsenic release is dependent on producing quality glass and a variable feedstock has the potential to complicate this. However, this challenge could be mitigated by the addition of significant amounts of glass-forming components. Because of the low potential for significant release and stabilities over geologic time-scales, vitrification scores very high in the effectiveness criterion.

3.4.3.3 Technical Independence: Low

This scoring criteria evaluates the interdependence of this method with the development of other methods. Any ex situ treatment method is highly dependent on the development of mining methods that are able to extract the arsenic dust safely: minimizing risk for arsenic release to the atmosphere, worker exposure, and maximizing dust recovery. As vitrification of the dust would be an ex situ process, this method ranks poorly in technical independence. An additional challenge would be the collection of arsenic and co-associated mercury emissions due to off-gassing during vitrification of the arsenic trioxide dusts.

As noted previously, in situ vitrification would not be effective at this site due to the depths of the chambers and stopes. In situ vitrification is typically only effective to depths of 6.1 m (U.S. EPA, 1991).

3.4.3.4 Confidence in Predictive Models: High

Vitrification has been proven to effectively stabilize both metal and radioactive wastes over extended time scales as long as a high-quality glass is produced. Research has shown that the presence of chlorides, fluorides, sulphides, and sulphates may interfere with the process, resulting in higher mobility of arsenic in the vitrified product (United States Environmental Protection Agency, 2002). There would be lower confidence in the performance predictability if a crystalline, versus vitrified, product was formed as these have been shown to have poorer performance in leaching tests (Ionescu, Meadowcroft, & Barr, 1997). It has been assumed in ranking this criteria that the pilot testing and OMM requirements for vitrification, discussed below, would ensure that a vitrified, and not crystalline, product would be produced.

3.4.3.5 Pilot Testing/Design/Pre-Installation Requirements: Low

Extensive pilot testing and design would be required prior to implementation. This would include dust preparation (i.e., how to recover the dust and transfer it to the vitrification plant, ratio of melt modifying reagents) and extensive testing to ensure that the composition of the dust in each chamber/stope is sufficiently well understood and that the design accounts for this variable feedstock. The volatile components of the dust would also need to be well understood so that the system could handle volatilization of arsenic and other compounds (e.g., mercury and chromium) (United States Environmental Protection Agency, 2002).

The design would also need to account for the temperature of the emissions from the vitrification plant. As temperatures of 1200°C are anticipated (Dundee Sustainable Technologies, 2016a) and the outdoor air in Yellowknife is well below freezing for much of the year, measures would be needed to ensure the air is cooled before being emitted to the atmosphere. Not doing so could result in an “ice fog” where moisture in the air crystallizes impeding visibility and/or posing a serious icing problem. This could be of concern to the nearby airport.

3.4.3.6 OMM Requirements: Very High (indicating very low level of OMM)

Continuous monitoring of the glass product specifications would be required during production; however, once the vitrification was complete, no further monitoring or maintenance would be required as long as the reactions were controlled and minimal crystals formation occurred.

3.4.3.7 Short-term/ Health & Safety Risk: Low (indicating high level of risk)

As with any ex situ process, there is a high risk of a short-term release and worker health and safety exposure. This risk can be mitigated through wetting the arsenic dust, and establishing health and safety protocols prior to initiating the remedial program. Wetting of the dust may be necessary for the vitrification process. Much of the risk involved in this method is contingent on advances in mining and dust extraction methods.

In addition, the high temperatures required for vitrification would be of themselves a health risk. Arsenic is a volatile metalloid, and arsenic oxides have been shown to volatilize at temperatures well below 400°C (Helsen, Bulck, Bael, Vanhoyland, & Mullens, 2004). To reduce the risk of toxic fumes, preprocessing of the arsenic dust to calcium arsenates or similar is recommended as these do not volatilize at as low temperatures. High levels of ultraviolet light will also be released during the melt and melt “pours” which would require additional vision protection.

Because of these risks, this method is given a low score for short-term health and safety risk, indicating a high level of short-term risk to workers and to the environment.

3.4.3.8 Practicality of Contingency Measures in Case of Failure: Low

In the event that the glass formed failed to effectively stabilize the arsenic dust, it would be difficult to apply an alternative method if vitrification of the dust failed to stabilize the arsenic. The vitrification process will increase overall volume due to additions to the mixture to promote glass formation. Contingency methods would be limited to either pump and treat if the glass is placed below ground (back in the stopes etc.) or in a landfill, or excavation and reprocessing.

3.4.3.9 Time Required for Completion: Low

At a production rate of 20,000 tonnes/year of glass proposed by (Dundee Sustainable Technologies, 2016a) for a full-scale plant, it would take approximately 35 years to fully process all 237,000 tonnes of arsenic trioxide dust, assuming a 20% arsenic loading. Loading rates would need to be determined via bench scale testing. A larger scale plant could be constructed to speed up the process but a larger plant would have a higher energy requirement. A tremendous amount of fuel would be needed to melt all the dust and the dust would need to be dried prior to treatment. Hydroelectric power is the primary energy source for Yellowknife with some power provided through diesel generation (thermal power) (Northwest Territories Power Corporation, 2014). Higher energy requirements associated with a vitrification plant might put a strain on local resources. It would also be possible to operate multiple plants in tandem but this could also substantially increase costs and fuel requirements.

3.4.3.10 Ease of Implementation: Low

In situ vitrification would be nearly impossible due to the depth of the dust chambers and the frozen state of the material. Therefore, removal would be necessary prior to processing. If an extraction process such as hydraulic borehole mining was involved, the resulting mixture would be a slurry mix of both frozen and unfrozen dust with varying levels of saturation. This dust would have to be either dried, or solubilized for further processing.

3.4.3.11 Compatibility with Future Uses: High

During treatment operation, it is estimated that a few acres of land would be required for the vitrification plant, including silos for dust storage, off-gas treatment system, etc. Depending on processing rate, and achievable dust loading, this space would be occupied for over 35 years, which may have a temporary impact on the development of areas adjacent to the processing area. However, once produced, the glass that is formed is essentially inert and should not impact further development on the site from a health standpoint. It may be possible to store the glass above ground or place it below ground. Because of its inert nature, it could conceivably be re-stoped or built upon.

The long-term storage of the glass could also impact future uses at the site if it is decided to store the glass on-site. Possible storage options are discussed further in Section 4.4.5.

3.4.3.12 Cost: Moderate[1]

The cost to vitrify the arsenic trioxide dust was estimated by Dundee to be approximately $1,000/tonne of arsenic, including energy requirements (Dundee Sustainable Technologies, 2016a). This translates to approximately $600/tonne of dust (using the calculated average arsenic content for the Giant Mine Dust of 60%) as the cost is based on the quantity of arsenic to be vitrified but would include vitrification of all the dust. To vitrify the 237,000 tonnes of dust on site, would cost approximately $142,000,000 not including the cost to extract the dust, transfer it to the treatment plant or manage the final vitrified product. This cost estimate has not been verified.

3.4.3.13 Compatibility with Cold Climates: Low

Continuous fuel supply would be a challenge as energy requirements for vitrification are high. There could be potential concerns with generation of an ice fog as previously discussed. The proximity of the site to the airport could pose a problem so this would need to be considered during stack design for off-gas emissions.

DST indicated that emissions would be cooled before release to the atmosphere and they have not reported any issues relating to ice fog at their pilot plant in Thetford Mines, Quebec (Dundee Sustainable Technologies, 2016a).

[1] It is understood that the cost of vitrification is now estimated at approximately $700/tonne of arsenic (equivalent to $420/tonne of dust containing 60% arsenic), based on recent communication with DST. The decrease in cost is attributed to using a furnace model that is more energy efficient than the previous furnace. This change in cost would result in an estimated cost of about $99.5M to vitrify the dust at Giant Mine, which would change the ranking of the cost criteria to High.

3.4.4 Mineral Precipitation Methods

Mineral Precipitation method reviews were conducted on March 3, 3017 by two groups as part of a comparison of Quality Assurance/Quality Control (QA/QC). The first group consisted of Michael Hay, Ph.D. from Arcadis and John Mahoney, Ph.D. from Mahoney Geochemical Consultants LLC; the second group consisted of Jeffrey Gillow, Ph.D. from Arcadis and Professor Heather Jamieson, Ph.D. from Queen's University. The results of each of their reviews are presented below, and separated by a slash (e.g., Moderate/Low for Group 1/Group 2 respectively).

A significant body of literature regarding arsenic stabilization or precipitation methods exists. Some, such as precipitation with lime, sulphide, and iron additives are in practice today at industrial scales. A thorough summary of these methods, as well as methods being developed at the laboratory scale, is given in the recent review: "*Review of arsenic metallurgy: Treatment of arsenical minerals and the immobilization of arsenic"* (Nazari, Radzinski, & Ghahreman, 2016). A brief summary of the primary field-implementable precipitation technologies is given below.

Lime Neutralization: Formation of calcium arsenates and calcium arsenites are an economical solution to arsenic dust management when the final storage area can be controlled and there is limited exposure to ambient water. Calcium arsenates show a higher level of stability compared to calcium arsenites and calcium arsenates combined with stabilization/solidification measures have performed well. Lime neutralization is reviewed as a stabilization component of cement paste backfill and cement stabilization reviews. Other calcium containing mineral precipitates that have been studied include arsenate phosphate hydroxy apatite compounds $(Ca_{10}As_xP_yO_4)_6(OH)_2$ which were resistant to transformation to calcium carbonate (Twidwell et all 2005, lee et al 2009, Zhang et al 2011), and arsenate analogues of fluoroapatite and svabite $(Ca_5(AsO_4)_3F$. However, due to the limited amount of research on these minerals, they were not considered further during this review.

Lime neutralization for arsenic treatment is currently employed at copper smelters in northern Chile in their water treatment process. However, the calcium arsenite products from this process must be disposed of in hazardous waste landfills due to poorer stability compared to calcium arsenates.

Sulphide Precipitation: Arsenic reduction and precipitation to orpiment, realgar, and other sulphide-arsenic minerals has been conducted at major mining operations (e.g., Equity Silver Mine in British Columbia, Canada and Sunshine antimony refinery in Idaho, USA). A number of sulphide precipitation reactions can be used. One method, the THIOTEQ method developed by Paques B.V., is specifically reviewed under the Ex Situ Reductive Bio-precipitation section of this review.

Geopolymer Precipitation: Geopolymerization is an emerging technology for immobilization of toxic metals in waste. Geopolymers refer, generally, to inorganic materials obtained from chemical reactions of alumino-silicate oxides with alkali silicates at low temperatures (Luo, Liu, Zhang, Zhou, & Xia, 2014). Geopolymer application to arsenic wastes has had mixed success. It appears that instead of being directly bound in the geopolymer structure, as is common for other metals, arsenic associates with iron-rich regions of the geopolymers, similar to the stabilization provided by ferric oxyhydroxides, discussed below (Provis, 2009). No studies were identified that utilized waste similar to the Giant Mine arsenic dust.

Ferric Iron Precipitation: Precipitation of arsenic with iron yields a number of metastable arsenic mineral precipitates and adsorbent mineral species, meaning that the minerals are stable under current conditions but could destabilize if conditions change. Arsenic can either be incorporated into or adsorb onto minerals such as jarosite, schwertmannite, goethite, and Fe(III)oxyhydroxide minerals (FOH). One of these minerals, scorodite, has been of particular interest to researchers due to its low solubility, high arsenic content (25-30% weight), and high stability, compactness, and good thickening properties. It is considered one of the safest long-term storage materials for arsenic (Huisman, Weghuis, & Gonzalez, 2011). (Riveros, Dutrizac, & Spencer, 2001). Scorodite is generally produced with a low iron to arsenic ratio (1.1:1) which makes it an economical option for arsenic management. A higher iron to arsenic ratio (>3:1) results in a mixture of crystalline scorodite, amorphous ferric arsenates, and ferric oxyhydroxides. While amorphous ferric arsenates exhibit poor stability by themselves, the mixture of scorodite and amorphous ferric arsenates results in overall higher stability, and therefore lower dissolved arsenic concentrations relative to either scorodite or the amorphous ferric arsenates alone. The reduction in soluble arsenic concentrations is due to either armouring of the early formed ferric arsenate phases, formation of a solid solution or because of the high adsorption affinity of pentavalent arsenic to ferric oxyhydroxides such as ferrihydrite.

Traditional arsenic immobilization through chemical synthesis of scorodite has been achievable at an industrial level for decades. This process requires high temperatures (>150°C), low pH (~0.7) and oxygen overpressures of up to 2,000 kPa (Huisman, Weghuis, & Gonzalez, 2011). During the initial 2002 review, gold recovery and production of scorodite by a pressure oxidation process was reviewed. The high temperature/pressure process was chosen at that time due to the following rationale:

- Lower iron requirements for the pressurized precipitation method (iron to arsenic (Fe:As) molar ratio from 1.1:1 to 1.2:1, versus greater than 3:1);
- Crystalline compounds would be produced, with reasonably well known stability characteristics; crystalline products are easier to filter and form relatively dense waste deposits, resulting in more efficient disposal;
- Plant operating parameters are available from large scale applications for the conversion of arsenic trioxide to scorodite;
- Elimination of the need for large quantities of chemical oxidants, such as hydrogen peroxide, to oxidize arsenic from As(III) to As(V); and
- Higher gold recoveries (typically over 90%).

This method was not chosen at the time due to high operational costs and potential risks associated with mining and dust extraction. Since then, developments have been made in chemical precipitation of scorodite process, including processing at lower temperature and ambient pressure.

<u>Ambient Temperature and Pressure Scorodite/Ferric Arsenate Precipitation</u>

During the initial phase of this review, it was determined that ambient pressure and temperature precipitation of a scorodite/ferric arsenate mixture should be reviewed specifically in further detail due to more recent developments in understanding the stability of iron arsenate species under ambient and circum-neutral environments, mentioned briefly above (Langmuir, Mahoney, & Rowson, 2006).

The dust would be extracted, and then the arsenic trioxide present in the dust would be dissolved. Arsenite that dissolves out of arsenic trioxide would require oxidation to arsenate; oxidants including persulfate, permanganate, hypochlorite, and sulphur dioxide could be appropriate. The choice of oxidant is primarily based upon its solubility and resultant pH. The stability of arsenical ferrihydrite depends upon the molar ratio of iron to arsenic and pH, discussed above. This would have to be determined through bench testing with the dust.

There is significant practical experience with the stability of arsenical ferrihydrite; the Inco CRED plant has operated since 1973 with 300-500 kg/day of arsenic precipitates impounded (over 38 km^2) at pH 5.5 and only 0.02 mg/L of dissolved arsenic (Harris & Krause, 1993). A tailings pond at the Horne Smelter in Quebec produced arsenic trioxide that was converted in a slurry process to arsenical ferrihydrite with arsenic present at <0.5 mg/L in a pH 9 tailings pond (Riveros, Dutrizac, & Spencer, 2001).

It was assumed that the arsenic dust would be extracted, solubilized, processed into stable ferric arsenates/scorodite minerals and then converted into a paste which could be re-injected into the stopes. However, the final disposal process would need to be evaluated based on local regulations and stabilization performance.

The results of the evaluations of mineral precipitation methods are summarized below (Table 16) and are described in more detail in the sections following.

Table 16. Evaluation Results: Mineral Precipitation

Evaluation Criteria	**Mineral Precipitation Group 1**	**Mineral Precipitation Group 2**
Technical Maturity	Very High	Moderate
Effectiveness (Long-Term Risk/Permanence)	High	Moderate
Technical Independence	Very Low	Very Low
Confidence in Predictive Models	High	High
Pilot Testing/Design/Pre-Installation Requirements	Moderate	Moderate
OMM Requirements	High	Moderate
Short-term/ H&S Risk	Low (indicating high risk)	Low (indicating high risk)
Practicality of Contingency Measures in Case of Failure	Low	Moderate
Time required for Completion	Moderate	Moderate
Ease of implementation	Moderate	Moderate
Compatibility with Future Uses	Moderate	Moderate
Cost	Very Low (indicating very high cost)	Very Low (indicating very high cost)
Compatibility with Cold Climates	High	Moderate

3.4.4.1 Technical Maturity: Very High/ Moderate

As described above, various methods of Ferric [Fe(III)] precipitation have been employed at a number of sites globally. Processes such as the one currently employed at the McClean Lake (Mahoney, Slaughter, Langmuir, & Rowson, 2007) can process at a rate of approximately 1 tonne of As per day at a flow rate of about 1500 m^3/day at an assumed maximum As concentration of 700 mg/L. The scorodite process at McClean Lake could be scaled up further. A reasonable estimation of processing would be a treatment concentration of 7,000 mg/L or more combined with a greater flow rate of solution. Scaling up the McClean Lake procedure could process all 237,000 tonnes within 10 years.

As with other treatment processes requiring reaction with dissolved arsenic, solubilization of the arsenic dust is a pre-requisite. Bench scale testing would need to be performed prior to moving forward with this method to identify a pre-processing method that could solubilize the arsenic dust and ensure proper reactivity.

3.4.4.2 Effectiveness (Long-term Risk/Permanence): High/ Moderate

Variations on this approach have been employed at mines throughout the world. Employing a high iron to arsenic ratio method allows for multiple levels of concentration control through the formation of scorodite, ferric arsenates and FOH, as discussed above. Bench scale testing would be required in order to fully understand and characterize the impact of subsurface geochemical conditions in long-term storage. However, depending on the hydraulic conductivity of the resultant paste, a maximum pore water concentration could be calculated, and Fe:As could likely be adjusted in order to limit arsenic flux to less than 2,000 kg/year.

Similar to oxidative bio-precipitation, the development of reducing environments due to climate change is a possibility that could have impacts on stability of the scorodite mineral and therefore the arsenic flux.

3.4.4.3 Technical Independence: Very Low/ Very Low

This scoring criteria evaluates the interdependence of this method with the development of other methods. Any ex situ treatment method is highly dependent on the development of mining methods that are able to extract the arsenic dust safely: minimizing risk for arsenic release to the atmosphere, worker exposure, and maximizing dust recovery. As mineral precipitation is an ex situ process, this method ranks poorly in technical independence.

An intermediary step of solubilizing the arsenic trioxide dust would be necessary likely involving mechanical mixing. While this process is straightforward, it adds an additional processes step and would require pilot tests to examine the most effective methods. Finally, residuals management would need to be considered, since arsenic depleted residuals may still have significant levels of arsenic. These residuals could be looped back into the process for re-extraction. However, final processing of these residuals would be an additional task for the overall dust management strategy.

3.4.4.4 Confidence in Predictive Models: High/ High

Scorodite, and ferric arsenates precipitated at a high Fe:As ratio have been shown to perform very well in long-term studies and thermodynamic models evaluating the stability of oxidized arsenic mineral species are well established (Krause & Ettel, 1988; Nordstrom, Majzlan, & Konigsberger, 2014). Field level data collection and evaluation are available through the AREVA Resources Tailings Optimization and Verification Program for Jeb Mill at McClean Lake, which has been operating for over 17 years (AREVA Resources Canada Inc., 2011). This program has gathered significant amounts of data which could be used to verify the long-term storage performance of this type of waste.

3.4.4.5 Pilot Testing/Design/Pre-Installation Requirements: Moderate/ Moderate

The hydrophobicity of the dust is a major concern and technical challenge. Understanding what conditions best solubilize dust will be a major component of the pilot testing and design. Bench scale testing protocols are well-established for scorodite-based treatment.

3.4.4.6 OMM Requirements: High/ Moderate (indicating low/moderate level of OMM)

OMM requirements would be contingent on the decision for final storage. Based on background groundwater geochemistry, scorodite and amorphous ferric arsenates show better stability than reduced arsenic mineral species. However, if a change in background groundwater geochemistry occurs, either due to climate change or other unforeseen event, there is a potential for degradation of minerals and re-release of arsenic. Because of this, it is recommended that annual monitoring be continued in perpetuity if possible.

If the stabilized material were stored at the surface in a lined and capped landfill, monitoring and maintaining a stable environment would be easier, but would require additional operation, maintenance and monitoring compared to re-stoping.

3.4.4.7 Short-term/ H&S Risk: Low/ Low (indicating high level of risk)

As with any ex situ process, there is a high risk of a short-term release and worker health and safety exposure. This risk can be mitigated through wetting the arsenic dust, and establishing health and safety protocols prior to initiating the remedial program. Much of the risk involved in this method is contingent on the extraction method used.

Process specific health and safety considerations include the use of strong acids and bases. Treatment of metals or ores with acid can lead to the formation of arsine, which is a highly toxic gas. Exposure to arsine in sufficient quantities can be fatal. It is non-irritating, produces no immediate symptoms, and odour is not an adequate indicator of arsine presence, so persons exposed to hazardous levels may be unaware of its presence. NIOSH has classified any concentrations of arsine greater than 3 ppm to be immediately dangerous for life and health (IDLH). Supplied air respirators would be required for arsine at any concentrations above 0.002 mg As/m^3 (NIOSH, 2014).

3.4.4.8 Practicality of Contingency Measures in Case of Failure: Low/ Moderate

Similar to the cement stabilization methods reviewed elsewhere within this report, the 3:1 Fe:As ratio contributes significantly to waste bulking. An estimate developed in PHREEQC, a thermodynamic modeling software, estimates that bulking would be at least 5-6 times initial volume. Failure to achieve effective stabilization and limitation of arsenic flux to 2,000 kg/year would result in the need to reinstate pump and treat over the area. Applying additional ex situ processing methods would require extracting and reprocessing a much larger quantity of waste. Because of these risks, this method scores poorly in this rating criterion.

3.4.4.9 Time Required for Completion: Moderate/ Moderate

The time required for the processing would be contingent on the size of the system. A general consensus among the experts was that 10-20 years of processing would be needed, including pilot testing to refine design parameters.

3.4.4.10 Ease of Implementation: Moderate/ Moderate

A transition from the frozen block method to a mineral precipitation method would be moderately complex, driven primarily by the ability to remove the material from the ground. If an extraction process such as hydraulic borehole mining was involved, the mixture being brought up would be a slurry with a mixture of both frozen and unfrozen dust with varying levels of saturation. A major challenge required in this process would be dissolution of the arsenic. The frozen nature of the dust could complicate that process. Once brought to the surface, the dust would have to be solubilized, and then fed into the oxidation and precipitation systems.

3.4.4.11 Compatibility with Future Uses: Moderate/ Moderate

Final storage decisions would have an impact on future uses of the land. Transportation of the waste material to the subsurface would increase the total costs of the remediation project, as would transportation off-site to a lined landfill. However, both of those options would be most compatible with the future uses of the Giant Mine Area since there would be little to no waste footprint onsite. Subsurface deposition would also be contingent on verification that the material could be stabile within the subsurface and control arsenic flux below the threshold of 2,000 kg/year. Surface storage of the dust would involve a portion of land dedicated to housing the stabilized dust, future use of that land could be limited.

3.4.4.12 Cost: Very Low/Very Low

Estimated iron costs were calculated using an industrial ferric sulphate (45% $Fe_2(SO_4)_3$). Iron cost alone would be over $300 million. Approximately 1.4 million m^3 of iron solution would be required to react with the 240,000 tonnes of AsO_3 at a 3:1 molar ratio. There would also be requirements for acid and base (generally hydrochloric acid and lime) for the acidification and subsequent neutralization reactions. Ferric sulphate solutions are already acidic, so needs for additional acid would most likely be minimal.

3.4.4.13 Compatibility with Cold Climates: High/ Moderate

This technology is currently being employed in at McClean Lake in Northern Saskatchewan, but for much lower concentrations and at throughput rates that are also much lower than expected at Giant Mine. While heating will most likely be required to optimize the process kinetics, none of those requirements would make this process infeasible in cold climates. But the increased operating temperatures would result in a higher level of energy expenditure, and thus higher operational costs.

While current subsurface conditions are oxidizing, there is a risk of long-term warming resulting in an increase in organic material in the groundwater as permafrost areas warm and release natural organic matter. The increase in organic material could produce reducing conditions across the mine area and potentially increase arsenic dissolution.

3.4.5 Ex situ Biological Precipitation

3.4.5.1 Biologically-Mediated Reductive Arsenic Precipitation

Biologically-Mediated Reductive Arsenic Precipitation was evaluated on February 22, 2017 by Professor Heather Jamieson, Ph.D. from Queen's University and Margaret Gentile, Ph.D. from Arcadis.

There are two dominant arsenic sulphide minerals: orpiment (As_2S_3) and realgar (AsS), that can be produced from dissolved arsenic using biologically mediated processes. Orpiment is an arsenic-dense mineral that is 61% arsenic, has no interstitial water, and is the primary product in most arsenic-sulphide producing processes. Both minerals can be formed by combining sulphide with arsenite in an acidic solution. Multiple commercially-produced systems have attempted to take advantage of this process to reduce the amount of soluble arsenic in mine-generated waters. The two dominant technologies are the only ones that have been tested on the industrial scale: THIOTEQ, made by Paques B.V. in The Netherlands and BioSulphide®, made by BioTeq in Canada. Both systems utilize anaerobic sulphate reducing bacteria (SRB) in an isolated bioreactor to produce bisulphide and hydrogen sulphide), which can then be added to a chemical reactor below pH 3 to abiotically precipitate orpiment. Arcadis experience with these systems indicate that the functionality of the systems can be very sensitive to small perturbations and can require mineral de-scaling as often as every 6 months.

For the purpose of this evaluation, it was assumed that the dust would be mined, brought to the surface, dissolved, and processed in a large-scale bioreactor.

The results of the evaluation of biologically-mediated reductive arsenic precipitation are summarized below and are described in more detail in the sections following.

Table 17. Evaluation Results: Biological Reduction

Evaluation Criteria	**Biological Reduction**
Technical Maturity	Moderate
Effectiveness (Long-term Risk/Permanence)	Low
Technical Independence	Very Low
Confidence in Predictive Models	Moderate
Pilot Testing/Design/Pre-Installation Requirements	Low
OMM Requirements	Low
Short-term/ H&S Risk	Low (indicating high risk)
Practicality of Contingency Measures in Case of Failure	Low
Time required for Completion	Moderate
Ease of implementation	Low
Compatibility with Future Uses	Low
Cost	Moderate
Compatibility with Cold Climates	Moderate

3.4.5.1.1 Technical Maturity: Moderate

Reductive biological precipitation processes are in operation at a number of industrial sites globally.

While this technology has been demonstrated at the industrial scale, this method was given a moderate score by the reviewers due to the lack of knowledge regarding dissolution of the arsenic dust. A pre-processing requirement of this technology is solubilizing the arsenic so it is more biologically available. Arsenic trioxide is generally considered soluble (6.2-11.9 g/l) (SRK Consulting, 2002). However, having a generally high solubility does not ensure rapid or easily accomplished complete dissolution of arsenic trioxide. Also, because the arsenic trioxide dust is a complex mixture with multiple components in addition to arsenic trioxide, it cannot be assumed to possess the same solubility as reagent grade arsenic trioxide. Bench scale testing would need to be performed prior to moving forward with this method to identify a pre-processing method that could solubilize the arsenic dust and ensure proper reactivity.

3.4.5.1.2 Effectiveness (Long-term Risk/Permanence): Low

The primary requirement for long-term stability with reduced arsenic minerals is the continued presence of reducing conditions. Assuming complete precipitation of arsenic trioxide into reduced mineral phases (e.g., orpiment and realgar), and maintenance of reducing conditions, long-term stability of these phases would be likely. An evaluation of the solubility reveals a solubility range of $10^{-62.51}$ mol/l – $10^{-64.72}$ mol/l for orpiment (Vlassopoulos, Bessinger, & O'Day, 2010). Realgar is more soluble with a predicted solubility of 10^{-20} mol/l (Lu & Zhu, 2011). In general, orpiment and realgar are more stable under acidic reducing conditions (Lu & Zhu, 2011).

While long-term stability is likely in ideal conditions, long-term stability of the mineral phases in an aqueous oxidative environment, like that at the Giant Mine, would be questionable. The current conditions in the arsenic trioxide storage areas at the Giant Mine are oxidizing and slightly acidic, with oxidation-reduction potential (ORP) readings generally between 145-180 mV and pH between 5.75-6.65. These are not ideal conditions for long-term storage of reduced arsenic mineral phases and significant arsenic release could happen if reducing conditions were not maintained. It is impossible to guarantee long-term stability of these mineral phases in-perpetuity in oxic environments, and therefore, reductive bioprecipitation is given a rating of low for long-term effectiveness.

3.4.5.1.3 Technical Independence: Very Low

This scoring criteria evaluates the interdependence of this method with the development of other methods. Any ex situ treatment method is highly dependent on the development of mining methods that are able to extract the arsenic dust safely: minimizing risk for arsenic release to the atmosphere, worker exposure, and maximizing dust recovery.

In addition to dust extraction, solubilization of the arsenic dust is necessary prior to the reduction reaction. This adds an additional layer of complexity to the treatment process, and necessitates the study and development of a method for arsenic solubilization that is practical for full scale treatment. Because of these reasons, reductive bioprecipitation is given a very low scoring for Technical Independence.

3.4.5.1.4 Confidence in Predictive Models: Moderate

This scoring criterion does not rate the effectiveness of the technology itself, but rather rates the confidence in the ability to predict the performance of the technology in the field based on developed models. Thermodynamic models evaluating the stability of reduced arsenic mineral species are well established (Vlassopoulos, Bessinger, & O'Day, 2010; Lu & Zhu, 2011). However, there is a lack of long-term testing and validation for these models, and no directly comparable analogs exist. Because of this, it was determined that there is a moderate level of confidence in predictive models.

3.4.5.1.5 Pilot Testing/Design/Pre-Installation Requirements: Low

Due to the geochemical and geomicrobiological methods required by this remedy, extensive bench scale and pilot studies would be necessary to identify design parameters and potential operational issues. Many unknowns exist regarding how the dust will react to the reduction process. One of the main concerns identified during the review was that in addition to arsenic trioxide, the dust also contains iron arsenates, calcium arsenates, roaster-generated iron oxides, and antimony phases. How these would respond to this process is an unknown and would need to be determined. Because this treatment method would require extensive field and pilot design work, it received a low score.

3.4.5.1.6 OMM Requirements: Low (indicating high level of OMM)

OMM requirements would be contingent on the final storage emplacement. If re-stoped after processing, the potential for re-oxidation of the sulphide minerals and re-release of arsenic exists, based on regional groundwater geochemistry. Frequent monitoring of the stabilized material would be necessary to monitor this potential for dissolution, and mitigation efforts would be necessary if arsenic was remobilized (e.g., injection of reducing agent to create and maintain a reducing environment).

If the stabilized material was stored at the surface in a lined and capped landfill, monitoring and maintaining a reducing environment would be easier, but still require some level of operation maintenance.

Because of the need for at least quarterly monitoring events and the high potential for requiring future mitigation activities due to arsenic dissolution, this method is given a low score in operation maintenance and monitoring.

3.4.5.1.7 Short-term/ H&S Risk: Low (indicating high level of risk)

As with any ex situ process, there is a high risk of a short-term release and worker exposure. This risk can be mitigated through wetting the arsenic dust, and establishing health and safety protocols prior to initiating the remedial program. Much of the risk involved in this method is contingent on advances in mining and dust extraction methods.

In addition to the risks associated with dust extraction, the potential exists for arsine, methylarsine, and hydrogen sulphide gas formation. Arsine gas is highly toxic. NIOSH has classified any concentrations of arsine greater than 3 ppm to be immediately dangerous for life and health (IDLH). Supplied air respirators would be required for arsine at any concentrations above 0.002 mg As/m^3 (NIOSH, 2014).

3.4.5.1.8 Practicality of Contingency Measures in Case of Failure: Low

This ranking criterion evaluates the ease at which an alternative remedial method could be applied if reductive bio-precipitation did not limit arsenic mobilization. Compared to solidification treatment methods, such as cementation and vitrification, the resulting mass of the treated material is smaller, but still larger than the volume of dust initially. This allows for an easier transition to an alternative treatment method compared to cement or vitrification. However, the nano-crystalline product produced through bio-precipitation would have a complex and unknown geochemistry that would complicate future contingency measures.

3.4.5.1.9 Time Required for Completion: Moderate

The reductive precipitation process is currently being implemented at a number of sites including the Freeport-McMoRan Copper and Gold Inc.'s Sierrita mine site in Arizona, and Barrick's Pueblo Viejo Gold Mine in the Dominican Republic. Processing rates at some of these bioreactors produce 20 tonnes hydrogen sulphide per day. Reacting the hydrogen sulphide with the arsenic trioxide dust would potentially give processing rates of as much as 80 tonnes per day of dust. If this processing rate could be maintained at the Giant Mine, the dust could be processed in approximately 10-15 years, giving this technology a moderate score for the time required for implementation criterion.

3.4.5.1.10 Ease of Implementation: Low

A number of technical challenges would have to be overcome for this process to be successfully implemented at the Giant Mine. First, the transition from the frozen block method to a biological reductive remedial method would require removal of the material from the ground. The challenges of implementing these mining methods are reviewed elsewhere (Section 3.3). After the material is removed from the subsurface, it would need to be processed to dissolve the arsenic trioxide into solution. If an extraction process such as hydraulic borehole mining were involved, the mixture being brought up would be a slurry mix of both frozen and unfrozen dust with varying levels of water saturation. A major challenge required in this process would be dissolution of the arsenic. A number of methods exist for dust dissolution, however this step in the treatment process would require significant pilot testing in order to select the most effective method.

After the dissolution of the arsenic, the solution would be reacted with the biogenic hydrogen sulphide, reducing the arsenic and creating stable arsenic sulphide mineral species, which could then be disposed of. The number of steps required in the processing of the dust, in addition to the significant volume of pilot testing required results in this method scoring low in the ease of implementation scoring criterion.

3.4.5.1.11 Compatibility with Future Uses: Low

A reactor with the capability to produce approximately 20 tonnes hydrogen sulphide per day should not cause significant site disturbance. However, the need to actively maintain a subsurface reducing atmosphere would be expensive and require permanent access, thereby causing a permanent site disturbances due to the requirement for access to injection locations. In addition, due to its expected low stability, periodic injections would be required to maintain the reductive atmosphere.

3.4.5.1.12 Cost: Moderate

Material costs for the hydrogen sulphide bioreactor (elemental sulphur and carbon source) are inexpensive compared to oxidative bio-precipitation. Because of this, the cost to process the dust is estimated to be around $150 million, which is within 25% of the current Frozen Block alternative. However, because this is not a complete remedy, mining costs also need to be included.

3.4.5.1.13 Compatibility with Cold Climates: Moderate

Reductive biological precipitation can take place at a wide variety of temperatures, but primarily is conducted at near 25°C. Compared to oxidative processing, which requires elevated temperatures, biological reduction of arsenic is scored moderate for compatibility in cold climates.

3.4.5.2 Biologically-Mediated Oxidative Arsenic Precipitation

Biologically-Mediated Oxidative Arsenic Precipitation was evaluated on February 22, 2017 by Professor Heather Jamieson, Ph.D. from Queen's University and Margaret Gentile, Ph.D. from Arcadis.

There are several biological mechanisms which influence arsenic stability and mobility. Arsenic speciation can be directly impacted by microorganisms through "*dissimilatory As(V) reduction, autotrophic/heterotrophic As(III) oxidation, and methylation of arsenic species*" (Okibe, et al., 2014). Controlling the oxidation state or degree of methylation impacts toxicity as well as mobility. As(V) is much less mobile in the environment, and higher degrees of methylation decrease overall arsenic toxicity (Akter, Owens, Davey, & Naidu, 2005).

As outlined previously, arsenic mobility can also be impacted by adsorption and coprecipitation reactions with secondary Fe(III) minerals. Bacterial leaching of copper and biooxidation of refractory gold concentrates have been well established at the industrial level for over 20 years (Acevedo, 2000). These processes harness microbial activity for the recovery and extraction of heavy metals with the advantage of its relative simplicity, mild operation conditions, low capital costs and energy input, and environmental compatibility. Large scale bio-reactors, most commonly continuous stirred tank reactors (CSTRs) or a series a CSTRs are implemented. Nutrients, oxygen, and carbon dioxide loading are controlled to induce the microbial population to produce the desired outcome - refining refractory ore deposits for better recovery in post-processing.

Interest in applying the bioleaching technology in hazardous material processing and storage has increased because of the low cost and mild operating conditions. Using the process described above, leaching and oxidation of arsenic-rich minerals, and subsequent precipitation as a stable scorodite mineral has been shown to be feasible at bench scale. Paques B.V. in conjunction with Wageningen University in the Netherlands are in the process of developing a pilot scale bioreactor for the precipitation of arsenic into scorodite. Bench scale studies have shown promising results including higher than 99% arsenic removal efficiency and low arsenic leaching potential (0.4 mg/l under TCLP conditions for 100 days) (Gonzalez-Contreras, Weigma, & Buisman, 2012). Bioscorodite crystallization takes place at an operating temperature of 72°C and pH of 1.2. Only one reactor is necessary to complete both biological iron oxidation and crystallization. In chemical precipitation reactions, both iron and arsenic must be oxidized prior to the precipitation reaction. Also, the ratio of iron to arsenic is lower in bio-precipitation (1:1) of scorodite compared to chemical precipitation (3:1), thus saving on both sludge production and the cost of iron. Scorodite is generally stable under a wide range of oxidative conditions.

The results of the evaluation of biologically-mediated oxidative arsenic precipitation are summarized below (Table 18) and are described in more detail in the sections following.

Table 18. Evaluation Results: Biological Oxidation

Evaluation Criteria	Biological Oxidation
Technical Maturity	Low
Effectiveness (Long-term Risk/Permanence)	Moderate
Technical Independence	Very Low
Confidence in Predictive Models	Moderate
Pilot Testing/Design/Pre-Installation Requirements	Low
OMM Requirements	Moderate
Short-term/ H&S Risk	Low (indicating high risk)
Practicality of Contingency Measures in Case of Failure	Low
Time required for Completion	Moderate
Ease of implementation	Low
Compatibility with Future Uses	Low
Cost	Low (indicating high cost)
Compatibility with Cold Climates	Low

3.4.5.2.1 Technical Maturity: Low

The biological oxidative precipitation of scorodite, while promising, has only been successfully performed at bench scale. Paques B.V. has partnered with Wageningen University in the Netherlands to continue this research. However, due to the extended time needed before implementation at the industrial scale, this method is given a low scoring for technical maturity.

In addition, similar to the reductive bioprecipitation method, solubilization of the arsenic dust is a pre-requisite. Bench scale testing would need to be performed prior to moving forward with this method to identify a pre-processing method that could solubilize the arsenic dust and ensure proper reactivity.

3.4.5.2.2 Effectiveness (Long-term Risk/Permanence): Moderate

Scorodite is metastable under the geochemical conditions at the Giant Mine (oxidizing and slightly acidic, with oxidation-reduction potential (ORP) readings generally between 145-180 mv and pH between 5.75-6.65 (SRK Consulting, 2002). However, literature indicates that at the pH of the Giant Mine groundwater (above 5), the conversion of scorodite to ferrihydrite and arsenic concentrations in the mg/L range is possible (see Figure 2) (Krause & Ettel, 1988). Effluent concentrations could therefore potentially reach around 100 mg/L. Additional evaluations would be necessary to estimate the annual arsenic flux from such a stabilized material. There is some concern that a transition to amorphic ferric arsenates could take place over time. Amorphous ferric arsenates are about 100 times more soluble than crystalline scorodite (Krause & Ettel, 1988).

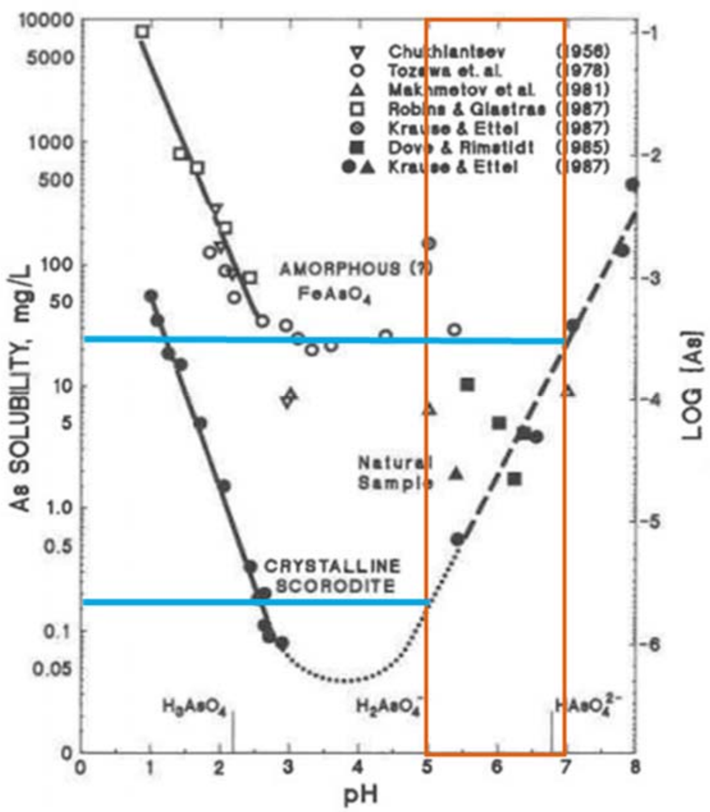

Figure 2. Solubility of apparently amorphous $FeAsO_4$ precipitates and of scorodite, $FeAsO_4 \cdot 2H_2O$. (adapted from Krause and Ettel, 1988).

Orange lines identify general range of pH conditions at the Giant Mine. Blue lines indicate expected solubility range.

Because of the increased solubility of amorphic ferric arsenates (Fe-As), batch testing of resulting precipitates during implementation would be required to ensure that scorodite is produced and not amorphous ferric arsenate or As-bearing ferrihydrite minerals. Current research indicates that one of the advantages of a biological scorodite process is that it very selectively produces crystalline scorodite, and amorphous Fe-As or a mixture would be less likely. However, there is only a small body of literature examining biological precipitation, and therefore presents a potential data gap (Okibe, et al., 2014; Gonzalez-Contreras, Weigma, & Buisman, 2012). In addition, since the starting material is not pure arsenic trioxide, determining Fe:As ratio in the reactor would take additional effort.

In addition, due to recent trends in global warming, the potential exists for a reducing environment to develop as ground temperatures increase, causing permafrost to recede and dissolved organic carbon to increase. Fluctuations in pH coupled with the development of a reducing environment could impact scorodite stability, resulting in an increased flux of arsenic into the environment.

3.4.5.2.3 Technical Independence: Very Low

This scoring criteria evaluates the interdependence of this method with the development of other methods. Any ex situ treatment method is highly dependent on the development of mining methods that are able to extract the arsenic dust safely: minimizing risk for arsenic release to the atmosphere, worker exposure, and maximizing dust recovery.

Similar to Reductive Bioprecipitation, solubilization of the arsenic dust is necessary prior to its oxidation within the bioreactor. This adds an additional layer of complexity to the process, and necessitates the study and development of a method for arsenic solubilization. Because of these reasons, oxidative bioprecipitation is given a very low scoring for Technical Independence.

3.4.5.2.4 Confidence in Predictive Models: Moderate

This scoring criteria does not rate the effectiveness of the technology itself, but rather rates the confidence in the ability to predict the performance of the technology in the field based on developed models. Thermodynamic models evaluating the stability of oxidized arsenic mineral species are well established (Krause & Ettel, 1988; Nordstrom, Majzlan, & Konigsberger, 2014). However, there is a lack of long-term testing and validation for these models, and no directly comparable analogs exist. Because of this, it was determined that there is a moderate level of confidence in predictive models.

3.4.5.2.5 Pilot Testing/Design/Pre-Installation Requirements: Low

Due to the geochemical and geomicrobiological methods required by this remedy, extensive bench scale and pilot studies will be necessary to identify design parameters and potential operational issues. Many unknowns exist regarding how this specific dust will react to the oxidation process, which is still only in pilot scale with reagent grade arsenic. The arsenic dust contains iron arsenates, calcium arsenates, roaster-generated iron oxides, and antimony phases in addition to arsenic trioxide. How these would respond to this process is an unknown and would need to be determined at the pilot scale first. Because this treatment method would require extensive field and pilot design work, it scores a Low within the Pilot Testing and Design Ranking Criterion.

3.4.5.2.6 OMM Requirements: Moderate

OMM requirements would be contingent on the final storage emplacement. Based on background groundwater geochemistry, scorodite and amorphous ferric arsenates are predicted to have better stability than reduced arsenic mineral species. However, if a change in background groundwater geochemistry occurs, either due to climate change or other mechanism, there is a potential for degradation of minerals and re-release of arsenic. Monitoring of the stabilized material and surrounding groundwater would be necessary to monitor this potential for dissolution. Mitigation efforts would be necessary if arsenic were remobilized. Because of the need for at least quarterly monitoring events and the high potential for future mitigation work due to arsenic dissolution, this method is given a low score in operation maintenance and monitoring.

If the stabilized material were stored at the surface in a lined and capped landfill, monitoring and maintaining a stable environment would be easier, but still require some level of operation maintenance.

3.4.5.2.7 Short-Term/ H&S Risk: Low (indicating high level of risk)

As with any ex situ process, there is a high risk of a short-term release and worker health and safety exposure. This risk can be mitigated through wetting the arsenic dust, and establishing health and safety protocols prior to initiating the remedial program. Much of the risk involved in this method is contingent on advances in mining and dust extraction methods.

3.4.5.2.8 Practicality of Contingency Measures in Case of Failure: Low

This ranking criterion evaluates the ease at which an alternative remedial method could be applied in the event that oxidative bio-precipitation did not effectively stabilize the arsenic dust.

Compared to solidification treatment methods, such as cementation and vitrification, which significantly increases the total volume of dust, precipitation bulking is reduced (2-3 times amount produced for reactions with 1:1 Fe:As ratio, vs. 5-6 times for 3:1 Fe:As mixtures). This would allow for an easier transition to an alternative ex situ treatment method. However, the bio-scorodite that would be produced will have a complex geochemistry and additional characterization testing would be necessary if a contingency measure were to be implemented in the future.

3.4.5.2.9 Time Required for Completion: Moderate

Very little information exists regarding the rates of arsenic bio-oxidation to scorodite. Because the technology is new, and currently unproven at the field scale, determining an accurate processing rate is difficult. Recent literature designs for CSTRs have given residence times of 40 hours for effective precipitation to occur (Gonzalez-Contreras, Weijma, & Buisman, Continuous Bioscorodite Crystallization in CSTRs for Arsenic Removal and Disposal, 2012).

Arsenic trioxide is generally considered soluble between 6.2 and 11.9 g/L. Assuming 240,000 tonnes of arsenic are dissolved into solution at 9 g/L, approximately 10^{11} L would need to be processed. If a bioreactor could be developed that could process (32,000 L/hr, while maintaining an effective residence time, a 5 year timeframe could be achieved for the process. This fast processing rate is a possibility, but due to the unknowns, oxidative bioprecipitation was conservatively ranked “moderate” for this criterion.

3.4.5.2.10 Ease of Implementation: Low

Multiple technical challenges would have to be addressed for this process to be successfully implemented at the Giant Mine. First, the transition from the frozen block method to a biological oxidative remedial method would require removal of the material from the ground. The challenges of implementing these mining methods are reviewed elsewhere (Section 3.3). If an extraction process such as hydraulic borehole mining was involved, the mixture being brought up would be a slurry mix of both frozen and unfrozen dust with varying levels of saturation. A major challenge required in this process will be dissolution of the arsenic. Methods exist for this process, however this step in the treatment process would require significant pilot testing in order to select the most effective method. After the dissolution of the arsenic, the solution would pumped to the bioreactor where it would subsequently be oxidized creating a bio-scorodite material.

One of the concerns that was identified during previous bench scale testing performed by Paques B.V. was scaling of the material along the sides of the bioreactor. At a large scale, this scaling could cause operational downtime. The number of steps required in the processing of the dust, in addition to the significant pilot testing required results in this method scoring low in the ease of implementation scoring criterion.

3.4.5.2.11 Compatibility with Future Uses: Low

With a residence time of 40 hours, the main reactor would need to have a working volume of approximately 5,700 m^3 for a 5 year timeframe, potentially on the order of a 930 m^2 surface area, plus room for a clarifier and materials handling during remedy. Therefore, the surface impact during the processing time would be non-trivial. Given that the materials will still be stored in place, long-term storage should not significantly impede future use of the site. There may be a need to haul some excess material due an increased volume of the treated dust, however, overall increase with this process is less than the bulking associated with chemical precipitation.

3.4.5.2.12 Cost: Low (indicating high cost)

Material costs for an oxidative bioreactor are more expensive than the reductive precipitation bioreactor. Iron cost alone would be $100 million (100,000 tonnes of iron for 240,000 tonnes of AsO_3 at 1:1 molar ratio). There would also be a requirement for an acid addition to keep the reactor at a pH less than 2 SU. Higher grade acid would be required in order to prevent impurities from impacting the reaction process. In addition, research has indicated that the biological oxidation reaction needs to take place at or above 70°C, to ensure effective precipitation of scorodite. The energy required to heat a 5,700,000 L bioreactor would need to be assessed and would increase operational costs significantly.

3.4.5.2.13 Compatibility with Cold Climates: Low

The oxidation process for the bioreactor requires that temperatures be held around 70°C. A preliminary estimate for the reactor size is around 5,500 cubic meters. To maintain a temperature of 70°C continuously would require a high energy input.

While current subsurface conditions are oxidizing, there is a risk of long-term warming resulting in an increase in organic material in the groundwater. The increase in organic material could produce reducing conditions across the mine area and increase arsenic dissolution.

3.4.6 Bitumen/Aspalt Stabilization

In the 2002 review, encapsulation of the arsenic dust by asphalt was evaluated and performed well. However, there were significant drawbacks to the process including volatilization of arsenic during heating at temperatures greater than 130°C, and the necessity to dry the dust prior to processing (SRK, 2002). In addition, bitumen stabilization was not as technically mature compared to the other technologies being evaluated. Arcadis contacted Dr. Jay Meegoda, a professor at the New Jersey Institute of Technology who has published research on leaching of heavy metals and other contaminants in stabilized asphalt matrices (Meegoda, et al., 2000; Cervinkova, Blaha, & Meegoda, 2007). During the call, Dr. Meegoda stated that research in bitumen/asphalt stabilization has not been an active area for several years. Industry application of bitumen stabilization has primarily been focused as a stabilizer for oil-derived wastes, and would not be suitable for long-term storage of the arsenic dust. Because of the lack of development on metals encapsulation by asphalt, this technology was not reviewed further.

3.5 Physical Isolation and Disposal

3.5.1 Sand Shell Purpose-Built Vault

The sand shell purpose-built vault method was evaluated on March 9, 2017 by Rob Whipple, M.Eng., P.Eng. of Rob Whipple Engineering, Inc. and Fletcher Baltz, P.E. of Arcadis.

Subsurface storage of treated material is a potential final storage solution for the arsenic dust that was evaluated during this review. Deep storage was initially reviewed in the 2002 SRK report (Supporting Document 10). In that document, it was assumed dust storage chambers would be excavated deep within the Giant Mine, below the existing workings. The arsenic dust would be removed from the shallow chambers, and, without exposing the dust to the surface, be transported to the deep storage locations.

In the sand-shell vault design, proposed by Rob Whipple (Whipple, 2016), the dust would be brought to the surface, and processed. The treated material would then be relocated to the subsurface in purpose-built concrete vaults. These vaults would be circular shafts excavated in bedrock and constructed so that the stabilized “capsule” would be contained by the concrete shell (shaft lining). This capsule would be surrounded by a semi-compressible medium (sand and/or gravel) and would not be in contact with the wall rock, separating it from the surrounding environment. The semi-compressible medium would have the capability to absorb minor ground movement and distribute stresses to the shell and thus limit potential damage to the concrete shell and “capsule.” The concrete lining and cement stabilization would provide additional structural and chemical stabilization for long-term storage. And an optional bitumen sealing at the top would limit exposure of surface infiltration to the dust masses. Any groundwater would have to first pass through the concrete shell, before encountering the stable mixture of cement and arsenic trioxide dust. In addition, the sand/gravel compressible medium provides a preferential flow conduit and drainage layer around the concrete shell and stabilized dust, minimizing direct contact of the stabilized dust with groundwater.

The results of the evaluation of the sand shell method with purpose-built vaults are summarized below and are described in more detail in the sections following.

Table 19. Evaluation Results: Sand Shell Purpose-Built Vault

Evaluation Criteria	Sand Shell Purpose-Built Vault
Technical Maturity	Very High
Effectiveness (Long-term Risk/Permanence)	High
Technical Independence	Low
Confidence in Predictive Models	Moderate
Pilot Testing/Design/Pre-Installation Requirements	High
OMM Requirements	High
Short-term/ H&S Risk	Moderate
Practicality of Contingency Measures in Case of Failure	Moderate
Time required for Completion	Moderate
Ease of implementation	High
Compatibility with Future Uses	Low

Evaluation Criteria	Sand Shell Purpose-Built Vault
Cost	Very Low (indicating very high cost)
Compatibility with Cold Climates	High

3.5.1.1 Technical Maturity: Very High

Subsurface disposal is a method that has been widely used in nuclear waste disposal for decades. The use of a sand-shell is not as well-developed; however, the process is straightforward and could be implemented easily with currently available mining methods and processes.

It must be noted that this rating applies only to the actual emplacement of the dust in the subsurface. The stabilization of the dust prior to placing in final storage is an integral part of an overall remedial alternative. The overall rating of this criterion would be dependent on the stabilization method chosen.

3.5.1.2 Effectiveness (Long-term Risk/Permanence): High

Long-term stability performance in terms of arsenic flux will be dependent on two factors: the stability of the stabilized dust and the long-term structural integrity (water-tightness) of the concrete lining in the containment chambers. The dust, stabilized through mineral precipitation, cementation, or other immobilization method, can be tested for material compatibility, strength, and hydraulic conductivity. The structural integrity can be assured by robust design, quality construction and monitoring for performance. Monitoring would include hydrologic monitoring of groundwater levels inside and outside the chamber walls, and structural monitoring of the containment shell. One of the largest potential risks is the long-term position of vault. During long-term storage, it is possible that the gravel base or sub-base could wash out or shift, causing the vault to shift. Designs should account for this to ensure that the vault remains vertical.

In addition, the stabilization of the dust prior to placing in final storage is an integral part of an overall remedial alternative. The overall rating of this score as applied in an integrated remedial alternative would be dependent primarily on the stabilization method chosen.

3.5.1.3 Technical Independence: Low

Any ex situ stabilization method requires safe and effective mining methods for the arsenic dust. Because of the requirement to remove the dust before re-emplacement. This method would also require the development of a stable arsenic material. Because of this, this method has been given a low ranking for technical independence, as it cannot be implemented unless additional technologies have reached a maturity that they could also be implemented on the site.

3.5.1.4 Confidence in Predictive Models: Moderate

The design of the chambers would be based on geologic data and established structural standards. However, no data exists for performance of the proposed concrete vaults in a sand shell. Separating the stabilized structure from the surrounding environment conceptually should provide level of stability and protection from its surroundings.

3.5.1.5 Pilot Testing/Design/Pre-Installation Requirements: High

Chamber construction alone would require minimal pilot testing, design, and pre-installation work. Locating a vault on a major fault or other weakness would present higher risk for chamber excavation and vault construction more so than for vault stability. Therefore, a thorough understanding of subsurface geology and identifying suitable locations for the purpose-built vaults will be necessary. If faults in the Giant mine have moved since the mine opened (due to active seismicity), then location choice becomes even more important.

3.5.1.6 OMM Requirements: High (indicating low level of OMM)

As with treatment methods where the dust would be stabilized and stored on-site, monitoring would be required. After initial implementation, quarterly sampling would be required to monitor the first wash and ensure that contaminated water is being effectively captured and treated. Quarterly monitoring could then likely be reduced to annual monitoring. It is recommended that annual monitoring be continued in perpetuity if possible.

3.5.1.7 Short-term/ H&S Risk: Moderate (indicating moderate risk)

Assuming that the dust has already been extracted and stabilized prior to emplacement (the risk of those activities evaluated elsewhere), risks specifically associated with the construction of the chambers would be comparable to standard level of risks at mining and construction sites with large excavations. These are known and manageable risks and therefore Sand Shell Method ranks moderate in this category.

3.5.1.8 Practicality of Contingency Measures in Case of Failure: Moderate

Contingency measures to address groundwater ingress and leaching through the chamber could be implemented by pumping from groundwater wells used for performance monitoring. Additional grouting could be implemented as an additional measure to prevent groundwater infiltration. In addition, the surrounding sand could be amended with stabilizing agents such as zero valent iron, which would add an additional layer of protection by providing a mechanism for removing dissolved arsenic egressing the concrete shell.

It must be noted that this method would need to be paired with a stabilization method. Most of the stabilization methods will generate a significant volume of treated dust and would be subject to the same issues. The sand-shell method does offer the additional protection of grouting or the injection of additional stabilizing agents, something that re-stoping does not allow for.

3.5.1.9 Time Required for Completion: Moderate

Excavation of the chambers would most likely be done concurrently with the stabilization process being implemented on the site. It is likely that excavation of the chambers would not be the limiting step in the overall treatment process. Combined with the other remedial methods, extracting, processing, and emplacement would be completed within 10-20 years.

3.5.1.10 Ease of Implementation: High

This category evaluates the transition from frozen block to the new method. It is likely that these chambers would be built outside of the influence of the frozen block area. Difficulties in transition would primarily lie with extraction of the dust.

3.5.1.11 Compatibility with Future Uses: Low

Due to the level of bulking required with the dust stabilization methods, a large number of chambers would need to be built off site, away from the mining area. Assuming a bulking factor of 10, over 1,000 8 m x 8 m x 86 m chambers would need to be constructed based on preliminary design estimates.

3.5.1.12 Cost: Very low (indicating very high cost)

Cost estimate developed by the project team estimated chamber construction alone to cost nearly 3 billion dollars. Giving this method a “very low” rating.

3.5.1.13 Compatibility with Cold Climates: High

The construction methods required to build the sand shells are common mining practices which are used in cold climates.

3.6 Vendor Proposals

The proposals discussed below were provided by the GMOB to the project team. Several of the technologies may have application to other aspects of the Giant Mine remediation effort (e.g., treatment of pumped groundwater or surface water), but the following review focusses on their applicability to arsenic dust treatment specifically.

3.6.1 DGF/Nanotek Proposal

Arcadis reviewed a proposal provided by DGF New Tech Canada and Nanotek to the GMOB, dated November 20, 2015. Nanotek has developed a proprietary nZVI polymer suspension which has the potential to be implemented on the site as a remedial alternative. As part of this proposal, Nanotek proposed bench scale tests on the arsenic trioxide dust at the Giant Mine using their trademarked nanoscale iron particles (nanoFe™) in a polymer fluid. According to the proposal, nanoFe™ has the capacity to oxidize arsenic to generate arsenic pentoxide (As_2O_5), which is less toxic and less mobile in the environment. The polymer fluid encapsulates arsenic pentoxide to make particles “waterproof” and prevent leaching. In other applications, Nanotek has observed a 90% reduction in arsenic contamination under ideal conditions.

The treatment process outlined within the proposal includes adsorption of arsenic trioxide to nZVI, oxidation to arsenic pentoxide, adsorption to nZVI then encapsulation by the polymer. The protocol calls for mixing of As dust with the nanoFe™ suspension in a lab, mixing the pretreated sample with an equal weight of soilTek ES™ (a sealant) then compacting the mixture.

3.6.1.1 Nanotek Scale Up- Giant Mine Applicability

The Nanotek proposal presented an alternative method of dust stabilization utilizing nZVI, whereby the dust would have to be mined, processed, mixed, reacted and compacted before re-emplacement in chambers and stopes, or ultimate removal off site to a landfill. The proposal provided only one article to investigate their claims (Morgada, et al., 2009). Additional information gathered during the SOK literature search has suggested that stabilization of the dust with nZVI would be prohibitively complicated to implement on a large scale. In addition, under ideal conditions, a 90% reduction in leaching capacity will not reduce arsenic levels to below the environmental and human health risk assessment levels (2,000 kg/year).

For this process to provide a feasible solution to manage the arsenic trioxide dust, issues regarding the long-term physical and geochemical stability of the sealant and the potential leaching of materials from the sealant/ ZVI mixture would need to be addressed, as well as possible material cost and implementation costs.

3.6.2 ecoStrategic Group Proposals

Arcadis reviewed two proposals provided by ecoStrategic Group to the GMOB, dated August 12, 2016, which are discussed in the following sections.

3.6.2.1 Proposal to Assess, Enhance and Commercially Develop *Polaromonas Bacterium* Found in Giant Yellowknife Mine as an Arsenic Bioremediation Tool by ecoStrategic Group

This work proposed to evaluate the bioremediation potential of three clades of *Polaromonas* for bioremediation of soil and as a “filtering agent” for arsenic in water. The proposal also sought to gain a better understanding of the effects of environmental conditions on the group of organisms capable of arsenic transformation that are indigenous to the Giant Mine. The key transformation the authors hope to exploit is the microbial oxidation of arsenite to arsenate. The ultimate goal is to create a commercially viable arsenic bioremediation culture.

The biotransformation of arsenic has been studied by a number of research groups but Osborne et al. (Osborne, et al., 2010) is cited as the group that has specifically studied organisms from Giant Mine. After making an initial study of the organisms the second phase of proposed work is bench/pilot testing of soil and water remediation approaches. The third phase of work would be “Proving Testing and fine tuning[sic]” as part of commercialization.

The proposal is a high-level summary of a multi-year research program. A few key questions/concerns as to the viability of the research include:

- It is unclear how organisms will be isolated and developed into a commercially viable culture;
- This technology is described as being appropriate to soil and water; it is highly likely that it will require all arsenic species to be dissolved prior to their transformation, and this poses a significant problem for the arsenic trioxide dust stored in stopes and chambers;
- The proposal is too general to assess whether the authors have a specific, actionable experimental plan; and

- The cost and schedule to go from an environmental mixed culture in a biofilm to a commercially viable bioremediation culture appears to very aggressive.

3.6.2.1.1 Applicability to Giant Mine Arsenic Trioxide

This technology appears to be targeted at arsenic containing soils and arsenic bearing water. It could potentially be developed into an alternative for water treatment or treatment of soils with some level of arsenic. The utility of biological arsenic oxidation for treating arsenic trioxide dust is a different problem. For this type of technology to work it would require the dust to be dissolved, converted to arsenic(V) by the microorganism and then treated to produce an acceptable form of captured/precipitated/adsorbed arsenic. The captured form of arsenic(V) would then need to be stored in a form to ensure long-term stability. In summary, this proposed technology represents a possible component of a full scale remedial approach but would essentially be a substitute for chemical precipitation of a stable arsenic phase or even capture on a filtration media. The research as described is too lacking in detail to endorse as a promising means to aid in treating the large volume of arsenic trioxide dust at the Giant Mine.

3.6.2.2 Proposal to Develop a New Technology to Remove Arsenic and Selenium From Water and to Implement Pilot Trials on Baker Creek at Giant Yellowknife Mine by ecoStrategic Group

ecoStrategeic group intends to conduct bench tests with the University of Calgary and UBC for selenium and combined selenium and arsenic removal. The first proposed approach for selenium removal is pH adjustment, specifically acidification. The combined selenium and arsenic remediation approach uses acidification followed by media filtration for contaminant removal.

The proposal work seeks to investigate selenium removal by pH adjustment which the authors claim is a “completely new approach to removing selenium from water.” This work will also include the use of media for removal of selenium and arsenic from water. The proposal mentions a number of potential removal media but also indicates that biological transformation of arsenic may be integral to the treatment process.

The plan for treatment and development of the technologies to pilot level is only presented at a very high level making evaluation of the prospects of success difficult to assess.

3.6.2.2.1 Applicability to Giant Mine Arsenic Trioxide

Like the other technology proposed by ecoSolutions, this method appears to be targeted at arsenic containing soils and arsenic bearing water. It represents an ex situ treatment process that would require extraction and dissolution of the dust. The arsenic would then apparently be adsorbed onto a treatment media which would have to be disposed of to prevent future liberation of arsenic from the spent media. The volume and mass of contaminated media generated would be a function of the loading achievable. The spent media may or may not be characterized as a hazardous waste depending on the characteristics of the spent media. It is probable that the volume of waste generated would be greater than processes such as scorodite formation. As with the previous proposal, the research as described is too lacking in detail to endorse as a promising means to aid in treating the large volume of arsenic trioxide dust at the Giant Mine.

3.6.3 Dundee Sustainable Technologies (DST) Proposal, January 2016

Arcadis reviewed a proposal provided by DST to the GMOB, dated January 13, 2016. DST proposes to stabilize the arsenic dust ex situ by adding the dust to a glass mixture. They report success with their process at the pilot stage and are in the process of scaling it up.

Previous issues with vitrification of arsenic trioxide were due to volatilization of the arsenic. The DST process reportedly results in <0.01% arsenic loss due to evaporation as they recycle the off-gas stream back into the process. This could also help reduce emissions of other volatile components (e.g., mercury).

The DST process consists of solubilizing the arsenic in the dust, recovering gold (and other metals), then precipitating calcium arsenate out of solution. The calcium arsenate is added to a glass mixture containing hematite, which stabilizes the arsenic, then melting the glass at a temperature of 1200°C. The result is 12-15% arsenic in a silica-glass matrix. TCLP analysis concluded that the glass is non-toxic with the addition of hematite (Fe_2O_3). The arsenic concentrate in the leachate can be as low as <0.1 mg/L. The stability of the glass is purported to be maintained over geological times (Dundee Sustainable Technologies, 2016a). Further information provided by DST indicated that a concentration of 20% arsenic can be achieved in the glass and material containing up to 45% arsenic can be processed (Dundee Sustainable Technologies, 2016b).

The cost to vitrify the arsenic trioxide dust is reported to be about $1,000/tonne of arsenic stabilized versus about $8,000/tonne for scorodite stabilization as reported in their proposal (Dundee Sustainable Technologies, 2016a). This cost does not account for extraction of the dust from the mine and is presumably the in-line cost to vitrify the arsenic generated as part of an operating mining process. In addition, the cost estimate for the scorodite method provided within the proposal is significantly higher than what was initially estimated in the 2002 SRK review and in the current review.

DST is operating a pilot plant in Thetford Mines, Quebec and processing 100 kg batches of glass and theoretically could handle up to 500 kg batches of glass. The full-scale plant they are developing would process up to 20,000 tonne/year of glass (Dundee Sustainable Technologies, 2016a). They are currently constructing (2017-2018) an industrial vitrification plant in Africa to process 3,500 tonne/year of arsenical dusts (Dundee Sustainable Technologies, 2017).

3.6.4 βio-βol Technology Proposal

Arcadis reviewed a proposal provided by Serena Domvile, the inventor and owner of βio-βol Technology, to the GMOB, titled *Conceptual Plan to Convert 250,000 Tonnes of Impure As_2O_3 into Gallium Arsenide Wafers, Converting CO_2 in Power Generator Emissions into Bio-Fuel to Offset Wafer Production Costs*, dated 2017. This proposal presents a potentially marketable use for the arsenic trioxide dust at the Giant Mine. The approach is to use the arsenic in the fabrication of gallium arsenide semiconductor 'wafers'. The approach uses a novel technology, βio-βol to improve the energy efficiency and economic viability of the project. The focus of the proposal is on the economics and energy considerations related to production. The means of removing the dust from the stopes and chambers is not directly addressed although it is acknowledged as a necessity.

The economic viability of this approach is closely linked to the market for gallium arsenide semiconductor wafers. The author provides an initial analysis that shows the project to be very economically viable if the assumptions are correct; however, they include market demand and pricing forecasts for the wafers, which are highly speculative.

It is recommended that the entire energy balance and economic analysis be carefully scrutinized before commissioning any laboratory or pilot scale testing. The proposal presents an innovative alternative beneficial reuse for the dust but involves a relatively novel technology, and is highly sensitive to the assumptions in the economic and energy analysis. Additional third-party review of the analysis provided is strongly recommended.

4 RESULTS ANALYSIS AND INTEGRATED ALTERNATIVES DISCUSSION

4.1 Methods Results

Table 20 and Figures 3 and 4 summarize the scores for the methods that were reviewed within this study. The results of the method analysis are described below. The scores for mining and storage methods were normalized to the highest ranking method in those categories (HBHM) and the scores for ex situ stabilization and in situ treatment methods were normalized to the respective highest ranking method (vitrification).

Table 20. Ranking Results of Method Evaluation

Rank	Method	Normalized Score
Mining and Storage Methods		
1	Hydraulic Borehole Mining	10
2	Sand Shell Storage Chamber	7.9
3	Remote Mechanical Mining	7.8
Stabilization and Treatment Methods		
1	Vitrification	10
2	Frozen Block	9.6
3	Mineral Precipitation 1	9.0
4	Cement Stabilization	8.9
5	Mineral Precipitation 2	8.0
6	Cement Paste Backfill	7.8
7	Biological Oxidation	6.8
8	Nano Iron/ZVI	6.7
9	Biological Reduction	6.2

Mining, Extraction and Storage:

Advancements in HBHM technology such as the integration of a mining tool with the hydraulic jets, and the ability to turn directionally and on an angle significantly increases the reach of this application. The technical experts interviewed for this technology agreed that it would be possible to recover greater than 98% of the dust using this method alone, compared to the 2002 estimate of 85%. The enclosed system of HBHM also reduces the risk for surface exposure of the dust, essentially extracting the dust and transporting it in a lined pipe directly to a treatment area. In addition, while remote mechanical mining methods may have significant capital costs to develop the proper infrastructure, HBHM does not require significant remote work or as significant a front-end development process for implementation. Costs for extraction were estimated at $40-60 million.

The Remote Mechanical Mining method scored highly in practicality of contingency measures due to the great flexibility of methods that could be implemented on site during dust extraction. Even though significant improvements in worker health and safety and release control (short-term risk) have been made, it still represents a high-risk activity and therefore still scores poorly in short-term/H&S risk criterion.

The Sand Shell Purpose-Built Vault scored highest in technical maturity and pilot testing/design and pre-installation requirements because the construction of the vaults does not implement any novel or new methods and could be done with standard characterization and design efforts.

These methods need to be combined with additional stabilization and emplacement methods in order to achieve a successful integrated remedial alternative.

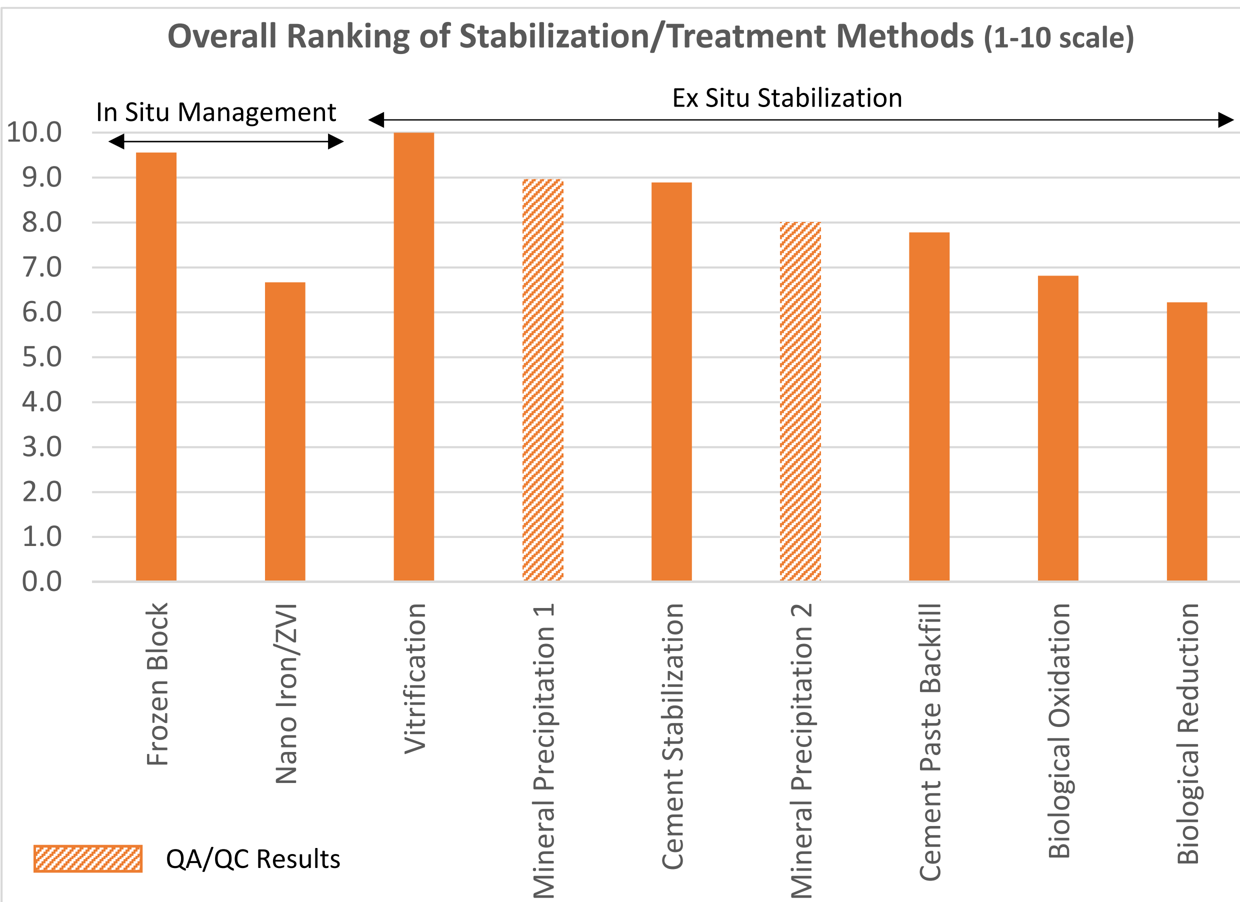

Figure 3. Normalized Scores for Evaluation of Stabilization and Treatment Methods

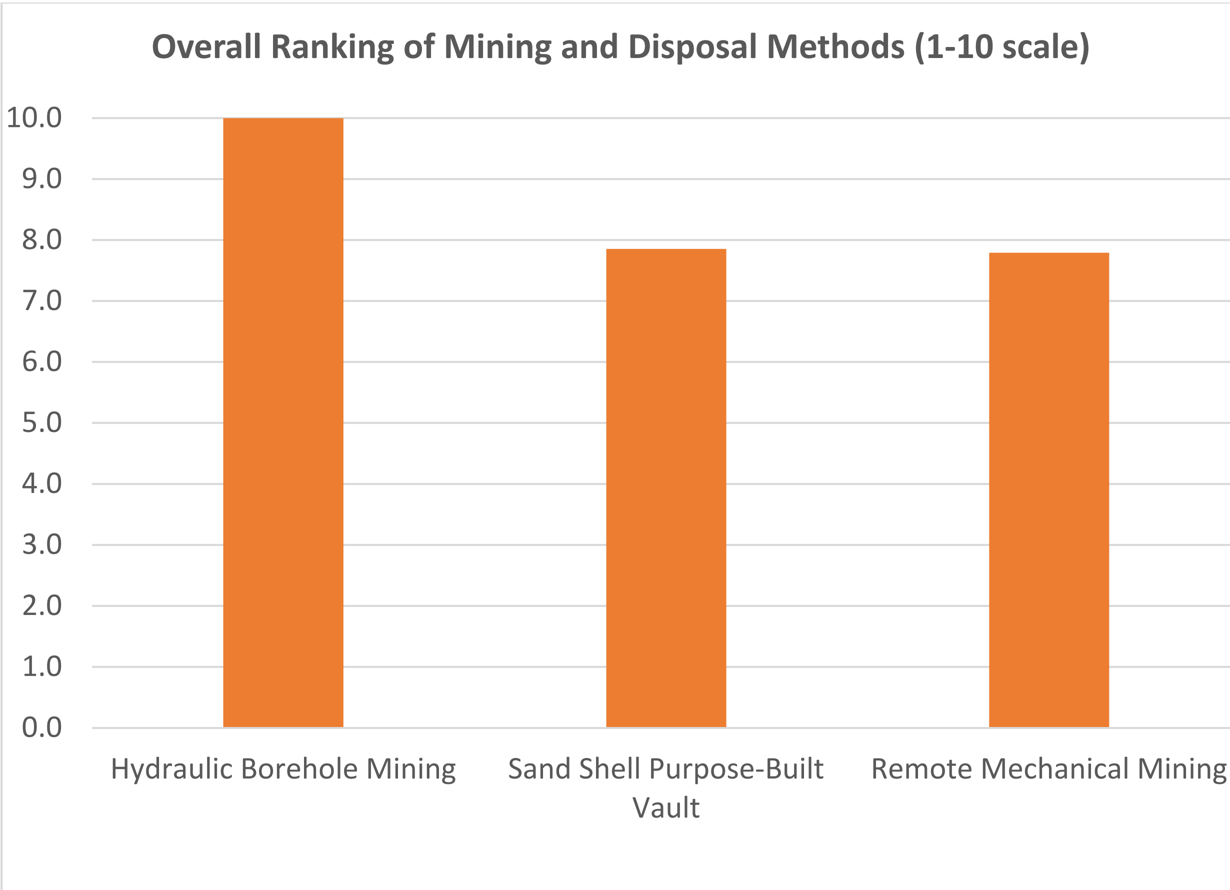

Figure 4. Normalized Scores for Evaluation of Mining and Disposal Methods

In Situ Management

The Frozen Block (FB) method ranked second in the scoring matrix for stabilization/treatment methods. It scored highest in short-term health and safety, compatibility in cold climates, technical independence, and ease of implementation. Because FB does not require extraction of the dust, or subsequent handling and processing, the short-term risk of release and exposure to workers is minimized. The process requires cold temperatures, and therefore is highly compatible with cold climates. It does not need additional steps for implementation such as dust extraction and dissolution, and is therefore an independent technology. However, the technology was scored moderate for overall effectiveness due to the fact that the dust is not chemically changed or permanently encapsulated and therefore the risk to the environment remains.

nZVI ranked second to last. A lack of technical maturity, and uncertainty in long-term effectiveness after the Frozen Block was allowed to thaw contributed to its poor score. There are no studies that the reviewers are aware of concerning nZVI and the high concentrations which could leach from the arsenic dust. The complex subsurface bedrock geology present at the site also complicates implementation of a uniform continuous reactive shell.

Dust Stabilization and Processing

Vitrification ranked first in the scoring matrix for stabilization/treatment methods. Vitrification scored the highest in effectiveness and OMM scoring criteria. Arsenic dust enclosed in glass is essentially immobilized, and the method therefore has a high level of effectiveness. Because of the high level of stability, little to no maintenance and monitoring would be needed. Pilot scale studies conducted by Dundee Sustainable Technologies with a similar dust are promising, and show a moderate level of technical maturity. Also, with the ability to extract gold as part of this process, there is the possibility to offset some of the processing costs through gold sale.

Other stabilization and processing methods can be divided into two categories: technologically mature and innovative. Processes such as scorodite/ferric arsenate stabilization and cement encapsulation were evaluated during the 2002 review. Those technologies are mature, and implemented widely. However, better understanding of the stabilization mechanisms and thermodynamics, and better process controls recommended these technologies for further evaluation within this review. These technologies scored well (average normalized score greater than 7). They are methods that could feasibly be implemented at the time of this review. Innovative technologies (biological oxidation and reduction) are methods that could be considered emergent technologies. These methods were not available at the time of the 2002 review, and have only recently emerged as feasible on the industrial scale. These technologies did not perform as well compared to the technologically mature methods. Biological reductive treatment, while implemented at the industrial scale currently, was ranked relatively poorly due to indications that the resulting precipitate would be unstable if stored on site in oxidative conditions. Biological oxidative precipitation has not yet reached field scale.

Cement Paste Backfill method combines the physical and chemical encapsulation of cement stabilization, but provides a method also for emplacement within the subsurface. This method also performed well, however, there are concerns with the magnitude of product produced as an outcome of the dust stabilization. Also, there is limited research regarding the initial release or wash out of arsenic from the cement monoliths and/or paste. Long-term performance is would need to be evaluated.

4.2 QA/QC Results

It must be noted that the combination of experts for each team was considered during the study. Experts who know the underlying mechanisms and the science may perceive the implementation of the work differently compared to an expert who has applied a concept in the field repeatedly. Therefore, it is valuable to try to combine review teams with experts with complementary areas of experience in order to capture all aspects of the review. Not doing this can result in data gaps and a higher uncertainty in the scoring process. As a QA/QC check on the approach, two different teams of experts reviewed the same technology.

Ambient scorodite precipitation was the method that was reviewed by two teams in order to evaluate the potential variance in method ranking. In general, there was concurrence with the scoring, with the experts agreeing on eight of the thirteen scoring criteria. The remaining methods scored within one grade of the other, with the exception of Technical Maturity. These results suggest that the scoring sheet and method ranking protocol is consistent so experts with similar backgrounds are able to reach agreement, i.e., the scoring process is repeatable. It must be noted that while repeatable, the resulting scores for the QA/QC evaluation did vary by approximately 10%. This suggests that the order of closely scoring methods, such as vitrification and frozen block, may shift if evaluated by other reviewers.

4.3 Sensitivity Analysis

A sensitivity analysis was performed on the results of this evaluation to determine the impact specific critical scoring criteria have on the rankings of methods. Four critical scoring criteria (Effectiveness, OMM requirements, Short-term/Health & Safety and Cost) were varied. These were considered critical criteria due to their impact on the long-term project outcome. Table 21 presents the different scenarios. Seven scenarios were run, promoting or demoting individual criterion weights, with the exception of Effectiveness which was the highest ranking, and Cost, which initially ranked as moderate. Effectiveness was demoted to high, and Cost was promoted twice to high and priority due to its potential importance in decision making. Tables 22 and 23 present the results of the sensitivity analysis.

Table 21. Sensitivity Analysis weighting summary

Criteria	Original Weighting	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
Effectiveness (Long-term Risk/Permanence)	Priority	High	Priority	Priority	Priority	Priority	Priority	Priority
OMM Requirements	High	High	Priority	Medium	High	High	High	High
Short-term/ H&S Risk	High	High	High	High	Priority	Medium	High	High
Cost	Medium	Medium	Medium	Medium	Medium	Medium	High	Priority

Table 22. Mining, Extraction and Storage Ranking. Colour identifies method.

Method Ranking	Original	score	Scenario 1	score	Scenario 2	score	Scenario 3	score	Scenario 4	score	Scenario 5	score	Scenario 6	score	Scenario 7	score
1	Hydraulic Borehole Mining	10	Hydraulic Borehole Mining	10	Hydraulic Borehole Mining	10	Hydraulic Borehole Mining	10	Hydraulic Borehole Mining	10	Hydraulic Borehole Mining	10	Hydraulic Borehole Mining	10	Hydraulic Borehole Mining	10
2	Sand Shell Purpose-Built Vault	7.9	Sand Shell Purpose-Built Vault	7.6	Sand Shell Purpose-Built Vault	7.9	Sand Shell Purpose-Built Vault	7.8	Sand Shell Purpose-Built Vault	7.8	Remote Mechanical Mining	7.9	Remote Mechanical Mining	7.6	Remote Mechanical Mining	7.1
3	Remote Mechanical Mining	7.8	Remote Mechanical Mining	7.5	Remote Mechanical Mining	7.8	Remote Mechanical Mining	7.8	Remote Mechanical Mining	7.5	Sand Shell Purpose-Built Vault	7.9	Sand Shell Purpose-Built Vault	7.5	Sand Shell Purpose-Built Vault	6.8

Table 23. Stabilization and Treatment Methods Ranking. Colour identifies method.

Method Ranking	Original	score	Scenario 1	score	Scenario 2	score	Scenario 3	score	Scenario 4	score	Scenario 5	score	Scenario 6	score	Scenario 7	score
1	Vitrification	10	Frozen Block	10	Vitrification	10	Vitrification	10	Frozen block	10	Vitrification	10	Vitrification	10	Vitrification	10
2	Frozen Block	9.6	Vitrification	9.6	Frozen block	9	Frozen block	9.8	Vitrification	9.7	Frozen block	9.2	Frozen block	9.6	Frozen Block	9.6
3	Mineral Precipitation 1	9	Mineral Precipitation 1	8.9	Mineral Precipitation 1	8.8	Mineral Precipitation 1	9	Mineral Precipitation 1	8.8	Mineral Precipitation 1	8.9	Mineral Precipitation 1	8.7	Mineral Precipitation 2	8.9
4	Cement Stabilization	8.9	Cement Stabilization	8.8	Cement Stabilization	8.8	Cement Stabilization	9	Cement Stabilization	8.7	Cement Stabilization	8.9	Cement Stabilization	8.7	Mineral Precipitation 1	8.8
5	Mineral Precipitation 2	8	Mineral Precipitation 2	8.2	Mineral Precipitation 2	7.7	Mineral Precipitation 2	8.2	Mineral Precipitation 2	7.9	Mineral Precipitation 2	7.9	Mineral Precipitation 2	8.1	Cement Stabilization	8.2
6	Cement Paste Backfill	7.8	Cement Paste Backfill	7.9	Cement Paste Backfill	7.5	Cement Paste Backfill	7.9	Cement Paste Backfill	7.7	Cement Paste Backfill	7.7	Cement Paste Backfill	7.9	Cement Paste Backfill	7.9
7	Biological Oxidation	6.8	Nano Iron/ZVI	7.5	Biological Oxidation	6.7	Biological Oxidation	6.9	Nano Iron/ZVI	7.4	Biological Oxidation	6.7	Biological Oxidation	6.8	Biological Oxidation	7.5
8	Nano Iron/ZVI	6.7	Biological Oxidation	6.8	Nano Iron/ZVI	6.3	Nano Iron/ZVI	6.9	Biological Oxidation	6.8	Nano Iron/ZVI	6.3	Nano Iron/ZVI	6.7	Biological Reduction	6.8
9	Biological Reduction	6.2	Biological Reduction	6.5	Biological Reduction	5.9	Biological Reduction	6.4	Biological Reduction	6.3	Biological Reduction	6.1	Biological Reduction	6.4	Nano Iron/ZVI	6.5

4.3.1 Sensitivity Analysis Results

As shown in Table 24, there was minimal movement in ranking for any of the scenarios evaluated. Of the Mining and Extraction method evaluated, Hydraulic Borehole Mining ranked the highest across all evaluated scenarios. Vitrification and Frozen Block methods held either first or second ranking among stabilization and treatment methods. Frozen Block ranked highest if the short term and health and safety risk weighting was elevated to "priority" or if effectiveness (long term risk/permanence) weighting was reduced from "priority" to "high." The fact that the Frozen Block method ranked consistently in the top two stabilization and treatment methods for all the scenarios suggests that it performed well relative to the other methods evaluated under the weighting scenarios tested.

Vitrification is the only dust stabilization and processing method that outperformed the Frozen Block method. Its high performance against the other stabilization and processing methods indicates that if an ex situ strategy is chosen in the future, vitrification should be considered.

Mineral Precipitation and Cement Stabilization are the two stabilization and processing methods that ranked within the top five. These methods are technically mature, which contributes to this result.

Table 24. Summary of Top 5 Scoring Methods Across the Sensitivity Analysis

Rank	Mining and Extraction Methods at each rank across all scenarios (# of times at rank)	Stabilization and Treatment Methods at each rank across all scenarios (# of times at rank)
1	Hydraulic Borehole Mining (8)	Vitrification (6), Frozen Block (2)
2	Sand Shell Purpose-Built Vault (5), Remote Mechanical Mining (3)	Vitrification (2), Frozen Block (6)
3	Sand Shell Purpose-Built Vault (3), Remote Mechanical Mining (5)	Mineral Precipitation 1 (7), Mineral Precipitation 2 (1)
4	n/a	Cement Stabilization (7), Mineral Precipitation 1 (1)
5	n/a	Mineral Precipitation 2 (7), Cement Stabilization (1)

4.4 Integrated Alternatives Overview

Remedial alternatives must integrate individual methods in order to present a complete remedial solution for arsenic dust management as most of the methods are not independent. Ex situ remedies must include an extraction method, treatment method, and a plan for final storage. In situ remedies do not require extraction, but must require a level of treatment (as with nZVI) or physical encapsulation (as with the Frozen Block Method) to ensure acceptable arsenic flux. All integrated remedial alternatives must also have a form of long-term water treatment to capture any remaining arsenic that is not treated by the method implemented.

The methods that were reviewed as part of this evaluation, and their place within the dust treatment process are presented in Table 25. An "N" indicates that a further step is required to present a complete remedial solution.

Table 25. Summary of Methods Reviewed and Additional Steps Required

Method	Extraction	Treatment	Storage
Frozen Block	n/a	Y	n/a
Nanoscale Zero Valent Iron	n/a	Y	n/a
Hydraulic Borehole Mining	Y	N	N
Remote Mechanical Mining	Y	N	N
Cement Stabilization	N	Y	N
Vitrification	N	Y	N
Mineral Precipitation (Scorodite/Ferric Arsenate)	N	Y	N
Biological Precipitation (Oxidative)	N	Y	N
Biological Precipitation (Reductive)	N	Y	N
Cement Paste Backfill	N	Y	N
Sand Shell-Purpose Built Vault	N	N	Y

Alternatives were determined based on the best scoring method combinations. As Nanoscale Zero Valent Iron and Biological Precipitation (oxidative/reductive) were considered to have very low and low effectiveness, respectively, they have not been carried forward in the discussion of alternatives. All of the treatment methods evaluated would require long-term water treatment, including the in situ methods that do not require extraction and storage.

The ex situ treatment methods with the highest scores include Vitrification, Mineral Precipitation, Cement Stabilization and Cement Paste Backfill. These methods would be combined with a mining method and storage option (e.g., sand shell purpose-built vaults) to create a complete treatment alternative. Storage options for the site are discussed in Section 4.4.5. The Frozen Block Alternative is the only in situ method evaluated that is currently believed to provide reliable long-term effectiveness. As it is already being implemented at the site, it is included in the list of alternatives but has not been discussed in detail in this section.

The alternatives evaluated are listed in Table 26 along with a brief description of the steps involved for each alternative. The stability of the stopes and chambers after extraction of the dust, if required, has not been included in this discussion.

As HBHM scored higher overall than Remote Mechanical Mining, HBHM has been carried forward as the preferred mining method in the alternatives. Any of the ex situ alternatives discussed could be implemented with either Remote Mechanical Mining or Hydraulic Borehole Mining as the extraction method.

Table 26. Evaluated Alternatives

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Brief Description	**Frozen Block**	**Vitrification with Extraction, Gold Processing and Storage**	**Cement Stabilization and Cement Paste Backfill with Extraction and Storage**	**Mineral Precipitation with Extraction and Storage**
Pre-treatment activities	--	Detailed characterization of dust for design purposes. Extraction of the arsenic trioxide dust.	Additional characterization of dust for design purposes. Extraction of the arsenic trioxide dust Detailed characterization of dust for design purposes.	Additional characterization of dust for design purposes. Extraction of the arsenic trioxide dust.
Implementation	Currently being implemented.	Construction of a vitrification plant. Construction of piping to transfer dust directly to treatment plant.	Mixing of dust with cement and additives.	Construction of a treatment plant. Extraction of arsenic, solubilization then precipitation of scorodite/ferric arsenate. Conversion of product into a paste.
Gold Processing and Sale	n/a	In-line gold extraction. .	Possible	Possible
Storage	n/a	Long-term storage of vitrified product required.	Long-term storage of cement paste/monoliths required. Long-term monitoring of storage conditions.	Long-term storage of scorodite/ferric arsenate paste required. Long-term monitoring of storage conditions.
Long-term Groundwater Treatment	Required	Required	Required	Required

4.4.1 Alternative 1: Frozen Block Alternative

The Frozen Block Alternative ranked highly in the evaluation of methods. It is essentially a standalone method with the addition of long-term water treatment. As it is already being implemented at the site, it is not discussed in further detail here. Further information about the Frozen Block Alternative is presented in Sections 1.2 and 3.1. A nZVI shell could be used as a complement to the frozen block (or other stabilization technology), which deals with the dust source.

4.4.2 Alternative 2: Vitrification with Extraction, Gold Processing and Storage

A vitrification treatment approach was proposed for the site by Dundee (Dundee Sustainable Technologies, 2016a). Detailed characterization of the arsenic trioxide dust in each chamber and stope would be required prior to implementation of this alternative in order to properly design the vitrification process.

The arsenic trioxide dust would need to be extracted by HBHM or a combination of remote mechanical mining methods, which may require wetting of the dust. A vitrification plant would be constructed on the site and an external source of power would be required to operate the plant. Ideally, extraction and treatment of the dust would be completed in tandem so that the dust could be piped directly to the vitrification plant to avoid interim storage and minimize the risk of dust release. The dust would need to be dried prior to vitrification.

Gold recovery would be completed prior to vitrification of the dust in line with the overall treatment process. Dundee proposed a gold extraction method via chlorination (Dundee Sustainable Technologies, 2016a); however, other more conventional gold processing methods could also be used. Depending on the gold extraction method, the generation of toxic by-products during gold processing, such as cyanide, would need to be considered. The gold extracted from the dust could then be sold to recover some of the treatment costs. Further details about gold processing and sale are provided in Section 4.5 Gold Recovery.

Long-term storage of the vitrified product would be required. Long-term storage options are discussed in further detail in Section 4.4.5 and could include: placing the glass back underground in the mine; off-site disposal at an existing landfill; construction of an on-site landfill; or above ground storage in silos or other permanent containment structures. Assuming that the vitrified product meets TCLP and risk-based analysis requirements, it could be disposed of at a municipal landfill; however, the large volume of glass requiring disposal may necessitate construction of a new landfill specifically for this purpose. Some of the vitrified product could be moved back into the chambers and stopes for permanent storage. It is expected that the volume of glass would be at least three times more than the original volume of dust as the glass would contain up to 20% arsenic (Dundee Sustainable Technologies, 2016a). As such a different long-term surface storage solution would be required to manage the majority of the glass.

As with all alternatives discussed, a long-term groundwater treatment program would be required for the site to manage any residual dust remaining in the mine.

4.4.3 Alternative 3: Cement Stabilization and Cement Paste Backfill with Extraction and Storage

During the Cement Paste Backfill method review, both experts involved in the evaluation stressed that cement paste backfill as a technology itself would most likely not provide the required strength and stabilization, or that significant dilution of the dust (corresponding with unfeasible increased volumes of treated mass) would be necessary in order to create a well-stabilized monolith. However, a hybrid of both cement stabilization and CPB, where the dust could be stabilized with a higher concentration of cement binder, but maintain the rheology of a pumpable fill is a promising hybrid method. Cement with lime additives has been shown to effectively stabilize arsenic through the formation of calcium arsenates. A higher cement concentration within CPB would enhance the stabilization properties of the backfill and also decrease overall porosity of the treated material, limiting arsenic transport to diffusion.

By maintaining pumpability, final CPB transport back into the subsurface could be simpler than transporting large blocks of cement (monoliths).

To implement this, a cement plant would likely need to be constructed on the site in order to provide the quantity of cement and additional additives required for the duration of the treatment and an external source of power would be required to operate the plant. Ideally, extraction and treatment of the dust would be completed in tandem so that the dust could be piped directly to the mixing plant to avoid interim storage and minimize the risk of dust release. Treated backfill could be re-injected using hydraulic borehole mining methods. The resulting cement could be pumped back underground and/or into an on-site landfill built specifically for this purpose. Storage options for the final cement product are discussed in further detail in Section 4.4.5.

Water treatment would be required to manage any arsenic leaching from the cement paste/monolith in the short-term. The concentration of arsenic leachate would be expected to decrease over time; however, long-term water treatment would still be required at the site to manage any residual dust remaining in the mine, as with all alternatives discussed. Depending on the stability of the cement, it may be necessary to cover it permanently to prevent water run-off from eroding the cement and causing arsenic release.

It would be possible to recover gold prior to cementation in order to sell the gold to help offset the costs of treatment. A gold extraction process could be completed prior to cement stabilization as an in line process.

4.4.4 Alternative 4: Mineral Precipitation with Extraction and Storage

Additional characterization of the arsenic trioxide dust would be required prior to implementation of a mineral precipitation alternative, although perhaps not to the extent required for vitrification.

The arsenic trioxide dust would need to be extracted by HBHM or a combination of remote mechanical mining methods, which may require wetting of the dust. The extracted dust would be solubilized and processed into stable ferric arsenates/scorodite mineral and then converted into a paste, which could be pumped back underground, into an on-site landfill built specifically for this purpose or stored in a different manner, as discussed further in Section 4.4.5. A processing and treatment plant would need to be constructed on the site and an external source of power would be required to operate the plant.

The plant will require large tanks to dissolve and oxidize the arsenic trioxide. Then a primary mixing tank where the ferric sulphate is added and mixed with the arsenic (V) solution. A neutralization tank with a residence time of at least 2 hours would be the next tank. Lime is added to a fixed pH value. Depending upon other requirements, a second neutralization tank may be required to bring the pH up to five or greater. Thickeners and systems to separate the precipitate from the liquid would be needed. A secondary water treatment plant will be needed to polish the collected solution.

Long-term water monitoring would be required to ensure that the arsenic is not released back into the environment. The stability of scorodite and ferric arsenate is dependent on the storage conditions and a change in background groundwater geochemistry could result in degradation of the minerals. If the stabilized material were stored at the surface in a lined and capped landfill, monitoring and maintaining a stable environment would be easier, but would require additional operation, maintenance and monitoring compared to re-stoping. It would be possible to recover gold prior to mineral precipitation in order to sell the gold to help offset the costs of treatment. A gold extraction process could be completed prior to cement stabilization as an in-line process

4.4.5 Long-Term Storage Options

Long-term storage of the treated arsenic would be required for all ex situ methods. Long-term storage options could include: placing the treated product back underground in the mine within the chambers/stopes or purpose-built vaults; off-site disposal at a new or existing landfill; construction of an on-site landfill; or above ground storage in silos or other permanent containment structures.

The construction of purpose-built vaults is discussed in detail in Section 3.5.3. While this is a feasible option for long-term storage of the treated dust, it may be more cost effective to store the product in a landfill constructed at surface. Due to the volume increase associated with most of the treatment methods evaluated, it is likely that an existing landfill in the area would not have the capacity or desire to accept all of the treated product. A landfill could be constructed on the site near the treatment facility; the treated product (glass, cement, mineral, etc.) could then be transferred directly into the landfill, then the landfill would be covered and closed properly.

Alternatively, the treated product could be stored at surface in silos or other permanent containment structures. As this would be a permanent solution, this would affect the long-term use of the site so this option may not be compatible with future land use. Cement monoliths could be stored permanently at surface assuming there are no long-term arsenic leaching concerns.

On-site surface storage of the stabilized dust could significantly impact future uses of the site. The volume of treated material increases significantly relative to the existing volume of dust, depending on the remedial method selected. The possibility of surface utilization of the treated materials, after a suitable cover was emplaced, could be considered. In addition to the footprint of a long-term storage option, additional factors such as impact of material transport, interference with wildlife, traditional land use, and landscape, aesthetics would need to be included in a more detailed evaluation.

4.5 Scoring of the Frozen Block Alternative as a Completed Remedy

Within the body of this document, the Frozen Block method and alternative, due to its familiarity, was used as a baseline to compare the other technologies. To give all technologies the same starting point, it was scored as a technology that had not yet been implemented; however, significant pilot testing, research and studies have been performed to test the Frozen Block method to date and it is important to capture this when determining if a transition to an alternative method is appropriate. In order to facilitate this, a supplemental score was developed that assumes complete implementation of the remedy has already occurred. As expected, the normalized score for the completed Frozen Block increases relative to the baseline. This score, not included with the overall assessment, can be used as a comparison of mature alternatives prior to implementation to evaluate whether a change in remedial strategy is warranted at that time. Table 27 compares the results of the Frozen Block (Pre-Implementation) and Completed (Post-Implementation) Frozen Block evaluations.

Table 27. Post-Implementation Frozen Block Alternative Score

Evaluation Criteria	Frozen Block	Numerical score	Post-Implementation FB	Numerical score	Rationale
Technical Maturity	High	12	High	12	
Effectiveness (Long Term Risk/Permanence)	Moderate	30	Moderate	30	
Technical Independence	Very High	5	Very High	5	
Confidence in Predictive Models	High	4	High	4	
Pilot Testing/Design/Pre-Installation Requirements	**Moderate**	**3**	**Very High**	**5**	All pilot testing and design has been completed, therefore minimal is necessary, and the score is high.
OMM Requirements	Moderate	15	Moderate	15	
Short Term/ H&S Risk	**High**	**20**	**Very High**	**25**	No additional invasive work would be required, therefore short term and worker health and safety risks would be minimal.
Practicality of Contingency Measures in Case of Failure	Moderate	9	Moderate	9	
Time required for Completion	**Moderate**	**3**	**Very High**	**5**	System would be operational and complete.
Ease of implementation	Very High	5	Very High	5	
Compatibility with Future Uses	Moderate	9	Moderate	9	
Cost	**Moderate**	**9**	**Very High**	**15**	Additional costs would be to OMM only, which is expected to be minimal compared to implementation costs.
Compatibility with Cold Climates	Very High	5	Very High	5	

Normalized Score	**7.9**	**8.8**

4.6 Gold Recovery

During the 2002 review, gold was valued at approximately $470 CAD per ounce. The low market value for gold disincentivized further investigation into remedial alternatives that included gold extraction due expected low financial return. In the intervening years, however, the gold value has nearly quadrupled from approximately $470 CAD per ounce to over $1,600 CAD. This development makes re-evaluation of previous technologies that include gold extraction and investigation of the compatibility of gold extraction with other remedial methods important.

In 2002, gold extraction was evaluated as part of the pressure oxidation process for arsenic stabilization and gold recovery (SRK, 2002b). The pressure oxidation process involves a chemical conversion of arsenic trioxide to crystalline iron arsenate compounds, predominantly of, or closely related to, the scorodite mineral form, and the recovery of gold by conventional cyanide leaching. During that evaluation, it was assumed that a 90% gold recovery could be achieved and that the entire dust mass could be treated within 15 years of processing. Costs and revenue were estimated as part of the report and are presented below (Table 28), correcting for inflation and updated gold market value.

Table 28. Gold Extraction Re-Evaluation for Pressurized Scorodite Precipitation Process.

Cost and Revenue Summary	2002 Cost and Revenue (SRK, 2002b)	2017 Cost and Revenue (includes inflation and gold market increases)
Capital Cost	$98,467,000	$132,524,000
Operating Cost (per year)	$18,723,000	$25,199,000 (Average Annual Operating Cost from 2017-2031 is $29,051,000)
Revenue (per year)	$3,840,000	$13,120,000
Plant Operating Phase	15 years	15 years
Total Cost (Capital + Total Operating- Total Revenue)	$321,562,000 ($432,780,000 with inflation)	$371,495,000
Revenue (total)	$57,600,000 ($77,522,000 with inflation)	$196,800,000
Change in Revenue 2002-2017		**$139,200,000** **($119,278,000 with inflation)**

Assuming a 2% annual increase for inflation and $1,600 CAD per ounce of gold for 2017-2031. As the value of gold changes regularly, this actual revenue could vary. Note that the cost to extract the dust is not included in the above calculation.

The increase in gold market value reduces the costs associated with this process compared to the 2002 assessment. The total cost for dust processing, using 2002 market value for gold, but brought current with a 2% annual inflation rate would cost over $410 million dollars (CAD). In other words, due to gold market values increasing over the past 15 years, the value of gold in the arsenic dust has increased over $135 million (CAD).

Other dust stabilization processes evaluated as part of this review can be adapted to work with the gold extraction. There would be two options for extraction, pre-stabilization and post-stabilization. Pre-stabilization extraction would entail using cyanidation leaching or other gold extraction process on the raw dust to remove gold. The residuals of this process would then be moved forward to subsequent treatment. Treatment methods such as CPB, cement stabilization, and vitrification would require pre-processing because the integrity of the stabilized monoliths is a key contributor to arsenic stability. One hazard of pre-stabilization extraction is the increased handling of the arsenic dust.

Post-stabilization gold extraction would work well in processes where non-monolithic stabilized mass is generated. Processes such as ambient temperature and pressure scorodite formation, or biological oxidation could work well. However, the cyanidation process does cause a change in pH, and the risk exists for the mineral species to destabilize during gold extraction. Alternative gold extraction approaches such as thiosulphate, which keeps reaction pH circumneutral, can be implemented. Thiosulphate extraction does come with other environmental risks, which will need to be taken into consideration if that method is implemented. Chlorination extraction has also been developed, using chlorine gas (Ojeda, Perino, & Ruiz, 2009), calcium chloride (Panias & Neou-Syngouna, 1990), and sodium hypochlorite (Dundee Sustainable Technologies, 2016a) . As with any of these methods, laboratory treatability studies would be needed to verify extraction efficiencies and to evaluate the benefits of gold extraction.

5 SUMMARY AND RECOMMENDATIONS

This study has identified a number of areas in which significant technical advancements have been made since the initial assessment of options for arsenic trioxide dust management at the Giant Mine. The original list of methods was reviewed using threshold criteria of technical maturity and risk, and incremental development since 2002. In addition, methods that have advanced since 2002 were evaluated (nano-ZVI and the sand shell method). The methods evaluated ranged from complete solutions for the dust management (such as the frozen block) to specific elements of a treatment approach that would include other methods (e.g., vitrification, hydraulic borehole mining, etc.).

The scoring system allowed for identification of the most promising methods, this is reflected in the overall score for a given method. The objective of the study was two-fold:

1) to identify, summarize, and rate new developments in methods for addressing the arsenic trioxide issue; and
2) to help identify promising avenues for future research.

The results of this State of Knowledge Review should be viewed in this context.

Ten methods were evaluated using the stated methodology. It is evident that there have been significant advances in hydraulic borehole mining. It performed well on all of the performance criteria and it appears, based on expert reviews and research, that dust extraction could be performed effectively and safely. It is also highly technically mature.

The Frozen Block method also performed very well. This method is already being implemented at the site.

As stated above, the top-ranked dust stabilization and processing method was Vitrification. Based on the potential for long-term stability of the resulting glass, moderate overall costs, and potential for gold recovery, it is recommended that future research on arsenic dust treatment involve further evalaution of vitrification-based technolgoies.

As discussed, these individual highly ranked methods were combined into potential integrated remedial alternatives. Any of these promising alternatives would benefit from additional, deeper technical and financial evaluation if they are to be considered for full-scale implementation.

The evaluations within this report should serve to aid in prioritizing research efforts. The methods identified as most promising via the ranking process can be further prioritized for research efforts by using specific criteria; the Technical Maturity and Pilot Testing/Design/Pre-Installation Requirements criteria are likely the most relevant criterion for this purpose.

As additional methods are identified or proposed, the same scoring process could be used to compare them to methods evaluated in this report. More novel or proprietary methods may be more challenging to evaluate but using the same criteria as a basis for analysis should ensure that such analyses have similar level of technical rigour applied.

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7 USE AND LIMITATIONS

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The conclusions presented represent the best judgment of the assessors. Nothing in this report is intended to constitute or provide a legal opinion. Should additional information which may affect the conclusions of this report become available to the GMOB, Arcadis requests that this information be brought to our attention so that we may re-assess the conclusions presented herein.

APPENDIX A

Draft Research Work Plan (January 16, 2017)

Giant Mine Oversight Board

STATE OF KNOWLEDGE REVIEW AND ASSESSMENT:

Arsenic Trioxide Remediation Methods- Draft Work Plan

GMOB #0001RSCH

January 16, 2016

STATE OF KNOWLEDGE REVIEW AND ASSESSMENT:

Arsenic Trioxide Remediation Methods-
Draft Work Plan

Prepared for:

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Date:

January 16, 2017

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METHODOLOGY – DETAILED RESEARCH PLAN

The Giant Mine is a former gold mine located five kilometres (km) north of Yellowknife in the Northwest Territories. Operating from 1948 to 1999, ore processing included milling to produce a concentrate that was fed to a "roaster" to burn off sulphur, which then liberated gold from an arsenic-bearing mineral (arsenopyrite). The result of this process was the production of arsenic trioxide, in addition to sulphur dioxide. The focus of this project is to review treatment methods for the approximately 237,000 tonnes of arsenic trioxide dust that was placed in 14 purpose-built chambers or stopes upon closure. Currently, the Frozen Block Remedial Alternative (FBA) is being implemented on site. This alternative was selected in 2013 after extensive studies and evaluation of alternatives, such as the 2002 SRK report *Arsenic Trioxide Management Alternatives- Final Report* (2002 SRK Report), which identified 56 potential treatment methods.

Since 2002, additional treatment methods for long term management of the waste may have developed, and a better long-term management solution may be feasible. This document describes the detailed research plan for a State of Knowledge (SOK) Review and Assessment of any technologies and methods that are potentially relevant to arsenic trioxide management at the Giant mine site that have developed since 2002.

Initial Method Review

As stated in the initial proposal given to GMOB, the methods reviewed in the 2002 SRK Report have been initially evaluated to identify areas where significant technical development has occurred. Based on survey responses from Arcadis and external technical experts, the following method subject areas from the 2002 SRK report will be re-evaluated during the 2016 SOK review:

- **In Situ Management**
    - Biological Treatment
    - In Situ Stabilization
- **Waste Stabilization and Disposal**
    - Cement encapsulation
    - Vitrification
    - Precipitation with iron/calcium or other additives
- **Removal of Dust**
    - Remote mechanical mining
    - Backfilling chambers and stopes/ Paste technology
    - Jet boring
    - New engineered/purpose built vaults (sand shell method)

Additional detail for specific methods under these subject areas is presented in the **List of Methods** document, provided in Appendix A of this document. In addition to the methods mentioned above, specific proposals sent to the Giant Mine Oversight Board will be evaluated during the review of the relevant methods.

Identification of Potential Information Sources (mining industry, academia, research organizations, government, etc.)

Given the breadth of methods to be reviewed and the several years since the completion of the previous review, an efficient means of data gathering is essential in order to make the SOK Review and Assessment practical within the budget and timescale specified within the RFP. The initial list of groups who may be approached for updated information includes the following:

- Drilling firms
  - Boart Longyear
  - Layne Christensen
  - Michels Corporation
  - Ellingson
- Ore residuals/materials handling firms
- Academia
  - Colorado School of Mines
  - University of Montana
  - University of Waterloo
  - Queens University
- Government entities
  - US Mine Safety and Health Administration (MSHA)
  - Natural Resources Canada (CanmetMINING)
  - World Bank
  - National Risk Management Research Laboratory (NRMRL)
- Research organizations with Industry Participation
  - Interstate Technology and Regulatory Council (ITRC)
  - International Network for Acid Prevention (INAP)
  - Mineralogical Association of Canada (MAC)
  - International Council on Mining and Metals (IMMM)
  - The Mining Association of Canada
- Mining Companies
  - AngloAmerican PLC
  - Cameco

BHP Billiton Ltd.In addition, our project team will be polled regarding their knowledge of specific projects where arsenic stability was evaluated (e.g. McLean Lake mine EIS, Saskatchewan).

Data Gathering (literature reviews, technical workshops, etc.)

Data to inform the assessment of methods will be collected using a focused approach that will maximize the efficiency of the process and minimize the collection of out of date information. Initial identifications of experts in each method or group of methods has been accomplished through a survey of Arcadis staff and collaborators. Clear consensus experts will be invited to participate in a 2-4-hour virtual meeting to discuss the state of the art in their area of expertise, which will cover multiple methods. Recommendations for follow-up actions to collect additional data and inform the technical assessment will be produced from the virtual meeting. In addition to the experts identified within the proposal, potential experts and those with experience in evaluating arsenic treatment identified to date include:

Grant Feasby P. Eng. – Mine remediation expert

John Hilton P. Eng. – Chemical engineer, involved with previous arsenic trioxide studies

Dr. Gie Tan (Kemetco Research Inc.) – Extractive metallurgy expert.

Literature will be reviewed in a focused manner to evaluate technical changes and novel technologies developed since the original assessment. Recent review articles, where available, will be used as a primary means to assess the state of the art in areas of interest. Abstracts of non-review articles and white papers will be evaluated based on date of publication, continuity of research and development (an indication of progress), technical maturity, technical impact, and other practical considerations (e.g., safety, implementability, cost). The most promising articles/papers will be identified and procured. Potential literature sources include:

Conference proceedings (e.g. International Conference on Mining Engineering);

Scholarly Journals (e.g. Journal of Hazardous Materials, Geochimica et Cosmochimica Acta); and

Vendor White Papers/ Technical sheets (e.g. Putzmeister Pump Systems).

Technical Assessment of Methods

Given the large pool of potential methods to be screened, a qualitative to semi-quantitative system will be used. A very high, high, moderate, low, or very low score will be used for each criteria/characteristic being evaluated. These qualitative scores will be assigned a numerical value (5, 4, 3, 2, 1 for very high, high, moderate, low, and very low). These scores will then be multiplied by a weighting factor using a similar system (i.e., high = 5, medium = 3, low =1). The weighted scores for each criterion will be totaled, allowing for a uniform means of comparison of a wide range methods. Adjusting weighting factors can also be used to simulate different stakeholder groups as well as provide the means to perform sensitivity analyses.

The scoring will occur in two stages: the first stage will be an evaluation against threshold criteria, and the second will be an evaluation against the complete set of criteria. Threshold criteria will be those below which a low-scoring method would be considered unsuitable for further consideration. Threshold criteria must be easily evaluated without significant effort in order to efficiently reduce the list of methods being evaluated.

Suggested threshold criteria are:

- Technical maturity and risk
- Incremental development since 2002 (when the SRK *Arsenic Trioxide Management Alternatives – Final Report* was produced)

Any method that receives a low score in either of the two threshold criteria will not be investigated or evaluated further. The results of the threshold criteria evaluation will be documented for future reference. The threshold evaluation will be completed by the technical director and project manager, with support by other staff based on input collected during initial surveys. The first stage of evaluation will be completed by December 15, 2016. The second stage of scoring will be completed by a group of 2-4 people with the technical expertise to assess the methods using their pre-existing knowledge, combined with information collected during the data gathering phase of the project. The ratings for each method will be recorded in a spreadsheet-based tool that will automatically convert the qualitative ratings into a numerical score. Each member of the group evaluating a method or methods will have access to the any information collected during evaluation via a shared storage location of files. The evaluation team will have this information for a minimum of one week before the scoring session is conducted.

The scoring session will be held using Skype for Business to allow for computer screen sharing as well as voice communication. Each scoring session will be facilitated by the Technical Director and/or the PM (the facilitator) who will ensure the process is used consistently between review teams. Additionally, that facilitator will record the results in the spreadsheet tool. Each facilitator will be instructed in how to handle areas where the team cannot reach consensus. In general, if there is a debate whether an item to receive a low or medium score, the period of discussion should not exceed approximately five minutes, as the score is unlikely to have a major impact on the overall results of the evaluation. If the discussion is centered around a medium or high score in a criterion, then more time for discussion will be afforded. The weight of each criterion also factors into how long a team should spend evaluating a single method against a single criterion. More time would be allocated to those criteria with higher weighting factors.

During method evaluations, each review team will be allocated one hour for a meeting to evaluate a single method, with one-half hour added per additional method to be evaluated. The initial hour will allow for the team to be briefed on the process, ask questions, and still complete the evaluation of a single method.

The results of the individual teams will be compiled into a single spreadsheet that will include the results of all ratings. This complete list of evaluated methods will also rank them according to their total weighted scores (sum of the products of the score and weight for each category). A draft complete scoring spreadsheet will be distributed to all participants for comment before being finalized. Any questions about a specific technology that arise from the review will be directed to the appropriate team that scored the technology. Questions regarding the overall process will be answered by the technical director.

As outlined in the RFP, a **Pilot Test Review** will be conducted using a single method gauged according to the criteria discussed above, and scored according to the ranking system defined in the next section. The **Pilot Test Review** will be submitted in draft to the GMOB and be the subject of a conference call, then finalized following GMOB input.

Setting of Performance/Assessment/Ranking Criteria

As stated above, a qualitative to semi-quantitative system of performance/assessment/ranking criteria (ranking criteria) will be used to in order to evaluate the methods. The setting of the ranking criteria will define the important characteristics of the desired handling/treatment/processing/isolation methods. The criteria used are inclusive of those used in the original assessment and will incorporate other essential ranking criteria that would improve the assessment. During the original SRK assessment, the following criteria were used in order to evaluate technologies:

- Methods must be technically viable;
- Methods must be field proven;
- Evaluation data must be available and adequate;
- Method must be robust- a long term solution;
- Method must be capable of acceptable implementation- including environmental acceptability; and
- Monitoring of method performance must be possible.

Working with these initial criteria, Arcadis has developed the following modified criteria to effectively evaluate identified methods:

- **Technical maturity**– probability of becoming a practical, useful technology, likely time required to develop a technology to the point of being implementable, availability of data for evaluation, fundamental soundness of technology
    - Low = implementation > 10 years out, Moderate = implementable within < 10 years, High = immediately implementable

- **Effectiveness (long term stability/permanence) –** how material of an impact will the method have compared to the currently implemented remedial strategy (performance evaluation defined as arsenic flux). Does the method have a high probability of a permanent solution?

    Low= long term stability unknown or unproven, Moderate= moderate long-term stability (100 years), High = long term stability likely.

- **Technical independence –** does the method provide benefit if it is the only change made, or, does it require additional technical changes or invention during implementation.
    - Low = requires additional unproven, expensive, or high risk methods to be effective, Moderate = requires some modification of existing condition using established methods, High = can be implemented effectively, essentially independent of other methods used at the site.

- **Confidence in predictive models**
    - Low = lack of or poor predictive models and/or the absence of long term performance data for technology, Moderate = accepted predictive models available or field data for 5-10 years of performance available, High = Field data for >10 years, and/or well validated predictive models exist for analogous systems.

- **Pilot testing/design/pre-installation requirements**
    - Low = requires extensive pilot/field/design work before implementation, Moderate = requires a modest level of pilot/field/design effort prior to implementation, High = requires minimal or no pilot testing, low-moderate level of design effort required

- **Operation, maintenance and monitoring (OMM) requirements – how much active management will be required**
    - Low = requires active (OMM) quarterly or more frequently, Moderate = requires annual OMM, High = passive remedy, requires only monitoring for compliance purposes

- **Risk –** long term risk, short term risk, worker health and safety
    - In order to make an effective comparison against previously evaluated methods, short term and worker health and safety risk categories, as defined in supporting document (SD) 18 of the 2002 SRK Report will be used. Long term stability, i.e. permanence, a priority in this review, is evaluated within the effectiveness category. These risk categories are described in more detail within SD 18, however a brief description is given below:
    - Risk type will be divided into three categories:
        - **Short-term risk –** The risk that a quantity of arsenic sufficient to affect ecological or human health could be released to the receiving environment during the preparation or implementation phase of each alternative and;
        - **Worker health and safety risks –** The conventional safety risks and the arsenic related health risks that would be faced by workers active in the preparation, implementation, and post-implementation activities.
    - Probabilities of arsenic releases will be developed and then converted into qualitative categories of risk (Table 1).

Table 1

Terminology used for Short- Term Risks (SRK, 2002)	
Qualitative Term	**Typical Risk of Significant Arsenic Release**
High	≥ 1 in 100
Moderate	≥ 1 in 1000
Low	≥ 1 in 10,000
Very Low	≤ 1 in 10,000

- Worker health and safety risk will be evaluated based on individual activities. Low, medium, and high risk qualifiers will be used.
    - Drilling and installation of wells and/or freezing systems
    - Dust extraction and transport
    - Dust processing
    - Water treatment
    - Residue disposal.
- During evaluation of long term risk, topic such as long-term geologic stability of underground storage areas, climate change impacts on air, water, soil temperatures, permafrost levels, precipitation rates etc., high water events (such as flooding in Baker Creek), and the influence of low-frequency, high consequence events such as floods and earthquakes will be evaluated.
- Impacts to the environment, such as degradation to permafrost will also be discussed.

- **Practicality of contingency measures in case of failure**
  - Low = difficult to apply an alternative method if the selected method is used, Moderate = the choice of a secondary back-up method is somewhat constrained in choice due to the primary method High= secondary methods easy to implement

- **Time required for implementation** – lead/development and implementation time required, in the context of conversion from the FBA
  - Low = Would require more than 70 years to implement, Moderate = would require 20-50 years to implement, High- would require less than 20 years to implement

- **Ease of Implementation-** Compatibility with the currently implemented remedial alternative.
  - The process of switching from the Frozen Block Alternative to a new long term approach will be a concern during implementation of any new remedy. Issues such as accommodation of thaw times, site conditions post-frozen block remedy, saturation of the waste, and site accessibility and stability will be discussed and evaluated.
  - Low = complicated and difficult transition from frozen block alternative, Moderate = moderately complex transition from frozen block alternative, High = easy transition from frozen block alternative.

- **Compatibility with Future Land Uses in Giant Mine Area**
  - Low= final remedial alternative does not add any benefit to future land use, Moderate = final remedial alternative adds some benefit to future land use, High = final remedial alternative adds significant benefit to future land use.

- **Cost – initial and total lifecycle cost**
  - Low = cost more than 25% greater than current remedy, Moderate = cost within 25% of current remedy, High = cost less than or equal to 75% of the cost of the current remedy

Figure 1 presents the rating breakdown and contribution of each criteria to the overall score. Major drivers guiding the assessment are Risk (worker health and safety, short term risk of release, and long term stability and permanence), operation maintenance and monitoring (OMM), and implementation costs. This makes up 57% of the total score.

Quality Assurance of Technology Ranking

The quality of scientific and engineering data provided in support of technologies under consideration will be evaluated in detail by the project team, under the leadership of the QA/QC Lead. As a means of assessing the reproducibility of our rating system, a subset of methods will be independently rated by a separate group of 2-4 personnel with sufficient expertise and information to perform the task. The ratings from the primary and the secondary group will be compared and assessed for comparability. This will be completed early in the process in order to identify any areas for improvement in the assessment methodology. It is anticipated that up to five methods would be subjected to this parallel ranking test.

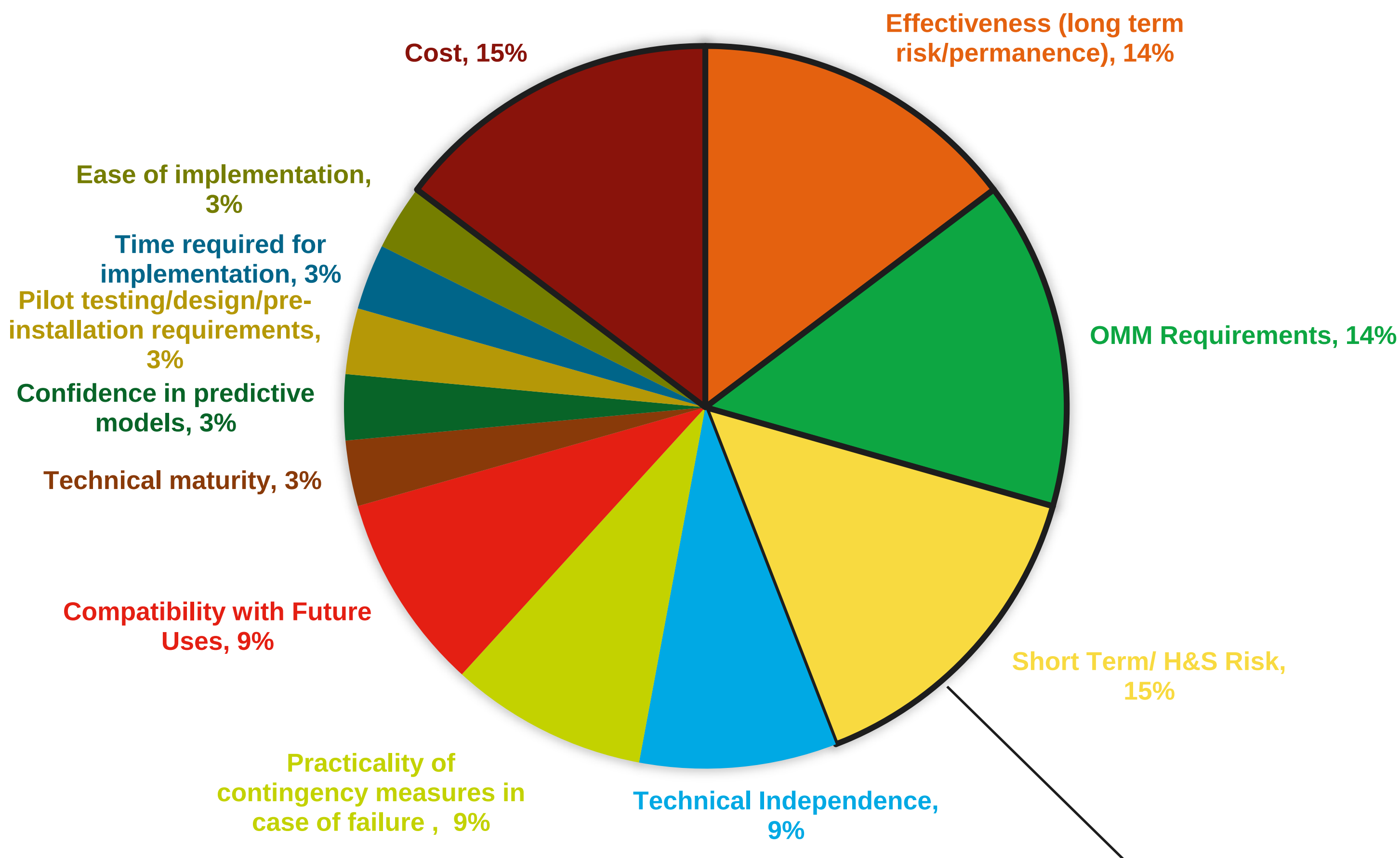
Reporting

Draft and final versions of the **SOK Review and Assessment Report** will be prepared in accordance with the approved TOC. A webinar will be held to present the results of the technology evaluation contained in the draft report. Each technology will be evaluated and presented according to the analytical framework and style of presentation (e.g., graphical/tabular form) agreed upon following review of the draft pilot test. In addition, the report will include notes/minutes from each virtual meeting with experts held during the course of the study. Key citations will be provided. Two companion PowerPoint presentations will be prepared, the first containing information on each method, the methodology of evaluation and relevant background material and recommendations. The second presentation will be a higher-level briefing style summary designed to communicate the objective, scope, methods, and output of the project in 20 minutes or less.

FIGURES

Figure 1
Scoring Breakdown

GMOB SOK Review
Yellowknife, NWT Canada



Major Drivers: (57%)

- Risk- H&S, short term, long term (28%)
- Maintenance (14%)
- Cost (15%)

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APPENDIX A

List of Methods

State of Knowledge Review and Assessment:
List of Methods to Review for Management of Giant Mine Arsenic Trioxide Dust

Methods that have had technological advancements since 2002 are shown in the table below in **bold**. These methods will be reviewed and evaluated in detail during the 2016 SOK review. Further research may identify additional methods that warrant evaluation. A brief summary of some of the technological advancements is provided following the table.

In Situ Management	Removal of Dust	Re-Processing to Recover Gold	Waste Stabilization and Disposal
Groundwater management methods: - Typical pump and treat. (Existing water treatment method uses ferric sulphate, lime slurry and settling and polishing ponds) - Passive water treatment methods for long-term reduced OMM - Segregation of groundwater flow - Partial flooding of mine - Inflow reduction *Isolation methods:* - Hydraulic cage - Grout curtain - Diversion of overlying surface water bodies - Ground freezing *In situ modifications:* - Engineered dilution - Dust freezing - **Biological treatment** - **In-situ stabilization (cement , nano-scale iron, or other additives)**	*Bulk mining methods:* - Open pit mining (for use in one area of stopes) - Re-stoping of dust - Freezing and re-stoping of frozen dust - **Remote mechanical mining** - Clamshell excavation - **Backfilling chambers and stopes** - **Paste technology** *Retrieving dust in a pipe:* - Wet vacuum - Dry vacuum - Fluidization from base - Flooding and pumps - Wet reverse circulation - Dry reverse circulation - **Jet boring** - Dredging *Other mining methods:* - Solution mining - Volatilization *Relocation Underground:* - Move dust deeper underground - Move above water table - **New engineered/ purpose built vaults**	*Direct shipment of crude dust* *Production and shipment of refined dust* - Fuming (selective sublimation) - Leaching and recrystallization (hot water, caustic, etc.) *Arsenic metal production* *Manufacture of added value products (no longer a viable option)* *Stabilization of As_2O_3 and preparation of refractory gold values for recovery* - Pressure oxidation - Biological treatments *Water Treatment (as needed for processing/ pre-processing):* - Water treatment for arsenic removal (existing water treatment method uses ferric sulphate, lime slurry and settling and polishing ponds) - Passive water treatment methods for long-term reduced OMM	*Physical Stabilization:* - Bitumen/asphalt encapsulation - **Cement encapsulation/ stabilization** - Zeolite or clay additives for stabilization - **Vitrification** - Vibrasonic *Chemical Stabilization* - **Precipitation with iron/calcium or other additives** - Slag disposal - Polysilicates *Isolation and Containment:* - Concrete/steel vaults - Lined basins

A summary of technological advancements since 2002 identified to date is provided below. Additional advancements may be identified as our literature review and dialogue with external experts proceeds.

- **Removal of Dust**
  - **Remote mechanical mining:** Numerous modifications and improvements have been made to current bulk and narrow vein mining extraction methods since the 2002 SRK report. Remote mechanical mining has removed the worker from much of the direct invasive work. For example, explosives can be loaded from locations away from the face with telescopic arms/explosives hoses. Once blasted, muck removal with electric (battery powered) load-haul-dump equipment reduces the risk of particulate exposure. These advances allow for a reduction in overall health and safety risks associated with any remedial alternative that requires extraction, and therefore warrants re-evaluation.

  - **Jet Boring:** In addition to remote mining advances, advances in borehole mining technology have made extraction methods more efficient and limit exposure. Hydraulic borehole mining, for example, has been used at the Olympic Dam Uranium mine in Australia to limit miners' exposure to radioactive materials.

  - **Backfilling and Dust Transportation:** Advancements in the fluid mechanics of high-solids flow have enabled both the extraction and backfilling of waste from the mine.

  - **Cement Paste:** Paste backfilling is being increasingly used as a method for tailings disposal. Mixtures of cement, tailings, and hydraulic binders are combined and redeposited in stopes or other chambers. The high solids content of these pastes reduces waste water and the cement assists in stabilizing the waste. Since 2002, significant advancements in the understanding of slurry and paste flow have been made, reducing risk of operational errors. An example application at Giant Mine would include arsenic waste extraction and stabilization at the surface using a cement grout. The resulting paste would then be piped back into the ground. This method has experienced sufficient development in the past 15 years to warrant re-evaluation.

  - **New Engineered, purpose built vaults**: Sand Shell: As part of a waste stabilization/solidification alternative, the sand shell method creates a semi-compressible medium (sand and/or gravel) that prevents an arsenic stabilized monolith from contacting the wall rock. Any ground movement will not damage the stabilized "capsule" ensuring longer term storage and monolith integrity compared to storing the material alone.

- **Waste Stabilization and Disposal**
  - **Cement Encapsulation/Stabilization:** During the 2002 SRK review, arsenic stabilization with cement was evaluated, and due to poor performance was not continued. However, arsenic stabilization with different types of admixtures (eg. lime, cement kiln dust) were not evaluated. Evaluation of cement stabilization with additional stabilizers could yield promising results.

  - **Vitrification:** Dundee Technologies has a proprietary vitrification and processing technology that is able to produce stable arsenic glass. The current pilot plant in Quebec produces 20,000 t/year of glass with a material loading of 45% arsenic. Due to the high stability of the glass, and the effective field demonstration, this technology warrants further evaluation.
    - Vendor proposals to be evaluated under this proposal are:
      - Dundee Sustainable Technologies- cyanide free gold extraction and vitrification

  - **Precipitation with iron/calcium or other additives**: During previous evaluation, pressurized scorodite precipitation was evaluated. Additional scorodite precipitation methods that are safer and more energy efficient have developed in the past 15 years and are operated at industrial levels. For example, Ecometales has partnered with Codelco to process up to 10,000 tons of arsenic per year.
- **In Situ Management**
  - **In Situ Biological Treatment:** Use of arsenic-oxidizing bacteria to treat arsenic-contaminated groundwater and surface water. Since 2002, the identification of bacteria able to precipitate and stabilize mobile arsenic has led to their application at remedial sites. A number of studies and proposals will be evaluated in this section with regards to in situ management of mobile-phase arsenic species. Biological treatment could be incorporated into remedial alternatives at the exterior of the shell or stabilized material as a final polishing step or contingency in case of accidental release (eg. failure of frozen shell).
    - Vendor proposals to be evaluated under this proposal are:
      - ecoStrategic Group- in-situ biological transformation
  - **In Situ Chemical Precipitation/Stabilization:** Since 2002, nanoscale iron technology has been investigated in detail with regards to the removal of arsenic species. Nanoscale iron has the capacity to adsorb both arsenite and arsenate and upon complete reaction, their unit volume will expand, serving to seal the transport pathways in which they are deposited. In addition, the technology available for the production of nanoscale iron colloids has dramatically developed allowing for the availability of colloids in numerous different forms and more importantly a reduction in cost from the $1,000/pound range to the $20-$100/pound range. Applications in the field have been performed relating to chlorinated solvents. In addition to nanoscale iron, ferrous iron precipitation with applied oxidant will also be evaluated.

    - Vendor proposals to be evaluated under this proposal are:
      - Nanotek nano-Zero Valent Iron

Changes from initial scoring system:

1) Included long term risk as part of effectiveness. Effectiveness is defined within the scope of the remedial alternative to reduce flux of arsenic from the mass in perpetuity. Long term risk is defined with the same metric, therefore to prevent redundancy, it was removed.
2) Refined title "Confidence and means to assess performance" to "Confidence in predictive models" This category describes whether there are predictive models or a strong body of evidence for the performance of the data. During the pilot review, the title was confusing.
3) Reworked scoring tool to include very high and very low scoring categories to expand ranking system and give more flexibility during rating.

Responses to Comments

"Regarding the methods, please make sure all technologies that were included in my November 17th email are explicitly considered (or mentioned). These included technologies offered by EcoStrategic, Dundee and Nanoteck. All parties are interested in their viability and we would like to provide an objective assessment of their potential."

We revised document to specifically include the Ecostrategic, Dundee and Nanotek proposals. During the review of the relevant methodology, Arcadis will specifically review the proposals (see Draft Pilot Review).

"In addition to these industry organizations, you may want to reach out directly to specific mining companies with potentially relevant expertise. Cameco, for example, will have knowledge of remote mining methods and BHP will be up to date on emerging jet boring technologies (e.g., not specifically for arsenic removal but slurry mining)."

We have reached out to Cameco and AngloAmerican PLC for their expertise. We will be reaching out to BHP shortly.

"As discussed, Andy is in conflict due to his role on the Giant Independent Peer Review Panel. However, contacting him for recommendations of others with relevant expertise is fine. If you have any uncertainty regarding whether others might be in conflict please contact Tony Brown."

We have removed him from the list within the methodologies. But will contact him for other potential contacts.

"I'm not sure if this is necessarily an appropriate threshold criteria. Some technologies would have been "developed" pre-2002 but were not sufficiently advanced at that stage to justify further consideration. However, the technologies may have evolved significantly since then. A judgement call will likely be necessary on this issue."

As per our call on January 6, 2016, we have clarified the Threshold Criterion as "Development since 2002"

"During our meeting we discussed the benefits of assessing the Frozen Block method to provide a baseline for comparison of other methods…since it sets the bar that needs to be beat. In addition, since GMOB is very familiar with the Frozen Block method, it is arguably a good candidate for the pilot. Any

results from the pilot would therefore get a "gut check" and the model could then be "calibrated" on that basis."

We have included an initial "gut check" review of the Frozen Block. We did not want to do the review of the FB as the pilot due differences in the amount of information available for review with the Frozen Block vs. the amount of information and research available for the other technologies.

"In addition to the criteria described below, the review should assess something like "Permanence". It is partially addressed under the O&M criteria but I don't think entirely. The frozen block was criticized because the proponent couldn't say with confidence that the dust would remain frozen/dry/immobile in perpetuity. The SOK should therefore assess this criterion explicitly and give it a relatively heavy weight."

We have revised the scoring criteria to include permanence in the "effectiveness" category. We have included a section within the methodology that discusses the main drivers of the ranking system.

"This timeframe should be adjusted upward and perhaps use "indefinitely". While it's true that there will ultimately be releases from every technology, the "sufficient to affect…" qualifier means that solutions such as removal, vitrification, etc. may perform sufficiently well. In contrast, there would be less confidence that the frozen block and other similar technologies would prevent a significant release over very long time horizons."

We have re-worded this to include "in perpetuity"

"I know this is a catch phrase but I'm not sure what this means in practical terms. Perhaps consider changing to "Compatibility with Future Land Uses"….which, incidentally may include industrial, residential, recreational and "traditional" land use."

We have clarified the descriptor to include future land use.

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APPENDIX B

Expert Surveys

Questionnaire- Mining Methods of Giant Mine Arsenic Trioxide Dust

Please help us narrow down the list of methods to review for the management of arsenic trioxide dust stored in the Giant Mine in Yellowknife, NT, Canada. A brief background of the site is provided below followed by a list of methods. Thank you in advance for your help!

Please return this questionnaire to Alison Conron (alison.conron@arcadis.com) and Kathryn Farris (Kathryn.Farris@arcadis.com). Please call us with any questions.

Background

At the Giant Mine, the 237,000 tonnes of arsenic trioxide waste (~60% Arsenic by mass) is stored underground. There are 15 purpose-built chambers and mined out stopes, 14 of which contain the arsenic trioxide waste. The chambers have regular block-like shapes, while the stopes have irregular shapes. The chambers and stopes are located between depths of 20 to 75 metres below the ground surface.

In 2001, a study of management alternatives for the arsenic trioxide dust was initiated. Selected alternatives were evaluated (see table below). These representative alternatives given below were not intended to rule out other options, but to guide further method investigation. Based on the results of the 2001 investigation, it was recommended that in situ management be investigated further, and work on the other alternatives should be limited to areas that could lead to significant reductions in costs and risks.

Currently, Alternative B3 is being implemented on the site. However, this action is treated as an interim remedial measure, and potential permanent solutions are still being evaluated as technologies advance.

The purpose of this survey is to identify whether substantial changes in mining/extraction technology have occurred in the past 15 years relating to mining and materials handling that could have significant impact on the cost effectiveness and safety of remedial alternatives that require dust removal.

Summary of Cost Ranges and Risks for Alternatives Reviewed Previously (From 2002 SRK Report)

Alternative	Overall Risk	Dominant Risk Category	Net Cost Range ($Million)
A1. Water Treatment with Minimum Control	High	Long term	30-70
A2. Water Treatment with Drawdown	Moderate	Long term	80-110
A3. Water Treatment with Seepage Control	Moderate	Long term	80-120
B2. Frozen Shell	Low	Long term	90-110
B3. Frozen Block	Low	Long term	90-120
C. Deep Disposal	Moderate	Worker H&S	190-230
D. Removal & Surface Disposal	High	Short term	600-1000
F. Removal, Gold Recovery & Arsenic Stabilization	Moderate	Worker H&S	400-500
G1. Removal & Cement Encapsulation	Moderate	Worker H&S	230-280

Site Specific Challenges/Relevant Information:

- Structural integrity of the cement bulkheads and crown pillars
    - A program to shore up structural components is underway, but uncertainties exist.
- Chemical Properties of arsenic trioxide waste
    - High purity arsenic trioxide dust, particle size generally <5 microns
    - Health and Safety (fully encapsulating suits) will be required for all dust-generating activities
    - Dust is hydrophobic and wetting is difficult.
- Location
    - Site is in Yellowknife, NWT Canada in partial permafrost

- Arsenic- and site-specific challenges are superimposed on general remediation challenges associated with northern environments

Methods

Since 2001, have there been any significant changes in the following mining technologies?

Bulk mining methods:

- Open pit mining (for use in one area of stopes)
- Re-stoping of dust
- Freezing and re-stoping of frozen dust
- **Remote mechanical mining**
- Clamshell excavation

Retrieving dust in a pipe:

- Wet vacuum
- Dry vacuum
- Fluidization from base
- Flooding and pumps
- Wet reverse circulation
- Dry reverse circulation
- **Jet boring**
- Dredging

Other mining methods:

- Solution mining
- Volatilization
- ____________________

Relocation Underground:

- Move As deeper underground
- Move above water table
- New engineered/purpose built vaults

Isolation and Containment:

- Concrete/steel vaults
- Lined basins

Any new mining/extraction methods that have been developed?

____

____

Please describe below what changes have been made (add lines if necessary):

____

____

____

____

Is there anyone with experience/expertise in these areas who you think we should contact?

____

We have prepared similar questionnaires focused on stabilization methods (chemical and physical) and other forms of in-situ treatment (isolation, groundwater control/extraction, in-situ modification). If you think you can contribute to the evaluation of these methods, please let us know and we will send the relevant questionnaire to you.

Thanks for your help!

Questionnaire- In Situ Management, Water Treatment and Waste Stabilization/ Disposal of Giant Mine Arsenic Trioxide Dust

Please help us narrow down the list of methods to review for the management of arsenic trioxide dust stored in the Giant Mine in Yellowknife, NT, Canada. A brief background of the site is provided below followed by a list of methods. Thank you in advance for your help! ***Billable number available upon receipt of completed survey. Our expectation is this initial response to the questionnaire will take about half an hour of your time. Based on the feedback obtained, we may well involve you as the project proceeds.***

Please return this questionnaire to Alison Conron (Alison.Conron@arcadis.com) and Kathryn Farris (Kathryn.Farris@arcadis.com). Please call us with any questions.

Background

At the Giant Mine, there are 237,000 tonnes of arsenic trioxide dust (~60% arsenic by mass) stored underground. There are 15 purpose-built chambers and mined out stopes, 14 of which contain the arsenic trioxide waste. The chambers have regular block-like shapes, while the stopes have irregular shapes. The chambers and stopes are located between depths of 20 to 75 metres below the ground surface.

In 2001, a study of management alternatives for the arsenic trioxide dust was initiated. Selected alternatives were evaluated (see table below). These representative alternatives given below were not intended to rule out other options, but to guide further method investigation. Based on the results of the 2001 investigation, it was recommended that in situ management be investigated further, and work on the other alternatives should be limited to areas that could lead to significant reductions in costs and risks.

A ground freezing pilot study is currently being implemented on the site. However, this action is treated as an interim remedial measure, and potential permanent solutions are still being evaluated as technologies advance. Previous studies focused on cement and bitumen stabilization, and calcium and iron precipitation. The groundwater at the mine is currently treated by the addition of ferric sulphate and lime slurry followed by a settling pond and polishing pond.

The purpose of this survey is to identify whether substantial changes in stabilization/water management/in-situ treatment technology have occurred in the past 15 years that could have significant impact on the cost effectiveness and safety of remedial alternatives. Specifically, enhancing overall stability of the arsenic trioxide waste compared to ground freezing.

Summary of Cost Ranges and Risks for Alternatives Reviewed Previously (From 2002 SRK Report)

Alternative	Overall Risk	Dominant Risk Category	Net Cost Range ($Million)
A1. Water Treatment with Minimum Control	High	Long term	30-70
A2. Water Treatment with Drawdown	Moderate	Long term	80-110
A3. Water Treatment with Seepage Control	Moderate	Long term	80-120
B2. Frozen Shell	Low	Long term	90-110
B3. Frozen Block	Low	Long term	90-120
C. Deep Disposal	Moderate	Worker H&S	190-230
D. Removal & Surface Disposal	High	Short term	600-1000
F. Removal, Gold Recovery & Arsenic Stabilization	Moderate	Worker H&S	400-500
G1. Removal & Cement Encapsulation	Moderate	Worker H&S	230-280

Site Specific Challenges/Relevant Information:

- Structural integrity of the cement bulkheads and crown pillars
    - A program to shore up structural components is underway, but uncertainties exist.

- Chemical properties of arsenic trioxide waste
  - High purity arsenic trioxide dust (60% by weight), particle size generally <5 microns
  - Health and Safety (fully encapsulating suits) will be required for all dust-generating activities
  - Dust is hydrophobic and wetting is difficult (not impossible).
- Arsenic chamber water quality
  - As concentrations >2000-4000 mg/L (potentially significantly higher)
  - pH 5.75-6.65
  - High TDS, Mg, sulfate, phosphate, slightly elevated ammonia
- Location
  - Site is located in Yellowknife, NT, Canada
  - Arsenic- and site-specific challenges are superimposed on general remediation challenges associated with northern environments

Supporting documents are available providing more information about the methods evaluated. Please let us know if you need to review these documents for reference

<u>Methods</u>

Since 2001, have there been any significant changes in the following in situ technologies?

Groundwater management methods:

- Typical pump and treat. (Existing water treatment method uses ferric sulphate, lime slurry and settling and polishing ponds)
- Passive water treatment methods for long-term reduced OMM
- Segregation of groundwater flow
- Partial flooding of mine
- Inflow reduction

Isolation methods:

- Hydraulic cage
- Grout curtain
- Diversion of overlying surface water bodies
- Ground freezing

In situ modifications:

- Engineered dilution
- Dust freezing
- Biological treatment
- In-situ stabilization (cement or other additives)

Physical Stabilization:

- Bitumen/asphalt encapsulation
- Cement encapsulation (different types of cements?)
- Zeolite or clay additives for stabilization
- Vitrification
- Vibrasonic

Chemical Stabilization

- Precipitation with iron/calcium or other additives
- Slag disposal
- Polysilicates

Water Treatment (as needed for processing/ pre-processing):

- Water treatment for arsenic removal (existing water treatment method uses ferric sulphate, lime slurry and settling and polishing ponds)
- Passive water treatment methods for long-term reduced OMM

Do you know of any additional arsenic trioxide in-situ treatment/stabilization remediation methods we should look into?

- ____________________
- ____________________
- ____________________
- ____________________

Please describe below what changes have been made (add lines if necessary):

____
____
____

Is there anyone else at Arcadis with experience/expertise in these areas who you think we should contact?

We have prepared a similar questionnaire focused on mining/extraction methods. If you think you can contribute to the evaluation of these methods, please let us know and we will send the relevant questionnaire to you.

Thanks for your help!

APPENDIX C

Technical Expert Reviewers

Expert Reviewers

Arcadis utilized both internal and external experts to review the different treatment methodologies as part of the Giant Mine State of Knowledge Review. Brief summaries of the experts' experience and background are provided below.

Arcadis Experts

Patricia Moran, Ph.D.

Dr. Patricia Moran is a Principal Geochemist with Arcadis U.S. with over 17 years of experience. She is experienced in geochemical characterization, geochemical modeling, and development of treatment strategies to evaluate and manage acid rock drainage and metal leaching. She focuses on geochemical modeling and development of treatment strategies to evaluate and manage mine influenced water including several northern mine sites. Relevant project work includes conducting numerous hydrogeochemistry-based projects that focused on defining the geochemical processes that control the release, speciation, transport and attenuation of arsenic.

Dr. Moran was an expert reviewer for cement stabilization and cement paste backfill technologies as part of the Giant Mine State of Knowledge Review.

Donald Carpenter, M.S., PG

Mr. Donald Carpenter is a Senior Vice President/Chief Geochemist with Arcadis U.S. and has more than 36 years of experience. He has extensive experience detailing remedial strategies to both regulatory agencies and the public and has a broad background in applying solution equilibria-based geochemical and geostatistical computer modeling methods to mining-related projects for ore metallurgy, delineation and reserve estimates, structural geology, and underground water control. Mr. Carpenter has conducted geological and hydrologic evaluations of numerous mine sites in North and South America. He was the lead for the arsenic evaluation projects in British Columbia, Texas and Maine.

Mr. Carpenter was an expert reviewer for vitrification as part of the Giant Mine State of Knowledge Review.

Jeff Gillow, Ph.D.

Mr. Jeff Gillow is a Technical Expert in Geochemistry with Arcadis U.S. with 26 years of experience. He has experience in environmental science with specific emphasis on the chemistry of inorganics (arsenic, sulfate, metals and radionuclides) in soil and groundwater at mining and industrial sites. He is an expert in the evaluation of the environmental aspects of mining, milling, and smelting operations including water quality, geochemistry and soil and water assessment and management strategies, as well as regulatory negotiations.

Mr. Gillow was an expert reviewer for vitrification and mineral precipitation as part of the Giant Mine State of Knowledge Review.

Margaret Gentile, Ph.D., PE

Dr. Margaret Gentile is a Principal Environmental Engineer with Arcadis U.S. and In Situ Reactive Treatment Lead for Arcadis North America with 16 years of experience in environmental engineering. Her PhD research focused on the microbial ecology of engineered biological treatment systems. Her project experience has a strong focus on in situ remediation design, implementation, and optimization for organic and inorganic contaminants. She particularly enjoys providing technical expertise on microbial and geochemical aspects of treatment, remediation of metals, and tackling large, complex plumes.

Dr. Gentile was an expert reviewer for oxidative and reductive biological precipitation technologies as part of the Giant Mine State of Knowledge Review.

David Vance, M.S.

Mr. David Vance is a Technical Expert and Associate Vice President with Arcadis U.S. with 38 years of experience. He is a practicing geoscientist with a background in geology, hydrogeology, microbiology, and chemistry. His career has focused on the hydrodynamics of multiphase fluid flow systems in a wide range of geologic environments, and the biogeochemical processes that take place in them. Specific innovative areas of focus and expertise have included biogeochemical driven processes effecting metal speciation, mineral dynamics and interfacial chemistry. At Arcadis, Mr. Vance is currently the corporate team leader for Non-Metallic Inorganics. He has in situ arsenite remediation experience and has used nano-scale iron to treat a PCE plume.

Mr. Vance was an expert reviewer for nanoscale zero valent iron technology as part of the Giant Mine State of Knowledge Review.

Michael Hay, Ph.D.

Dr. Michael Hay, PhD, is a Senior Geochemist and the Geochemical Modeling focus area lead within Arcadis U.S. He has 14 years of experience in environmental chemistry. He specializes in the in situ remediation of groundwater impacted with metals and inorganics, with consulting and postdoctoral research expertise in geochemical and reactive transport modeling. Prior to joining Arcadis, he was a research hydrologist for the U.S. Geological Survey, studying metals transport at mining- and milling-impacted sites.

Dr. Hay was an expert reviewer for mineral precipitation as part of the Giant Mine State of Knowledge Review.

Rich Royer, Ph.D.

Dr. Richard Royer is a National Technical Expert in Remediation with Arcadis U.S., and has 24 years of experience. He has expertise in biodegradation, biogeochemistry, metal-microbe interactions, aquatic chemistry, bio-fouling, and microbially influenced corrosion, and has designed, conducted and interpreted numerous laboratory and field environmental studies. As a Treatability Research Laboratory Director, Dr. Royer led a team charged with the evaluation of more than 50 novel and emerging environmental technologies. Remedial technologies evaluated during his tenure spanned multiple disciplines including bioremediation, water treatment, analytical chemistry, and site characterization. Recently, Dr. Royer led a study on arsenic trioxide waste stabilization for treatment of 11,000 tonnes of waste material from an ore roasting operation. The study was able to successfully stabilize arsenic trioxide waste both through processing of the waste to generate scorodite as well as via stabilization with Portland cement with other amendments.

Mr. Royer was an expert reviewer for nanoscale zero valent iron and BioBol technologies as well as the Technical Lead for the Giant Mine State of Knowledge Review.

John Vogan, P.Eng. (ON)

Mr. Vogan is a Vice-President of Arcadis Canada and has more than 28 years' experience in managing environmental programs, including more than 17 years in remediation technology development. He is responsible for supporting Arcadis client teams and technical project execution throughout Canada, and sourcing technical expertise from the United States and elsewhere for these projects. Prior to joining Arcadis, Mr. Vogan led a university spin-off in situ remediation company which established an innovative groundwater treatment technology in the global marketplace. He has co-authored more than 30 technical publications and has taught several short courses in collaboration with the USEPA. For over 10 years he managed his company's funding of collaborative research and development programs (co-funded by GE, DuPont, and Rio Tinto), at the University of Waterloo, worth more than $0.5M annually. Mr. Vogan currently manages two large mine remediation projects in northern Manitoba involving several of the Canadian and United States experts proposed for this project, and recently collaborated with Environment Canada researchers on evaluating innovative technologies for soil and groundwater treatment of emerging fluorinated contaminants.

Mr. Vogan was an expert reviewer for nanoscale zero valent iron technology as well as the Project Manager for the Giant Mine State of Knowledge Review.

Wayne Cormack, M.Eng., CIH

Mr. Wayne Cormack is a Senior Consultant with Arcadis Canada with 36 years of experience. He is a Certified Industrial Hygienist with experience in health and safety-related issues at northern mine sites in the Northwest Territories, Yukon and Nunavut including hazard and risk assessment and design and review of air monitoring programs. He has experience in assessment of worker exposure to chemical and physical hazards, asbestos management, mould investigations and design and review of air monitoring programs.

Mr. Cormack was an expert reviewer for Health & Safety as part of the Giant Mine State of Knowledge Review.

J. Fletcher Baltz, M.S., PE (NY)

Mr. Fletcher Baltz is a Principal Geotechnical Engineer with Arcadis U.S. with over 35 years of experience in heavy civil and geotechnical design and construction. Mr. Baltz has been responsible for design and construction of geotechnical components for hydropower projects, including geotechnical investigations, dam safety inspections, shaft and tunnel construction and inspections, rock slope inspections and stabilization, slope stability analyses, dam stability analyses, liquefaction analyses/remediation, post-tensioned rock anchor, grouting, surface rock excavation, earth fill placement, earth/sheet pile cofferdams, and geotechnical instrumentation/monitoring. Mr. Baltz's experience also includes caisson pile foundations, site work design, preparation of construction specifications and bidding documents, construction cost estimates and feasibility studies.

Mr. Baltz was an expert reviewer for the sand shell purpose-built vault method as part of the Giant Mine State of Knowledge Review.

External Experts

Rob Whipple, M.Eng., P.Eng. (ON): Rob Whipple Engineering Inc.

Mr. Rob Whipple has 36 years of diverse experience in mining and mining engineering consulting including 13 years of experience in rocks mechanics. His experience includes assessing ground control processes, rock mass evaluation, first level numerical modelling, geotechnical assessments, ground support design, quality control, ground movement monitoring, investigations and remedies at mine sites across Canada, including geotechnical assessments for closure plans of abandoned, active and future mines. Relevant projects he has been involved in include: ground control work in northern Québec (sub-arctic conditions); Chief Surveyor at Lupin Mine; and Chief Draftsperson for the George Lake gold exploration project.

Mr. Whipple was an expert reviewer for remote mechanical mining methods, purpose-built vaults and jet boring for the Giant Mine State of Knowledge Review.

Colin Kinley: Kinley Exploration LLC

Colin is a Founder and Managing Director of Jet Mining Pty Ltd. (Jet), based in Perth Australia. Jet provides Hydraulic Borehole Mining (HBHM) Technology to the Australian regional mining markets. The company is providing technical engineering advisory services for the Prefeasibility, Feasibility, Pilot and mining of minerals by Hydraulic Borehole Mining. Mr. Kinley has worked for over 25 years, specifically in the development of engineered bulk sampling and development of HBHM mining equipment and technologies. Jet provides unique services for the targeted mining of diamonds, uranium, tin, gold, mineral sands and unique, difficult access and submerged high value soft ores.

His previous involvement with Giant Mine included an evaluation for drilling and dust extraction at the Giant Mine (memo dated March 13, 2002, in appendix A in Supporting Document 7 of the 2002 SRK report).

Mr. Kinley was an expert reviewer for jet boring technology as part of the Giant Mine State of Knowledge Review.

John Mahoney: Mahoney Geochemical Consultants LLC

Dr. John Mahoney is Principal Geochemist with Mahoney Geochemical Consulting LLC. Dr. Mahoney specializes in Aqueous Environmental Geochemistry and hydrogeochemical modeling as applied to industrial and mining related projects. He has conducted detailed studies and geochemical modeling for various mining operations (North America, South America, Indonesia, Botswana and South Africa) and for contaminated sites (fuels spills, chlorinated solvents and metals) primarily in the Western United States. Currently he is developing hydrogeochemical and transport models to evaluate issues associated with the in-situ recovery of uranium and subsequent restoration of these zones.

He has previously worked with Arcadis to evaluate the suitability of cement stabilization and mineral precipitation for arsenic trioxide waste from a gold mine in Ghana. He has no specific prior experience at the Giant Mine.

Dr. Mahoney was an expert reviewer for mineral precipitation as part of the Giant Mine State of Knowledge Review.

Terry Mudder: Times Limited

Dr. Terry I. Mudder is co-owner (with his wife, Dr. Karen Hagelstein) of Times Limited, a consulting firm located in Sheridan, Wyoming (USA). He was previously employed as Chief Environmental Engineer and Research Chemist at the Homestake Mine, and later a partner and corporate consultant with SRK

Consulting. Dr. Mudder holds B.S. and M.S. degrees in Chemistry, and a Ph.D. in Environmental Science and Engineering. He has more than 30 years of experience in investigation of various aspects of mining and cyanide wastes. He served as an adjunct professor, guest lecturer, and thesis advisor at universities worldwide. He has worked on scores of mining projects, authored nearly one hundred publications, and been involved with numerous short courses on acid mine drainage, rehabilitation, and cyanide.

Dr. Mudder has been instrumental in developing and applying novel chemical, physical, and biological treatment processes for which he has received international awards and patents. He has been a member of many national and international scientific organizations and associated professional committees, as well as a manuscript reviewer. He has been the Technical Advisor for *Mining Environmental Management* for nearly a decade, for which he has written numerous editorial and opinion articles. In February 2014 Dr. Mudder was inducted into the International Mining magazine's Hall of Fame and was recognized with an award in Environmental Management and Stewardship.

Dr. Mudder provided insight into cement stabilization technology as part of the Giant Mine State of Knowledge Review.

Mostafa Benzaazoua: Université du Québec en Abitibi-Témiscamingue

Dr. Mostafa Benzaazoua is a professer at l'Université du Québec en Abitibi-Témiscamingue (UQAT) in Rouyn-Noranda, Québec. He is also an associate professor at McGill University in the Department of Mining and Materials Engineering. He has a Ph.D. in geosciences from l'Institut National Polytechnique de Loraine. He is a member of the Canadian Institute of Mining, Metallurgy and Petroleum. Dr. Benzaazoua's areas of specialization include: applied minerology; environmental geochemistry; integrated management of mine waste, mine backfilling and environmental desulfurization; treatment and valuation of industrial and mining waste; and mineral treatment.

Dr. Benzaazoua was an expert reviewer for cement stabilization and cement paste backfill technologies as part of the Giant Mine State of Knowledge Review.

Rob Caldwell: SGS

Mr. Rob Caldwell, B.Sc. is the Metallurgical Operations Manager for Environmental Testing at SGS Minerals Services. He has 30 years of experience in hazardous, nuclear and mixed waste research and management, with the last 10 years primarily focusing on the minerals industry. Mr. Caldwell has worked for the Canadian, US and UK governments in the areas of hazardous and nuclear waste assessment and containment. His expertise includes waste containment process development, particularly stabilization/ solidification, including the design of laboratory and full scale projects. His work has resulted in the development of a number of standard methods including the CTEU-9 and AALT extraction methods which form part of Quebec Directive 019, as well as the hazardous waste delisting mechanism employed by British Columbia. Mr. Caldwell provides management for programs involving the environmental characterization of ores, waste rocks and the residues of extractive metallurgy programs undertaken by the Mineral Processing, Gold, and Hydrometallurgy groups for SGS.

Mr. Caldwell was an expert reviewer for cement stabilization and cement paste backfill technologies as part of the Giant Mine State of Knowledge Review.

Steven Wuschke: Cameco Corporation

Mr. Steven Wuschke, P.Eng. is a Principal Mine Engineer at Cameco Corporation. He has 47 years of experience in various mining technical, operations and government roles. Mr. Wushke was an expert reviewer for remote mining methods as part of the Giant Mine State of Knowledge Review.

Scott Bishop: Cameco Corporation

Mr. Scott Bishop, P.Eng. is the Manager of Technical Services at Cameco Corporation. He has 26 years of experience in mining technical roles. Mr. Bishop was an expert reviewer for remote mining methods as part of the Giant Mine State of Knowledge Review.

James Hatley: Cameco Corporation

Mr. James Hatley is the Manager of Technical Evaluations at Cameco Corporation. He has 21 years of experience in mining. His experience spans both operations and project management experience. Mr. Hatley has managed teams for multiple companies that have successfully completed the implementation of new engineering technologies in the mining environment to recover previously un-minable ore, mitigate unplanned events and greatly enhance corporate and business unit value. Mr. Hatley was an expert reviewer for remote mining methods as part of the Giant Mine State of Knowledge Review.

Heather Jamieson: Queen's University

Dr. Heather Jamieson is a Professor in the Department of Geological Sciences and Geological Engineering at Queen's University in Kingston, Ontario. She also holds an appointment and teaches courses in the School of Environmental Studies at Queen's. Her expertise is in the area of environmental geochemistry, particularly the mineralogical controls on the mobility of metals and metalloids (notably arsenic) in mine waste and the application of synchrotron-based X-ray experiments and other microanalytical methods to metal speciation in mine tailings, soils, sediments and household dust. Much of her fieldwork is in the Canadian Arctic but she has also conducted research in Nova Scotia, California, Montana, Spain and Australia. Dr. Jamieson has conducted extensive research at the Giant Mine, including speciation of arsenic in the mine tailings, lakes, soils and sediments.

Dr. Jamieson was an expert reviewer for mineral precipitation, oxidative and reductive biological precipitation and chemical precipitation technologies as part of the Giant Mine State of Knowledge Review.

APPENDIX D

Method Scoring Sheet

Giant Mine Oversight Board- State of Knowledge Review
Method Rating Sheet- Template
Giant Mine, Northwest Territories, Canada

Technology

Insert Method Name

Criteria	Ranking	Description	Scoring Criteria	Notes/Rationale
Technical Maturity		Probability of becoming a practical, useful technology, likely time required to develop a technology to the point of being implementable, availability of data for evaluation, fundamental soundness of technology.	Low = implementation > 10 years out, Moderate = implementable within < 10 years, High = immediately implementable	
Effectiveness (Long Term Stability/Permanence)		How material of an impact will the method have compared to the currently implemented remedial strategy (performance evaluation defined as arsenic flux). Does the method have a high probability of a being a permanent solution?	Low= long term stability unknown or unproven, Moderate= moderate long-term stability (100 years), High = long term stability likely.	
Technical Independence		How many additional levels and steps are required within the integrated treatment process for the complete remedy? Are these additional methods unproven, expensive or high risk?	Low = requires many additional unproven, expensive, or high risk methods to be effective, Moderate = requires moderate interim processing steps using established methods, High = standalone process.	
Confidence in Predictive Models		degree of confidence in predicting long term performance.	Low = lack of or poor predictive models and/or the absence of long term performance data for technology, Moderate = accepted predictive models available or field data for 5-10 years of performance available, High = Field data for >10 years, and/or well validated predictive models exist for analogous systems.	
Pilot Testing, Design and Pre-Installation Requirements		Includes evaluation of upscale to production model.	Low = requires extensive pilot/field/design work before implementation, Moderate = requires a modest level of pilot/field/design effort prior to implementation, High = requires minimal or no pilot testing, low-moderate level of design effort required.	
Operation, Maintenance and Monitoring		How much active maintenance and system operation would be required after the implementation of the remedial alternative.	Low = requires active OMM quarterly or more frequently, Moderate = requires annual OMM, High = passive remedy, requires only monitoring for compliance purposes after remedial alternative is implemented	
Risk (Short Term, Worker H&S)		Short-term risk – The risk that a quantity of arsenic sufficient to affect ecological or human health could be released to the receiving environment during the preparation or implementation phase of each alternative and; Worker health and safety risks – The conventional safety risks and the arsenic related health risks that would be faced by workers active in the preparation, implementation, and post-implementation activities	**Please see module to the right to evaluate health and safety risks**	
Practicality of Contingency Measures in Case of Failure			Low = difficult to apply an alternative method if the selected method is used, Moderate = the choice of a secondary back-up method is somewhat constrained in choice due to the primary method, High= secondary methods easy to implement	
Time Required for Implementation		Lead/development and implementation time required, in the context of conversion from the FBA, includes pilot studies	Low = Would require more than 20 years to implement, Moderate = would require 10-20 years to implement, High= would require less than 10 years to implement	
Ease of Implementation		The process of switching from FBA to a new long term approach will be a concern during implementation of any new remedy. Issues such as accomodation of thaw times, site conditions post FB remedy, saturation of the waste, and site accessibility and stability will be contributing factors	Low = complicated and difficult transition from frozen block alternative, Moderate = moderately complex transition from frozen block alternative, High = easy transition from frozen block alternative.	
Compatibility with Future Land Uses in Giant Mine Area		Level of surface disturbance during the remedial implementation and effect to surface after completion of the remedial alternative.	oFinal: Very Low/ Low = final remedial alternative significantly disrupts or could impact present or future development of land, Moderate = implementation of final remedial alternative will impact current or future development of land, and somebut long-term impacts may be anticipatedare minimal, High = final remedial alternative may impact short term use, but has minimal footprint and minimally disrupts current and future development of land, Very High = final remedial alternative causes minimally invasivedisruption both in the short-term during implementation and in long term.	
Cost		The estimated cost range for the frozen block, assuming 2% annual increase since the 2002 SRK report, is $120-160 million dollars.	Very Low= $200+M, Low= $160-200M, Moderate= $120-$160M, High= $80-$140M, Very High= <$40-$80M	
Compatibility in Cold Climates			Low= major issues arise from implementing technology in cold climates, Moderate= moderate or unknown issues in implementing technology, High= technology is already successfully used in cold climates.	

Risk	Low	Max value for the individual Risk Categories	
	Risk for significant Arsenic Release for each category		
Short term risk	0	**Risk that a quantity of arsenic sufficient to affect ecological or human health could be released to the receiving environment during the preparation or implementation**	
Worker H&S	0	**Conventional safety risks and the arsenic related health risks that would be faced by workers active in the preparation implemetntation and post-implementation activities**	
		Drilling and installation of wells and/or other subsurface installations	0
		Dust extraction and transport	0
		Dust Processing	0
		Water treatment	0
		Residue disposal	0
Max of Risk Categories	**0**		

Contributing factors to ranking

Discuss below the main concerns under each health and safety component eg. dust extraction - high worker health and safety concerns.

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