Geotechnical and Cold Regions Aspects: The Giant Mine Remediation Project

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ABSTRACT
The Giant Mine is located in discontinuous permafrost near Yellowknife, NT. It produced gold between 1948 and 2004. The roasting process used to liberate the gold released arsenic-rich gases which were captured as arsenic trioxide 237,000 tonnes of which were stored underground in sealed stopes and chambers. The dust is hazardous to people and the environment. In 1999, INAC undertook to develop a long-term management plan and engaged necessary areas of expertise. After evaluation of potential alternatives (in-situ and above ground) the in-situ "frozen block" method was selected. The project is presently at a regulatory and advanced design stage.

RÉSUMÉ
La mine "Giant" est située sur pergélisol discontinu près de Yellowknife, NT. Elle a produit de l'or entre les années 1948 et 2004. Le procédé de grillage utilisé pour libérer l'or dégageait du gaz riche d'arsenic qui a été capturés comme poussière trioxyde de diarsenic de 237,000 tonnes et ensuite stockée dans des barils et des chambres. La poussière est dangereuse pour les gens et l'environnement. En 1999, AINC a entrepris de développer une gestion à long terme plan et a engagé l'expertise nécessaire. Après l'évaluation des alternatives potentielles (in situ et au-dessus du sol), la méthode in situ "bloc congelé" a été sélectionnée. Le projet est actuellement en processus réglementaire et en phase de conception avancée.

1.0 INTRODUCTION

The Giant Mine is located in Yellowknife, NWT about 5kms north of the City centre. It borders North Yellowknife Bay which is part of Great Slave Lake, and is in a region of widespread discontinuous permafrost. Several First Nations Communities are also located in the immediate area. The Mine produced gold from 1943 until 1999 and gold ore for offsite processing from 2000 to 2004.

Gold in the Giant Mine ore is associated with an arsenic bearing mineral known as arsenopyrite. The roasting process used to liberate the gold from the arsenopyrite led to production of arsenic-rich gases.

During the period 1951 to 1999, operators at the Giant Mine captured arsenic-rich gases in the form of arsenic trioxide dust which was pumped into sealed underground storage areas. The dust is ± 60% arsenic which is hazardous to both people and the environment.

Mining was based on underground methods supplemented between 1974 and 1990 by operations at a number of open pits. Early mining is described by Authors such as Pitcher (1953) and McDonald (1953). Five mined-out stopes and ten purpose built storage chambers were used for storage of arsenic trioxide dust. The overall mining operation also included processing facilities, tailings impoundments, a water treatment plant, and settling and polishing ponds. A water course (Baker Creek) flows through the site and discharges into North Yellowknife Bay.

The Mine owner went into receivership in 1999, following which Indian and Northern Affairs Canada (INAC) undertook to prepare a comprehensive mine closure plan, an important element of which included development of a long-term management plan for the arsenic trioxide dust.

One of the conditions applicable to the Water License granted by the Northwest Territories Water Board in 1993 was that an investigation and evaluation of the Arsenic Storage vaults should be carried out from the standpoints of abandonment and restoration, and that the relevant studies should cover the aspects of rock mechanics, geohydrology, geochemistry, permafrost, and risk assessment. Royal Oak Mines Inc. (then Owner of the Mine) carried out some initial work on the subject studies and in 1995 retained a number of independent consultants with specialized expertise. Some of the work completed, such as installation of thermisters to investigate the state of permafrost in the mine area, is discussed later herein.

After assuming responsibility for long term management of the project as a whole in 1999 when Royal Oak Mines was assigned into receivership, INAC quickly recognized that the project would be many facetted, technically complex, and virtually without direct precedent. Consequently INAC appointed a two member Independent Peer Review Panel and a Technical Advisor, comprising a group of companies led by SRK Consulting Inc. (SRK) to advise on the management alternatives for the arsenic trioxide. INAC also implemented care and maintenance activities that focused on protection of human safety and the environment. Fortunately a measure of control over contamination of groundwater in the environs of the Mine was provided by pumping arsenic contaminated water from the underground workings during operations and treatment prior to release to the environment. Care and maintenance activities continued the active pumping and treatment of arsenic contaminated water after cessation of mining operations. INAC also initiated a program of consultation with the stakeholders involved, including First Nations Communities, (such as the Yellowknife Dene First Nation) and interested local public. In recognition of the paramount importance of the geological and hydrogeological aspects of the studies, at an early date INAC also brought together a panel of experts in the field of hydrogeology which was tasked with reviewing the available data on the hydrogeology of the Mine and with advising INAC in carrying out appropriate studies and investigations to advance this key area of understanding. Similarly, at an early date, INAC hosted several technical workshops in Yellowknife to which it invited key engineers and scientists to help identify the component technologies and/or processes that could play a role in development of an overall management alternative for the arsenic trioxide dust stored underground at the Mine. INAC then expanded the Independent Peer Review Panel (IPRP) to nine recognized experts whose qualifications and experience collectively covered the various specialty fields important to the study of management alternatives, namely geotechnical, mining, mineral processing and environmental engineering, as well as toxicology, hydrogeology, and risk assessment.

In practice, many focused studies were involved in developing the overall management plan a number of which have already been described in various publications. These include literature reviews and thermal modeling associated with insitu freezing of the arsenic trioxide dust (Noel et Al, 2004); an understanding of the pattern of groundwater occurrence at the Mine (Mackie et Al, 2005); the hydrogeological conceptual model of the Mine (Mackie, 2006); and thermal analysis of an experimental thermosyphon installed at the Mine (Noel and Hockley, 2004). This paper deals primarily with the geotechnical considerations involved, (particularly as they applied to the arsenic trioxide dust), with reference to other related matters such as the influence of the permafrost, and the practical aspects of achieving the "frozen block" management concept selected.

2.0 HISTORICAL BACKGROUND

In the early years of mining, permafrost was encountered underground in the central mine area and formed an "envelope" of frozen ground, extending from the bottom of the active layer near surface, to more than 75 metres (250 feet) below surface. Rock temperatures were below freezing in the ore stopes developed within the permafrost envelope. In these stopes, the frost was observed to recede from the rock walls during the mining process, but the frost rapidly returned when the stopes were mined out. No water seepage was observed in the frozen rock.

Prior to the installation of the initial arsenic recovery process in 1951, the mine operators investigated several alternative methods for storing or permanently disposing of the arsenic trioxide dust.

The critical criterion established for a successful arsenic trioxide dust disposal method was to limit the potential for water to contact the dust. It was believed by the mine operator that the underground disposal option offered the lowest risks, at an acceptable cost. Practical experience showed that permafrost occurred in the upper approximately 250 feet at the Mine Site and that a thick blanket of overburden was a prerequisite for permafrost formation. Three main criteria were originally identified for storage of the arsenic dust underground in specially prepared stopes or chambers, namely (i) the storage area had to be enclosed in an envelope of permafrost, (ii) all openings from the arsenic stopes to other mine workings must be sealed to prevent any escape of the arsenic-bearing dust to them, and (iii) the storage area was to be excavated only in competent ground and had to be dry before arsenic dust placement commenced.

A small chamber was excavated underground in 1951, specifically for the purpose of storing the arsenic trioxide dust from a new gas cleaning circuit. The chamber was isolated form the mine workings with concrete bulkheads, and the arsenic dust was pneumatically conveyed through a piping system into the chamber. The storage system was successful, and four more purpose-built chambers were similarly constructed to store the dust through the 1950's.

By the early 1960's, the first ore stopes in the vicinity of the processing plant had been mined out. These excavations were located within the permafrost envelope and were generally dry. Several of the stopes appeared suitable for arsenic dust storage and, from 1962 through 1976, five stopes were used to store the dust. The practice of developing purpose-built chambers to store arsenic dust was continued in 1976 and five more chambers were constructed to store dust production through to 1999. An additional chamber was completed in 1999, but was not used. A total of ten purpose-built chambers and five mined-out slopes were used to store the dust. Three of the stopes, namely B212 to 214 are joined together. The chambers and stopes vary considerably in dimensions, shape and volume as indicated in Table 1. The chambers are generally shaped like a rectangular block with vertical walls. In contrast, the stopes were originally excavated to follow the ore body and are quite irregular. They are generally narrower than the chambers and have inclined walls. In addition they had extensive access workings resulting in numerous openings into ore chutes, raises and drifts, most of which are probably filled with arsenic trioxide dust. An air space was left between the top of the stored dust and the roof of the stope or chamber.

Table 1: Dimensions of Stopes and Chambers

<table>
<tr><th rowspan="2">Identifier</th><th colspan="3">Extent of Chambers / Stopes</th><th rowspan="2">Distance Surface to top (m)</th><th rowspan="2">Stored Arsenic Dust (m^3)</th></tr>
<tr><th>Width (m)</th><th>Height (m)</th><th>Length (m)</th></tr>
<tr><td>B208 (S)</td><td>30.0</td><td>54.9</td><td>83.4</td><td>32.3</td><td>22,847</td></tr>
<tr><td>B212 (S)</td><td rowspan="3">42.5</td><td rowspan="3">61.0</td><td rowspan="3">102.3</td><td rowspan="3">31.1</td><td rowspan="3">54,368</td></tr>
<tr><td>B213 (S)</td></tr>
<tr><td>B214 (S)</td></tr>
<tr><td>C212 (S)</td><td>22.4</td><td>53.0</td><td>92.0</td><td>29.9</td><td>18,070</td></tr>
<tr><td>B230 (C)</td><td>9.1</td><td>22.0</td><td>23.7</td><td>67.4</td><td>2,832</td></tr>
<tr><td>B233 (C)</td><td>15.9</td><td>43.9</td><td>36.1</td><td>37.2</td><td>12,307</td></tr>
<tr><td>B234 (C)</td><td>12.7</td><td>44.8</td><td>35.6</td><td>35.7</td><td>12,035</td></tr>
<tr><td>B235 (C)</td><td>15.0</td><td>54.9</td><td>36.3</td><td>33.5</td><td rowspan="2">31,856</td></tr>
<tr><td>B236 (C)</td><td>14.2</td><td>51.8</td><td>35.3</td><td>39.0</td></tr>
<tr><td>C9 (C)</td><td>17.8</td><td>56.4</td><td>34.7</td><td>33.2</td><td>13,337</td></tr>
<tr><td>C10 (C)</td><td>11.1</td><td>54.9</td><td>26.3</td><td>29.6</td><td>5,663</td></tr>
<tr><td>B11 (C)</td><td>14.9</td><td>21,9</td><td>37.6</td><td>25.0</td><td>9,833</td></tr>
<tr><td>B12 (C)</td><td>14.1</td><td>36.0</td><td>62.0</td><td>22.9</td><td>25,485</td></tr>
<tr><td>B14 (C)</td><td>15.5</td><td>24.1</td><td>54.6</td><td>22.9</td><td>12,006</td></tr>
<tr><td>B 15 (C)</td><td>17.2</td><td>34.1</td><td>63.0</td><td>25.6</td><td>Empty</td></tr>
<tr><td colspan="6">Note; (S) = Stope; (C) = Chamber</td></tr>
</table>

By the late 1970's, there was strong evidence that the permafrost in the arsenic storage areas of the mine was receding and the movement of water in these areas was increasing. This may have been caused by the progressive development of mine workings adjacent to the storage areas and the movement of warm ventilation air in the workings. In addition, the development of open pits in the Baker Creek valley removed some of the insulating rock and overburden.

From the mid 1980's on, the criteria for selecting suitable areas for development of storage chambers no longer included the presence of permafrost. An area was considered suitable for storage chambers if the rock was competent, the areas could be effectively sealed off from other mine workings, and the excavation was generally dry before the dust storage commenced. The last four chambers were excavated partially above the elevation of the original permafrost envelope.

3.0 SITE GEOLOGY AND HYDROGEOLOGY

3.1 Permafrost

The meteorological station at Yellowknife Airport (elevation 205m), has collected climatic data since 1942. Air temperatures during the monitoring period ranged from a minimum of -51°C to a maximum of +32°C. The estimated mean annual temperature is -5.2°C based on measurements up to 1990. Aspler (1978) reported a freezing index of 3400°C days and a thawing index of 1700°C days for Yellowknife.

Yellowknife is in an area of discontinuous permafrost. As described by various Authors, Bateman (1919) and Brown (1970), and others identified in the literature review by Noel et Al (2004), frozen overburden and underlying bedrock occurs in topographic depressions underlain by silts and clays with muskeg cover. Where bedrock is exposed in higher ground areas, it is not frozen. The frozen silt and clay overburden contains ice lenses and is thaw unstable. The occurrence of permafrost during initial mining and disposal of arsenic trioxide in special stopes excavated in permafrost is described by McDonald (1953). In fact, the criteria for acceptability of such stopes as storage repositories was that they were anticipated to remain frozen and dry. Research on the pattern of permafrost occurrence in the initial tailings disposal area is described by Frenette et Al (1972). As the Tailings Area was expanded, permafrost was also encountered in foundation areas for a number of prominent zoned earth and rockfill retention dams and factored into their design e.g. Geocon (1982).

3.2 Geology

The Giant Mine is located in the Yellowknife greenstone belt which is divided by numerous faults (Meyer and Horne, 1980). Three of the faults are particularly important, namely the West Bay, Townsite and Akaitcho Faults. The arsenic chambers and stopes are located in a volume of rock that is bounded by these major faults. These faults do not intersect any of the arsenic chambers or stopes with the possible exception of empty Chamber B15.

The background rock, away from the major faults, is of two types, known as sericite schist and chlorite schist. The sencite schist rocks have particularly well-developed small scale fractures, leading to increased hydraulic conductivity and stability problems. The chlorite schist appears to be more ductile, and therefore does not fracture as readily. The B212, B213 and B214 stopes occupy a hinge in a major fold in the sencite schists. The combination of intense fracturing with horizontal orientations mean that this area is prone to instability, as evidenced by the presence of several wall failures. The rock surrounding the other stopes and chambers is generally either chlorite schist or sencite schist where the fractures are orientated close to vertical. These areas are expected to be more stable. The Open Pits are integral parts of the major structures mined underground. Bedrock is exposed in many higher ground areas. Glacial overburden (silts and clays overlying glacial till) up to about 20m in combined thickness, with a muskeg cover, occupy low lying areas.

3.3 Hydrogeology

Given the solubility of the arsenic trioxide, there is concern that arsenic would leach into the groundwater system and ultimately into the environment when the mine is allowed to flood. It was recognized at an early date that the development of a remediation plan for the site would require a good understanding of mine hydrogeology and controls on regional groundwater flow. To gain this understanding INAC arranged for meetings of a Hydrogeology Experts Group, specialty studies by the Technical Advisor, installation of monitoring wells across the site, and groundwater modeling of the Mine to illustrate current groundwater interaction with the dewatered mine and possible reflooded conditions. The reader is referred to Mackie et Al (2005) and Mackie (2006) for details of the work carried out.

4.0 GEOTECHNICAL CHARACTERIZATION OF STORAGE AREAS

4.1 General

There were a variety of important items which required study from a geotechnical perspective. They included (i) the engineering properties of the arsenic trioxide in storage, (ii) stability of the walls of storage chambers and stopes, (iii) crown pillar stability, (iv) interaction of open pits and adjacent storage areas, (v) stability of access workings such as tunnels and drifts, (vi) and stability of bulkheads which secure the storage areas. Item (i) is discussed in detail below and brief comments are also given later on items (iii) and (vi).

4.2 Arsenic Trioxide in Storage

The arsenic trioxide dust was collected at the Baghouse and moved to the storage areas through a 4 inch pipe, low pressure compressed air being the conveying medium. As all openings to the storage areas had been sealed in preparation for arsenic trioxide placement, a return air pipe formed a closed circuit between the Baghouse and storage areas and normally no loss of dust occurred during transportation. Delivery into each storage area was through a bulkhead at its upper level. In view of this and the pneumatic method of placement, the arsenic trioxide in-situ only experienced consolidation initially in a dry state and under its self-weight. The earlier stopes and chambers were dry by virtue of being excavated into permafrost bedrock. Placement usually continued until a given stope or chamber was filled to capacity before moving to the next. Mine personnel found that the dust would compact over a period of time, creating additional space and several of the storage excavations were “topped up” after a period of settling.

Studies were carried out in the early 1980’s into the feasibility of reclaiming the arsenic trioxide from storage and purifying it for marketing in several end uses. A number of reclaim strategies were initially identified based on working from the surface and utilizing (variously) vacuum methods for dry material; slurrying in place and recovering it hydraulically; and lifting the material out by mechanical equipment such as a cable drag type bucket elevator or vertical auger (screw) type power arm. In order to test the applicability of such strategies, and make a selection of the most suitable method and equipment, it was necessary to characterize the arsenic trioxide in storage in an engineering sense.

There was virtually no data available on the physical properties of the arsenic trioxide dust in storage, other than an indication of its average in-place unit weight based on the volume of the storage areas and the tonnage of dust placed. The first geotechnical investigation of the arsenic trioxide in-situ was carried out in 1981 in connection with the plans to recover the material for purification and marketing (Geocon, 1981). The procedures used were modifications of those used in conventional geotechnical drilling and sampling but with appropriate safety protocols and equipment in recognition of the toxic nature of the material. Drilling was carried out from the surface with a truck-mounted Sanderson Cyclone Mode TH70. The holes were advanced in overburden with an 8 ¾ inch tricone bit using air as the drilling fluid. In bedrock, an Ingersoll-Rand downhole hammer with nominal 5 ½ inch carbide button bit was used to advance the holes. When stope backs were penetrated, the downhole bit was replaced by a reverse circulation cutting bit which allowed for the passage of sampling tools. Sampling of the arsenic trioxide was carried out by standard 1 3/8 inch ID split spoon samplers and 2 inch Shelby tube type samplers. Bulk samples were also recovered by applying a vacuum to the drill rods used for sampling.

The holes were drilled into chambers and stopes B230, B233, B234, B234, B236, B208 and C9. Most penetrated the dust to depths of 30 metres or more, and in all of the holes, extended intervals of dry loose material were encountered, with occasional layers of harder crusted material. Some holes encountered wet conditions near the bottom. Samples were recovered with some difficulty and were significantly disturbed in some cases. Laboratory testing yielded results which in summary are as follows:

Specific gravity	2.6 to 3.2
Moisture content	0.6 to 6.3%
Maximum density (measured)	70 to 90 bl./cu.ft.
Minimum density (inferred)	40 to 55 lb./cu.ft.
In place density (inferred)	84 to 101 lb./cu.ft.

Several of the inferred in-place densities were probably higher than the true values due to compaction of the samples. The lowest value in the reported inferred range was probably representative of the actual in-situ conditions. The wide range between the minimum and maximum densities indicated that the material was highly compressible. This was consistent with the observations that the dust would compact over a period of time, enabling “topping up” of some excavations, as already noted. The highest measured moisture content suggested that some of the sampled material was wet but was not saturated with water. Water was encountered in the two boreholes which extended to the bottoms of chambers. This, together with evidence of seepage from the lower bulkheads, suggests that the material from near the bottom of some of the chambers and stopes may have been saturated at the time of the study. Testing of the grain size distribution on five samples from two periods of production, using microscope image analysis, showed the material to be extremely fine-grained, with a particle size distribution of 92 to 97% less than 4.5 microns. (New Brunswick Research and Productivity Council, 1988).

Work carried out by the Mine in 1994 and 1995 in support of renewal of the Water License included installation of thermisters to investigate the state of permafrost in the mine area. Six holes with thermister installations were completed in June 1994 to depths representative of the lowest point of any storage area. Five of the holes were located in the vicinity of the then active and inactive storage areas. The results suggested that the occurrence of permafrost at the time was not widespread across the whole mine property.

A review of the available geotechnical data base indicated that it was necessary to supplement it considerably for purposes of the Remediation Plan and particularly the Arsenic Trioxide Management Project. An investigation program was therefore designed and implemented by the Technical Advisor in 2004 which included primary drilling in selected crown pillars and drilling and testing within the storage areas (SRK 2004). The work was designed to (i) further investigate the geotechnical properties of the in-situ dust, (ii) collect in-situ samples for laboratory testing, and (iii) install long-term monitoring equipment in select, representative arsenic trioxide dust chambers and stopes. The objectives were to collect data to assess the:

- loading and bearing capacity of the dust for design of backfilling procedures if required (based on associated crown pillar stability evaluation);
- variability of different dust vintages (ie: from different periods of dust production and storage) with respect to chemical, geotechnical, and thermal properties, both in the original dust and due to possible weathering influence; and
- thermal and piezometric conditions in the selected chambers and stopes to allow for a better understanding of the heat transfer and water saturation/movement within the dust mass.

The planning and methodology used in the program, as well as the test results are summarized below:

(i) An occupational health and safety plan was developed.

(ii) The investigation of the arsenic trioxide insitu was carried out by several methods. One approach was by cone penetration testing (CPT). Because of the unusual physical conditions which had to be contended with, such as the open void above the dust in storage, the cone was deployed using standard BQ drill rods rather than the smaller rods which are normal for the equipment. Other modifications were also made to some details of the equipment.

Six test holes were investigated by CPT methods. Up to 31 ft. (10m) of cone penetration was obtained in each hole. Table 2 summarizes the CPT intervals at each drill hole.

Table 2: Down-hole Lengths for CPT Boreholes

Hole	Distance to Breakthrough	Distance to top of dust	Distance to bottom of cone push	Dip from horizontal
	(m)	(m)	(m)	(degrees)
B235-P13	31.7	39.0	51.2	90
B233-P9	41.1	48.8	54.9	90
C212-2	36.6	42.7	50.9	88
B208-1	29.0	32.0	40.5	67
B212-4	27.7	29.3	40.2	66
B214-1	31.2	32.3	43.3	55

Because of the unusual nature of the arsenic trioxide in a geotechnical sense, INAC retained Hughes In-situ Engineering to provide specialist services for the CPT program.

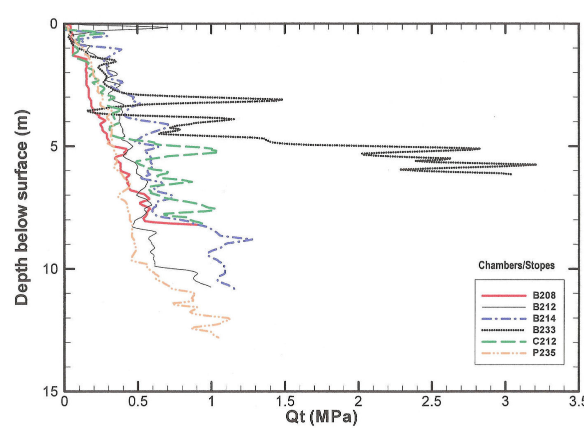
(iii) Samples of the arsenic trioxide were recovered for laboratory testing of geotechnical, geochemical and thermal properties. Samples were taken by a 1 3/8 inch ID standard split spoon sampler lowered through the drill rods using a wireline system, with provision for pushing the sampler using a special casing advancer. A considerable amount of experimentation was required in order to optimize the results obtained.

(iv) An array of vibrating wire transducers, to measure water pressure, and resistance thermisters to measure temperature, was installed in each drill hole sampled.

(v) During sampling, it was observed that sampled material was generally dry, with varying levels of humidity yielding a range of powdery to clumping dust. Dust was generally a homogenous, light tan powder, with visible layering and colour darkening in some layers. Sample recovery was general poor near the surface of the dust and increased with sample depth. Wet sample material was encountered at the dust surface in vertical holes B233-P9 and B235-P13. Sampling in both vertical holes was terminated above the bottom of the respective chamber. This moisture is thought to have been introduced by drilling and is not considered indicative of insitu conditions. Saturated material was encountered over a depth of approximately 0.25m (1 ft) at the base of B214-1. Arsenic trioxide dust was sampled over the entire dust interval encountered in this hole as well in holes C212-2 and B208-1. The arsenic trioxide encountered H212-4 was sampled over the top 21 m (70 ft) as well as over the bottom 4.5m (15 ft.).

A detailed analysis of the results of the CPT and sampling programs was carried out. The CPT and SPT results provided an indication of the in-situ density and strength. One of the results of the CPT work, namely a plot of cone tip stress vs depth is given in Figure (1).

Figure 1: CPT Results. Depth vs. Cone Tip Stress



(vi) None of the investigations recovered intact samples.

(vii) Laboratory geotechnical, geochemical and thermal testing of arsenic trioxide dust was carried out on samples collected during the drilling and sampling program and recovered from product in storage on surface. Testing was done at a number of Laboratories including SGS Lakefield Research, CANMET, and EBA Engineering Consultants.

Table 3: Physical properties of arsenic trioxide dust measured in the studies.

Parameter	Earlier Data (1981 to 2002)	New Data (2004)	Combined Range / Average
Grain Size	92 - 97% <0.0045mm	72 - 98 % <0.0045mm	72 - 98% / 88.5% (<0.0045mm)
Dry Density (kg/m3)			
Maximum	1107 - 1459 kg/m3	1414 - 1726 kg/m3	1107 - 1726 kg/m3
Minimum	636 - 891 kg/m3	1333 - 1369 kg/m3	636 - 1369 kg/m3
In-situ	1341 - 1623 kg/m3		avg. = 1402 kg/m3
Specific Gravity	2.59 – 3.79 (avg. 3.17)	3.29 - 3.77 (avg. 3.48)	2.59 - 3.79 / 3.38
Atterberg Limits			
Liquid limit	inconclusive	25.0 - 41.7%	25.0 - 41.7% / 31.9%
Plastic limit	19% - 24%	Nonplastic & 28.5% - 35.3%	19.0 - 35.3% / 28.6%
Angle of Repose	46° - 58°	NT	46° - 58°
Angle of Internal Friction	33° - 35°	NT	33° - 35°
Hydraulic Conductivity (at 1150 kg/m3)	7 x 10-7 m/s	NT	7 x 10-7 m/s
Thermal Conductivity		0.47 - 2.02 W/m-k	0.47 - 2.02 W/m-k
at 0% H2O	0.093 W/m-k		0.093 W/m-k
at 1% H2O	0.100 W/m-k		0.100 W/m-k
Freezing point of saturated solution	-0.7°C	NT	-0.7°C
Note: NT = Not Tested			

The geotechnical data was utilized in many aspects of the overall project. Two only have been selected for brief mention herein, namely the crown pillars and bulkheads.

4.3 Crown Pillars and Bulkheads

An evaluation of the crown pillars of the stopes and chambers containing arsenic trioxide dust was carried out to determine whether they would be stable while the final remediation plan was carried out. The plan would involve work above and around the crown pillars, such as installation of the various freezing elements for the "frozen block" case. Detailed evaluation included analysis of the risks of crown pillar collapse. It led to drilling at a number of the stopes/chambers for geotechnical purposes and examination by video camera. Five areas were observed which required remediation. The measure that best mitigates the risk of potential crown pillar instability was engineered backfilling of the voids between the stope back and the dust.

The storage chambers and stopes have been secured with bulkheads at the top and bottom. The "upper" bulkheads have an inspection and safety role, while the "lower" bulkheads are load-bearing. The bulkheads were built over a long period of time from the early 1950's to the late 1990's. In total, there are sixty one bulkheads of which 26 are lower bulkheads. The majority of the lower bulkheads are of reinforced concrete construction and are anchored with hitches into the bedrock. Some of the lower bulkheads are deteriorating and seepage of arsenic contaminated water occurring at several lower bulkheads is the cause of most of the arsenic contamination in the mine water that is currently pumped and treated.

5.0 MANAGEMENT ALTERNATIVES EVALUATED

INAC's selection of a method to remediate the arsenic trioxide dust storage areas was a careful process involving dozens of scientific and engineering studies as well as extensive consultation with local stakeholders. Space permits only a general description of the process herein. Over 56 methods that were potentially applicable to the long term management of the arsenic trioxide dust were evaluated as to feasibility, risk and cost. From these methods twelve alternatives were assessed which included seven in-situ alternatives that would keep the dust underground and five ex-situ alternatives that would see the dust taken to surface for disposal or re-processing. Risk assessment techniques were applied to characterize possible human health and ecological risks associated with potential arsenic releases from the underground storage areas. After taking into account uncertainties in the risk assessment, the Technical Advisor concluded that 2,000 kg per year would be an appropriate target for the maximum arsenic releases from the Giant Mine. That level of arsenic release would result in human health risks below the applicable thresholds, and would keep arsenic concentrations in North Yellowknife Bay at or below the Canadian Council of Ministers of the Environment (CCME) criterion for the protection of freshwater aquatic life.

Nine alternatives capable of meeting that objective were then assessed on the basis of risks and costs.

Table 4 summarizes the results of these assessments. Alternatives A through C would keep the dust underground. The analysis concluded that the best *in situ* alternative was Alternative B3, isolating the arsenic trioxide dust in its current location by creating a block of frozen dust and rock, monitoring in perpetuity, and if necessary maintaining isolation by periodic re-freezing. The water treatment alternatives, A1, A2 and A3, would require long-term operation of an active pumping and treatment system, and therefore were concluded to present higher risks of arsenic release over the long term. Alternative C, mining the dust from its current locations and disposing it in new caverns at the base of the mine, was predicted to result in very low long-term risks but with significant increase in worker health and safety risks during mining of the dust.

Table 4: Summary of Methods to Remediate Arsenic Trioxide Dust

Alternative	Risk of Arsenic Release		Worker Health & Safety Risk	Cost Range (2002 $ Million)
	Short term	Long Term		
A1. Water Treatment with Minimal Control	Low	High	Low	30-70
A2. Water Treatment with Drawdown	Low	Moderate	Low	80-110
A3. Water Treatment with Seepage Control	Low	Moderate	Low	80-120
B2. Frozen Shell	Very Low	Low	Low	90-110
B3. Frozen Block	Very Low	Low	Low	90-120
C. Deep Disposal	Low	Very Low (b)	Moderate (b)	190-230
D. Removal and Surface Disposal	High	Very Low	Moderate	600-1000
F. Removal, Gold Recovery & Arsenic Stabilization	Moderate	Very Low	Moderate	400-500
G1. Removal & Cement Encapsulation	Moderate	Low	Moderate	230-280
Notes: (a) Alternatives B1, E and G2 were concluded to be infeasible and therefore were not further evaluated. (b) Subsequent review by the IPRP concluded that the ratings shown here (IPRP 2003) probably underestimate both the long-term risks and the worker health and safety risks associated with Alternative C.				

Alternatives D through G would require that the dust be brought to surface. Alternative G1, comprising mining the dust, mixing it with cement, and storing it in a secure on-site landfill, was recommended as the best *ex situ* alternative. Alternative D, removing the dust and trucking it to a hazardous waste disposal site in Alberta, presented too high a risk of arsenic release even assuming that the disposal site could accept such a large quantity of arsenic trioxide dust.. Alternative F, mining the dust and re-processing it to recover gold and stabilize the arsenic, was concluded to have a similar risk profile to Alternative G1. The Technical Advisor recommended the much less costly Alternative G1 as the best *ex situ* alternative.

The Technical Advisor also recommended that both the best *in situ* alternative and the best *ex situ* alternative be carried through to the final round of public discussion which culminated in a workshop held in Yellowknife, May 26-27, 2003. In response to questions raised at the workshop, both the IPRP and the Technical Advisor completed a further review of Alternative C, Deep Disposal. After considering the public feedback and the follow-up studies, the Technical Advisor made the following recommendation to DIAND:

"The *in situ* alternative recommended in the (SRK) December 2002 report, namely Alternative B3 – Ground Freezing as a Frozen Block, should be adopted as the preferred approach for managing the arsenic trioxide dust stored underground at the Giant Mine. Elements of the alternative should be modified to take into account suggestions made by the general public, the Yellowknives Dene, and the GNWT." The IPRP agreed in principle with the selection of Alternative B3 (IPRP 2003) which then became the focus of public consultations and more detailed studies (SRK 2005) and (IPRP 2005).

The frozen block method of remediation (see Figure 2) will see the arsenic permanently encapsulated in frozen ground thus minimizing the potential release of arsenic by isolating the material from flowing water (surface and groundwater).

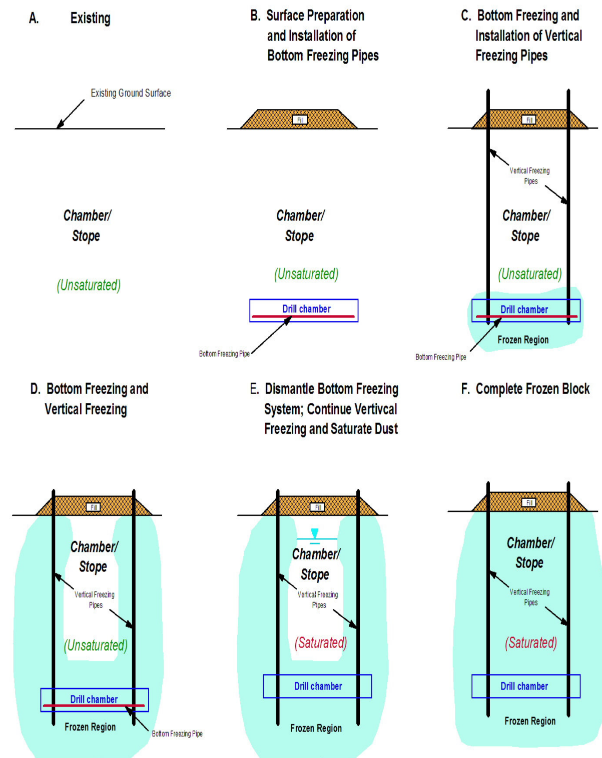


Figure 2 – Frozen Block – conceptual approach)

6.0 REMEDIATION BY GROUND FREEZING – PRACTICAL ISSUES

In addition to the theoretical aspects of the various remedial measures considered, it was also necessary to resolve important practical matters. A case in point was the need to construct an experimental thermosyphon to verify the operational capability of thermosyphons to depths reaching 300m. (Noel and Hockley, 2004). Many other practical considerations pertain to the "frozen block" concept including:

(i) Surface preparation prior to installation of the perimeter freeze pipes, such as construction of access ramps, local diversions of Baker Creek; and backfilling of part of the B1 Open Pit where it partly overlies Stopes B208, B212-13-14.

(ii) Construction of new tunnels to allow for efficient drilling from below each of the chambers and stopes to form the "bottom freezing system".

(iii) Freeze pipes drilled from surface will generally be vertical. However a large portion of the freeze pipes for Stopes B212-13-14 will have to be inclined to avoid the adjacent stopes or to target various small raises. Some drilled from both surface and underground will intercept other small mine workings which will have to be backfilled.

7.0 STATUS OF PROJECT

An application for a Water License to undertake remediation at the Giant Mine Site was submitted to the Mackenzie Valley Land and Water Board in October, 2007 along with the Giant Mine Remediation Plan.

On March 31, 2008 the City of Yellowknife referred the application for a Water License for the Giant Mine Remediation Project to environmental assessment under the *Mackenzie Valley Resource Management Act*. The basis for the referral is that the proposed activities to take place during the term of the water license will have, in the City's opinion, an adverse impact on the environment within its municipal boundaries. The Mackenzie Valley Environmental Impact Review Board received this referral on April 7, 2008 and has begun the EA process. The remediation project will not commence until the assessment is concluded, although care and maintenance activities at the site will continue in the interim. INAC is currently preparing to conduct a freeze demonstration test on site with a variety of important objectives including optimizing the technical approach, understanding selected practical aspects better, and refining the overall project cost estimate.

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9.0 REFERENCES

Aspler, L.B. Surficial Geology, Permafrost and Related Engineering Problems, Yellowknife, N.W.T. in Mineral Industry Report 1976, Indian and Northern Affairs Canada, Geological Division, Yellowknife, NWT, EGS 1978-11.

Bateman, J.H. Permafrost at Giant Yellowknife. Transactions of the Royal Society of Canada. Vol. XL111, June. 1919.

Brown, R. J. E. Permafrost in Canada. Its Influence on Northern Development. University of Toronto Press. 1970.

Brown, C.E.G. and Dadson, A.S. Geology of the Giant Yellowknife Mine. The Canadian Mining and Metallurgical Bulletin, March 1953.

Frenette, M., Larochelle, P., Pantu, I. Mine Waste Containment Studies at Giant Mine and Con Mine of Yellowknife. Instrumentation and Research, 1971 Annual Report Centre De Recherches Sur L'eau, Laval University. January, 1972.

Geocon Inc. Report to Giant Yellowknife Mine Limited. Mine Backfill Sampling Programme. December, 1981.

Independent Peer Review Panel. Report on Review of SRK's Final Report to INAC dated December, 2002. March 2003.

Mackie, D. Multi-level Data as a Key Component for a Hydrogeological Conceptual Model of an Underground Mine. 59th Joint CGS - 1AH Specialty Conference, Vancouver, 2006.

Mackie, D., Royle, M., and Liskowich, M. Understanding Groundwater at the Giant Mine. Part II. Results and Use of the Numerical Model. 58th Joint CGS - IAH Specialty Conference. Saskatoon, 2005.

McDonald, D.C. Mining at Giant Yellowknife. The Canadian Mining and Metallurgical Bulletin, April, 1953.

Meyer, W. and Horne, M.F. Address to 81st Annual Meeting. Canadian Institute of Mining and Metallurgy. 1980.

New Brunswick Research & Productivity Council. Fuming of Crude Arsenic Trioxide Baghouse Dust. October 1988.

Noel, M. Hockley, D., Konrad, J-M, Fredlund, M. Literature Reviews and Thermal Modelling to Assess In Situ Freezing of Arsenic Trioxide Dust at the Giant Mine in Yellowknife, NWT, Canada. 37th Canadian Geotechnical Conference. Geo Quebec, Quebec City, Quebec. 2004

Noel, M. Hockley, D. Thermal Analysis of an Experimental Thermosyphon Installed at the Giant Mine in Yellowknife, NT, Canada. 37th Canadian Geotechnical Conference. Geo Quebec, Quebec City, Quebec. 2004.

Pitcher, P.N. The Giant Yellowknife Operation. CIM Transactions. Vol. LV1. March, 1953

SRK Consulting Inc. Report to Department of Indian and Northern Development. Yellowknife, NT. Arsenic Trioxide Management Alternatives, Giant Mine. December, 2002

SRK. Arsenic Trioxide Chamber Drilling and Testing Program (2004). December, 2004.

SRK Consulting Inc. Final Draft Report to Department of Indian Affairs and Northern Development, Yellowknife, NT. Giant Mine Remediation Plan October, 2005.

Independent Peer Review Panel. Report to Indian and Northern Affairs Canada, Yellowknife, NT. Review of SRK's Final Draft – Giant Mine Remediation Plan. December, 2005.