Frozen Block Wetting Studies Giant Mine Remediation Project

Report Prepared for

Aboriginal Affairs & Northern Development Canada

Report Prepared by

SRK Consulting (Canada) Inc.
Project 1CI001.026

August 2012

Frozen Block Wetting Studies, Giant Mine Remediation Project

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SRK Project Number 1CI001.026

August 2012

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1 Introduction

The Giant Mine Project Team is proceeding with two lines of investigation in support of engineering and design of the project's frozen block method for managing the underground arsenic dust.

- A Freeze Optimization Study (FOS) was initiated in 2009, and data collected up to the end of June 2012 are currently being assessed.
- Methods to wet the arsenic dust were discussed in the October 2011 Technical Session with parties to the environmental assessment, and described in Undertaking 10, provided to the Mackenzie Valley Environmental Impact Review Board in late 2011.

The wetting studies were initiated in early 2012, and the remainder of this document provides an update on activities completed in Q1 and Q2 2012. Specifically:

- Section 2 describes physical and chemical phenomena that could be important during wetting of the partially cooled arsenic trioxide dust;
- Section 3 presents the results of modelling studies completed to further assess selected phenomena;
- Section 4 outlines overall requirements for the wetting system design and recommends testing needed to support further engineering; and
- Section 5 summarizes conclusions to date.

Results of the FOS will be documented in a separate report. It is worth noting here that one indication from the FOS is that "dry frozen blocks" function equally well as "wet frozen blocks". In other words, wetting of the dust may not be required. However, those results remain under discussion and AANDC therefore requested that SRK complete and document the initial phase of wetting studies as planned.

2 Review of Phenomena

Adding water to a partially cooled, very fine-grained and soluble dust in a manner that achieves a reasonably uniform moisture distribution could involve a dozen or more complex physical and chemical phenomena. To identify which phenomena need to be further assessed, a three-step procedure was followed:

- Phenomena of potential concern were identified in brainstorming sessions of the Technical Advisor team, and through review of literature and project documents.
- Available information about each phenomena was assembled and evaluated.
- Phenomena were categorized as no concern, concern mitigable by simple engineering controls, or requiring further assessment.

Table 1 presents a summary of the results. Of the identified concerns, many can be mitigated simply by wetting the dust from the bottom upwards, rather than by attempting to infiltrate water downwards from the dust surface. Others could be mitigated by adding water at a rate that exceeds the rate of freezing. It was therefore decided that the next step in the study should be a modelling investigation to assess possible rates of bottom-up wetting, and to compare them to expected freezing rates.

Two other phenomena, liquefaction settlement /collapse and freeze concentration of salinity were also recommended for further assessment. Again, modelling studies were seen as the best first step.

Table 1: Summary of Phenomena and Potential Concerns

Phenomenon	Possible Concerns	Project or Literature Evidence	Conclusion
Material is very loose	• Could be very high infiltration zones • Lots of water needed to saturate • Slower to freeze • Could lead to liquefaction settlement or collapse during wetting	• Geocon 1981 – Bulk densities 640-1500 kg/m^3 ▪ sg 2.6-3.8 – Flows up drill stem and prevents SPT test – Drill rods fall under self-weight • SRK 2004 – Bulk densities 1300-1700 kg/m^3 ▪ sg 3.3-3.8 – Drill stem accelerates under self-weight only • Piezocone testing – Very loose layers with low friction angle – Collapsible under shock loading	• Permeability controls on wetting rates need to be examined • Potential for liquefaction settlement or collapse needs to be examined
Occasional hard layers	• Could act as barriers to vertical infiltration	• Geocon 1981 – Refusal reached within dust • SRK 2004 – Tricone drilling needed to advance bit • Piezocone testing – "zones at depth that are particularly strong" – "probably cohesive in nature ... maybe a result of wetting and drying or some cementing process"	• Easily mitigated by avoiding vertical infiltration, .i.e. no concern if wetting is from the bottom up
Material is very fine-grained	• Low permeability • Could be high unfrozen water content	• Geocon 1981 – 92-97% < 4.5 microns • SRK 2004 – 72-98% < 4.5 microns • Lakefield 2004 – p80 10-55 microns	• Permeability controls on wetting rates need to be examined
Material could be very dry	• Could create hydrophobicity • Preferential flow paths possible under conditions of vertical infiltration	• "range of powdery to clumping dust" – SRK 2004 • Preferential flow iterature – e.g. Wang et al 1998 – 10-20% wetting in 1m scale studies	• Material is unlikely to be hyper-dry after many years underground • In any case, risk is easily mitigated by avoiding vertical infiltration, .i.e. by wetting from the bottom up
Long-term re-distribution of moisture	• Development of unfrozen zones – Probably not going to produce unfrozen zones – More likely to be of benefit	• Thermodynamics • System will re-distribute to reach minimum overall energy	• No concern
Unstable flow due to air back-pressure	• Could create back pressure that can cause preferential flow at scale of drawpoints under conditions of vertical infiltration	• Preferential flow literature – e.g. Wang et al 1998	• No concern if wetting is from bottom up

Permanent air pockets	• Air bubbles trapped in soil normally dissolve in water over time, but not if water is frozen	• Standard triaxial test method requires back pressuring to compress bubbles and promote dissolution	• No concern. Isolated bubbles of air will not impede overall wetting.
Ice segregation	• Where rate of freezing is greater than rate of water flow, bands of segregated ice can develop	• Silt size materials have medium to high frost susceptibility • e.g. Andersland and Ladanyi, Frozen Ground Engineering, page 38	• Only a concern if freezing rates are much greater than wetting rates • Need to examine relative rates of freezing and wetting
Salt exclusion	• Slow freezing could allow salts to be concentrated in pockets that become very difficult to freeze	– SRK 2005 estimated salt concentrations in chamber water: Mg 100-600 mg/L, Na 40-100 mg/L, Cl 40-170 mg/L, SO4 500-3600 mg/L, Ca 150-500 mg/L	• Need to examine possible size of sline exclusion zones
Capillary effects	• Capillary fringe above or in front of saturated zone could freeze and prevent full saturation	• Lakefield 2004 – 35 cm capillary rise in 20 hours – 30 cm infiltration in 20 hours	• Unlikely to be a concern if wetting rates are high enough
Frost jacking	• Freezing of dust could push wells or freeze pipes upwards out of chamber, or cause rupture	• e.g. Frozen Ground Engineering pg 199 – Typically a seasonal effect caused by freeze-thaw cycles	• No concern. Chambers and stopes will not be subject to freeze-thaw cycles.

3 Modelling Studies

3.1 Assessment of Bottom up Wetting Rates

The patterns to be expected during bottom up wetting of the arsenic trioxide dust, and the range of possible wetting rates, were examined using the groundwater model FEFlow.

Figure 1 shows the model setup and inputs. The flow domain simulated a rectangular chamber, 52 m x 31 m in plan and with a height of 58 m. A water injection well was simulated by placing a series of constant head boundary nodes in the centre of the chamber. The arsenic trioxide dust was modelled using Van Genuchten equations for capillary head and unsaturated hydraulic conductivity. The saturated hydraulic conductivity was set to $7x10^{-7}$ m/s, which is the current best estimate (see Table 5.1.2 of the DAR).

Figure 2 shows typical outputs from the flow modelling. Model runs, assuming only saturated flow, predicted a very rapid filling. However, model runs that included unsaturated flow reducing the effective hydraulic conductivity, led to estimated filling times ranging from weeks to about one year.

A series of sensitivity runs were also completed to test the effects of the input parameters. The estimated filling times were most sensitive to:

- Size of the chamber or stope;
- The pressure applied to the injection well; and
- The length of the well screen.

The model domain shown in Figure 1 simulates the largest stope, B2-12. Many of the chambers and stopes are much smaller. For example, Chamber 14 has half the volume of B2-12. Model runs with smaller domains indicated that, in rough terms, stopes or chambers that are half the size can be expected to fill in one quarter the time, all other things being equal.

The sensitivity to applied pressure and screen length indicate possible controls on wetting. Well screen size and applied injection pressure are both engineering design parameters. Screen size could be adjusted during system design, and applied injection pressure could also be adjusted during the wetting process.

3.2 Comparison of Wetting and Freezing Rates

Many of the phenomena identified in Table 1 are not possible if the rate water enters the dust exceeds the rate at which the water can be frozen. To assess the possible balance between those two rates, a series of calculations were completed.

As demonstrated by the results of the FEFlow modelling, the parts of a chamber that are farthest away from an injection will be the slowest to fill with water. For example, the results in Figure 2 show that the location farthest from the well takes about 300 days to fill with water. Since the simulated chamber was 58 m high, these results indicate an average rate of water rise of just under 0.2 m/d.

The farthest corner of a chamber or stope, being right next to a rock wall that is at -10ºC, will also be the place where the water freezes most rapidly. These locations therefore represent the most conservative point to compare water inflow and freezing rates.

Figure 3 shows the geometry used for the comparison. Intuitively, water is more likely to freeze, the closer one gets to the rock wall. The calculations were therefore set up to compare inflow and freezing rates at various distances from the wall. In modelling jargon, this corresponds to selecting “representative elementary volume” (REV) of various sizes. The sizes tested ranges from 1 m in width and height to 0.1 mm. (In all cases, the volume was assumed to be right against the rock wall.)

Table 2 shows the results of the comparison. The first portion of the table shows the assumed REV dimensions. The second portion estimates the rate of water flow into the REV, and converts it to a rate of latent heat supply, i.e. how fast heat would need to be removed to freeze the inflowing water. The third portion of the table estimates the rate that heat would actually be conducted out of the REV and into the rock wall, which is conservatively assumed to remain at -10ºC.

Comparing the bottom lines of the second and third portions of the table indicates that the rates of water inflow significantly exceeds the rates of heat removal for REV’s of 1.0, 0.1, or 0.01 m in width. Only when the REV is less than 0.001 m or 1 mm in width does the rate of heat extraction approach the rate of water inflow. In other words, freezing rates would only keep up with inflow rates in a very narrow zone about 1 mm from the rock wall.

Table 2: Results of Comparison of Water Inflow and Heat Extraction Rates

Dimensions of representative elementary volume					
Length of REV (m)	1.0	1.0	1.0	1.0	1.0
Width of REV (m)	1.0	0.1	0.01	0.001	0.0001
Height of REV (m)	1.0	0.1	0.01	0.001	0.0001
Upflowing water provides latent heat supply					
Height of chamber (m)	58	58	58	58	58
Time for water to fill (d)	300	300	300	300	300
Rate of water rise (m/d)	0.193	0.193	0.193	0.193	0.193
REV surface area for water inflow (m^2)	1.0	0.1	0.01	0.001	0.0001
Porosity	0.6	0.6	0.6	0.6	1.6
Water inflow rate (m^3/d)	0.116	0.0116	0.00116	0.000116	3.1E-05
Latent heat of freezing (kJ/m^3)	334000	334000	334000	334000	335000
Rate of latent heat supply (kJ/d)	38744	3874	387	39	10
Heat is extracted into cold rock					
Assumed rock wall temperature (^{0}C)	-10	-10	-10	-10	-10
Dust thermal conductivity (J s-1 m-1 C-1)	1.89	1.89	1.89	1.89	1.89
Distance from wall to center of REV	0.5	0.05	0.005	0.0005	0.00005
Heat flux (J s-1 m-2)	37.8	378	3780	37800	378000
REV surface area for heat extraction (m^2)	1	0.1	0.01	0.001	0.0001
Rate of heat extraction (kJ d-1)	38	38	38	38	38

Given the number of conservative assumptions used in this analysis, and the availability of measures to enhance water inflow rates, the 1 mm estimate is likely to be highly conservative. In fact, it seems more likely that water inflow rates would significantly exceed freezing rates everywhere in the dust, or could be forced to do so with minimal engineering intervention. The implication is that there will be no complications from the Table 1 phenomena, as these phenomena only arise when wetting rates are less than freezing rates.

3.3 Liquefaction Settlement or Collapse

Completely saturating a highly porous material has the potential to cause localized settlement or collapse. A simple method to evaluate the potential for wetting to induce settlement or collapse is to compare the water content at saturation to the water content needed to exceed the material's liquid limit.

Investigations of *in situ* conditions within the arsenic dust chambers and stopes indicate that at least some of the dust is very loosely deposited. Table 5.1.2 of the DAR quotes estimates of dry bulk densities ranging from 1100-1700 kg/m^3, with an average of about 1400 kg/m^3. Using the specific gravity of pure arsenic trioxide as a basis, that translates to a porosity of about 60%. Even assuming significant impurities in the dust, the porosity is likely to be around 50%. In other words, at saturation, the dust would be about 50% water by volume, or 36% by weight (500/1400).

Attempts to measure the liquid limit of the arsenic trioxide dust have been problematic, and the range of (questionable) values is from 25.0% to 41.7%. Table 5.1.2 of the DAR recommends 32% as a best estimate. Using that value, the indication is that the saturated dust would be prone to liquefaction.

Figure 4 illustrates two possible outcomes. In Figure 4(b) the introduction of water into the chamber causes localized collapse of the dust, resulting in settlement of the overlying material. That situation is not expected to be a problem. But Figure 4(c) shows a second possibility, where the overlying material "arches" or "hangs up", leading to formation of a void. Subsequent failure of the arch would create a stress on the underlying dust and any confining bulkheads in the connected access tunnels.

Even the latter effect is not necessarily a problem as all questionable bulkheads are to be stabilized prior to wetting. However, if the possibility of collapse is high, one would need to put additional effort (and cost) into bulkhead stabilization. For that reason, a better understanding of the likelihood of collapse would be of benefit to further engineering and design. Recommendations for additional investigation of liquefaction settlement and collapse potential are included in Section 4.

3.4 Freeze Concentration of Salinity

Estimates of the volumes of water that would remain unfrozen due to salt exclusion were derived by two methods.

The first method conservatively assumed that all of the ions present in the arsenic trioxide dust porewater would behave as one of the strong salts: calcium chloride, or sodium chloride. Phase diagrams for the two pure phase systems were then obtained and the lever rule used to estimate the weight percentage of brine and ice for each scenario. The phase diagrams are shown in Figure 5 and the resulting estimates in Table 3.

The second method also assumed that all of the ions were a strong salt (in this case NaCL) and then applied an empirical equation commonly used in permafrost engineering studies. The equation is shown in Figure 5, and the resulting estimates are shown in the last column of Table 3.

The bottom two rows of Table 3 convert the estimated brine percentages to volumes of water that would remain unfrozen in Chamber 10. Even with the conservative assumption used in these methods, the estimated volumes of unfrozen brine are a very small percentage of the total chamber volume.

Table 3: Estimates of Unfrozen Brine Volumes due to Salinity Exclusion

Assumption Method of calculation	$CaCl_2$ system Phase diagram	NaCL system Phase diagram	NaCl system A&L (1996)
Equivalent salt concentration (g/L)	1.2	1.2	1.2
Mass of brine/mass of ice	2.2%	1.8%	1.4%
Water in saturated Chamber 10 (m^3)	3400	3400	3400
Max unfrozen brine in Chamber 10 (m^3)	75	63	50

4 Recommendations

4.1 Wetting System Design

Previous discussions of methods of wetting the dust have included a number of possibilities, ranging from simply adding water to the dust surface to lowering a borehole mining machine into the dust and jetting water in at pressures high enough to physically mix the water and dust. The results provided herein show that neither of those extremes is likely to be appropriate. Wetting from the top down can lead to several problematic phenomena. On the other hand, simple wetting from the bottom up is likely to be very effective, and no additional mixing energy is needed.

Broad guidelines for design of the wetting system are:

- Wet the dust from the bottom up using injection wells (only);
- Select the number of injection wells for each chamber and stope based on the desired maximum wetting time and the particular chamber or stope geometry. It is expected that one well will be adequate for smaller volumes, but two or three wells might be needed in the larger, or more convoluted stopes;
- Select well screen sizes and injection pressures using a combination of conventional well design methods and modelling of unsaturated water injection; and
- Check designs to confirm that wetting rates will be high enough to exceed freezing rates. Include sensitivity analyses to account for the significant variability of the dust and/or uncertainty about its local properties. If estimated wetting rates are close to freezing rates, review the above steps and revise the design.

4.2 Further Investigation

The potential for the dust to undergo liquefaction settlement or collapse will have implications for design of the bulkhead stabilization measures that will need to be in place prior to wetting. Unfortunately, the currently available data does not allow a definitive conclusion about the extent of the settlement/collapse potential.

However, a relatively simple test method, known as a double oedometer test is available. That method starts with an oedometer consolidation test on a dry sample. The test is halted and the sample wetted, and the test then continued. Materials with a significant collapse potential typically exhibit a step change in consolidation upon wetting, and the magnitude of the step can be related to the risk of collapse.

It is recommended that samples of the arsenic trioxide dust be tested using the double oedometer method, and the results used to set requirements for the bulkhead stabilization component of the design.

5 Conclusions

Phenomena with the potential to impede wetting of the partially cooled arsenic trioxide dust have been evaluated. Most of these phenomena are concluded to be either of no concern or controllable through relatively simple engineering measures.

The modelling studies reported herein have also led to identification of engineering design and operational measures that can be used to control the rate of wetting. It appears that wetting of the dust using only injection wells is feasible. Selection of the number of wells and the size of the well screens will allow total wetting times to be limited. Control of the water injection pressure will allow rates of wetting to be increased or reduced as needed.

One phenomenon, liquefaction settlement or collapse, cannot be ruled out using the limited available data and does have consequences for further design. Further laboratory testing of collapse potential is recommended.

This report, “**Frozen Block Wetting Studies Giant Mine Remediation Project**”, has been prepared by SRK Consulting (Canada) Inc.

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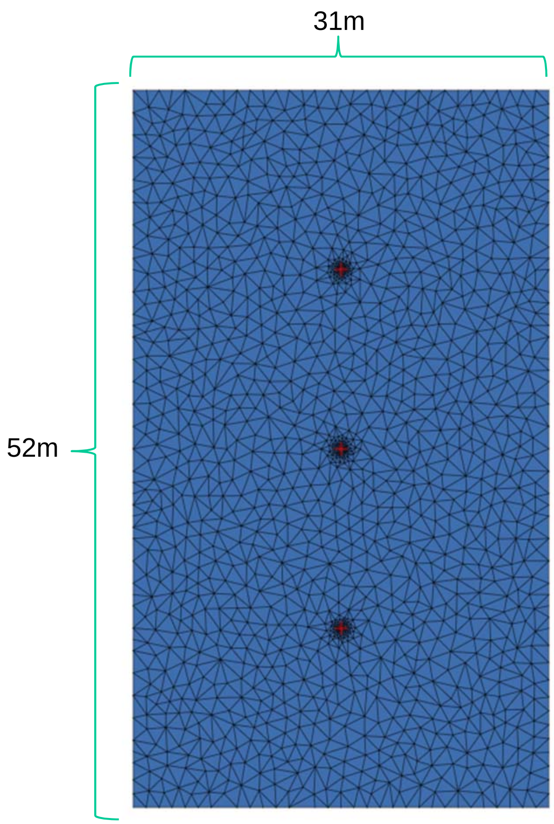
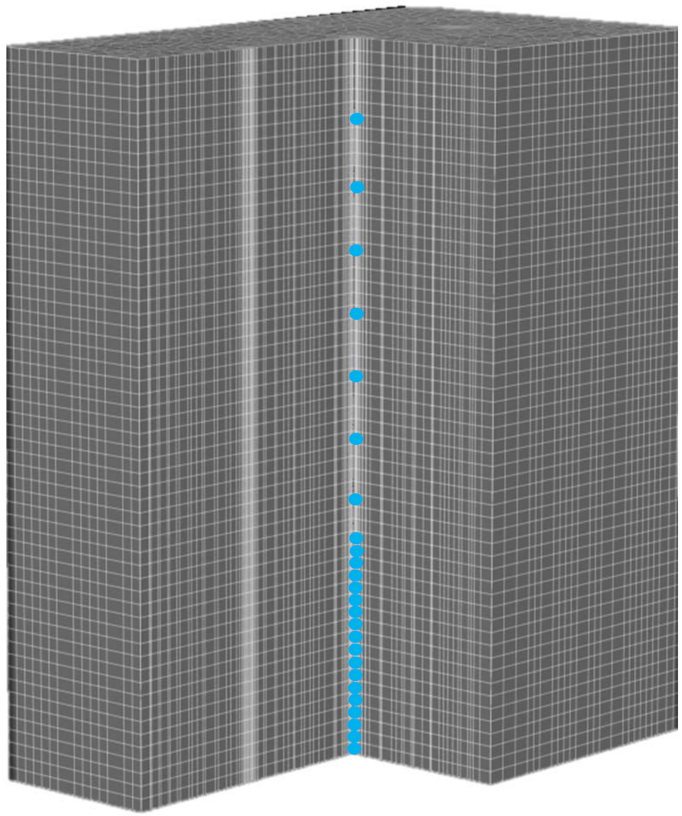
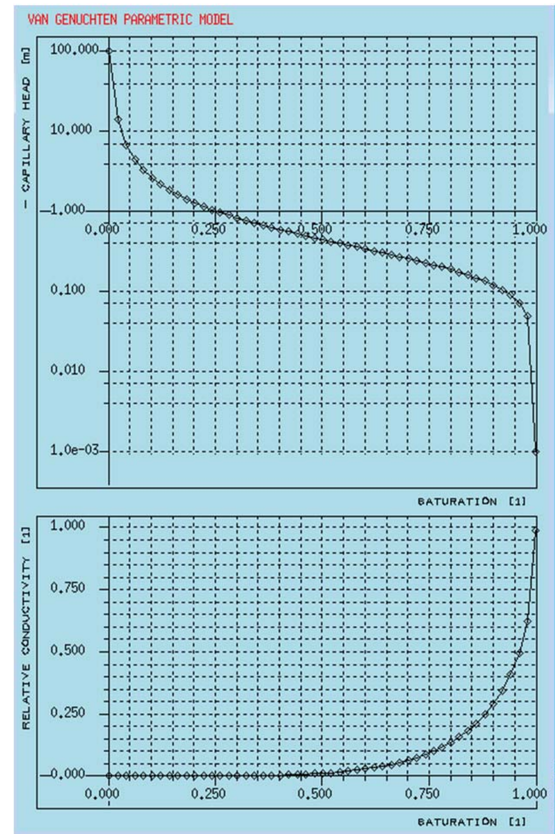
Figures



(a) Plan view of model domain. There were 58 layers like this.



(b) Example of injection well boundary condition setup: Run 2, with bottom 17m continuous screen and every few m above that. Blue circles are constant head boundary nodes.



(c) Screenshot of van Genuchten curves. Parameters were S_s=1.0, S_r=0.0025, A=4.1 m^{-1} and n=1.964. K_{sat} was 7x10^{-7} m/s.

srk consulting	ABORIGINAL AFFAIRS & NORTHERN DEVELOPMENT CANADA	Frozen Block Wetting Studies **Inputs for Wetting Simulations**		
Job No: 1CI001.026 Filename: FrozenBlockWettingStudyFigures.ppt	Giant Mine	Date: August 2012	Approved: DH	Figure: **1**

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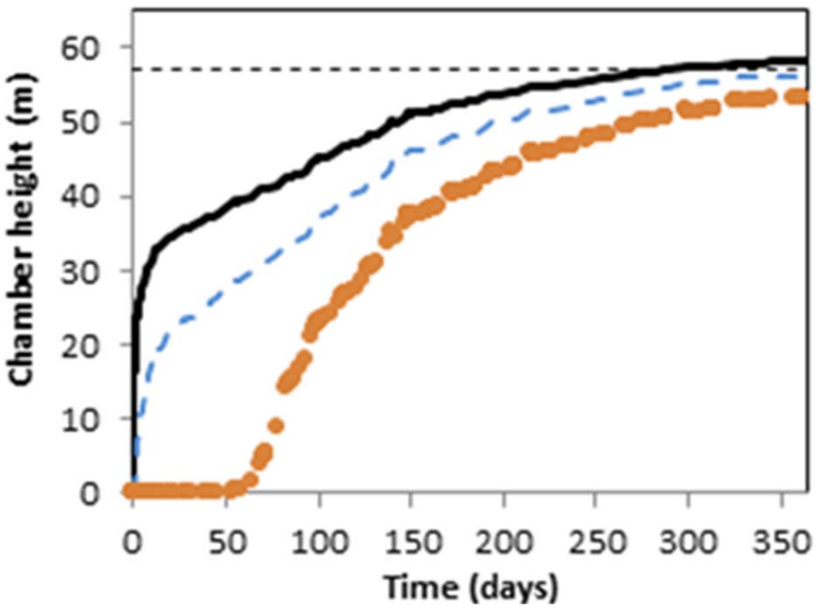

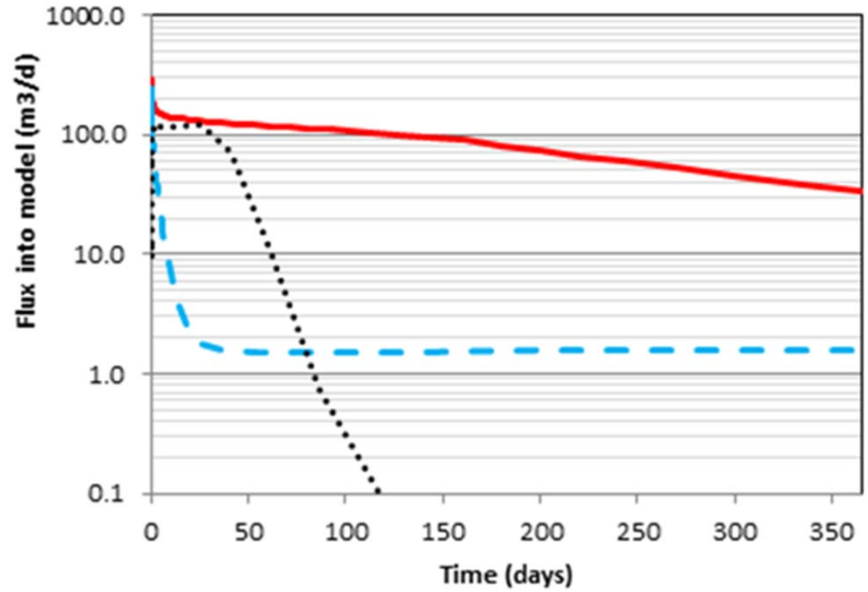

(a) Results of wetting simulation with applied head of 8 m above the chamber top. Solid black line shows water level near well. Dashed blue line shows water level midway between well and rock wall. Brown dots show estimated water levels in corner of chamber at farthest point from well. Chamber is fully wetted after about one year.

(b) Comparison of water inflow rates from three runs. The dashed blue line shows . the same run as (a), an unsaturated flow model with applied head of 8 m. The dotted black line shows much more rapid filling when the head at the well is increased to 100 m. The red line shows results when the 8 m simulation is run without the unsaturated flow constraints.

srk consulting	ABORIGINAL AFFAIRS & NORTHERN DEVELOPMENT CANADA	Frozen Block Wetting Studies **Example Outputs from Wetting Simulations**
Job No: 1CI001.026 Filename: FrozenBlockWettingStudyFigures.ppt	Giant Mine	Date: August 2012 / Approved: DH / Figure: 2

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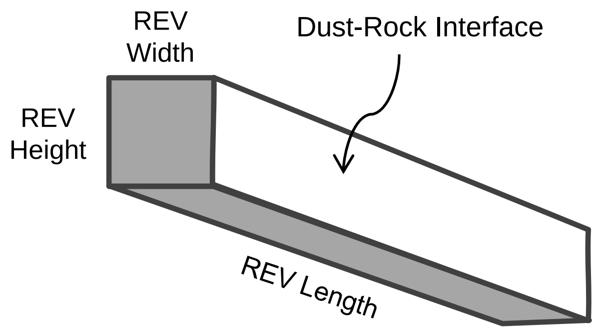
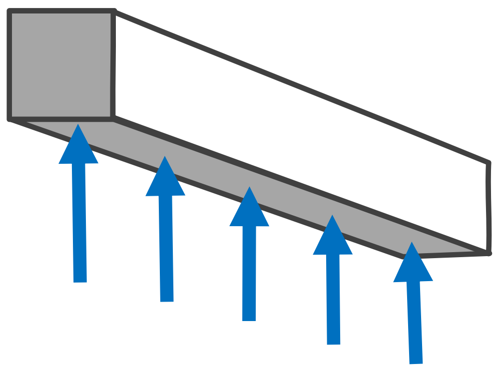
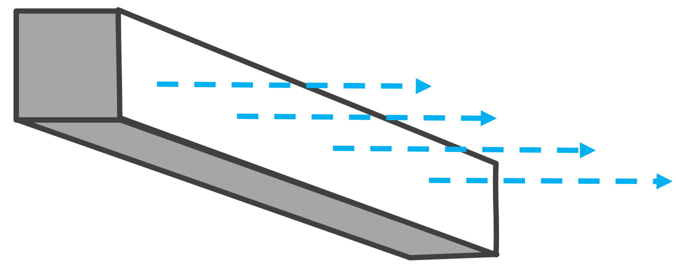


(a) Representative elementary volume (REV) of dust along wall of chamber or stope.



(b) Water upflow due to bottom up wetting, and carrying latent heat potential into REV.



(c) Extraction of heat from REV by conduction towards -10^{o}C rock.

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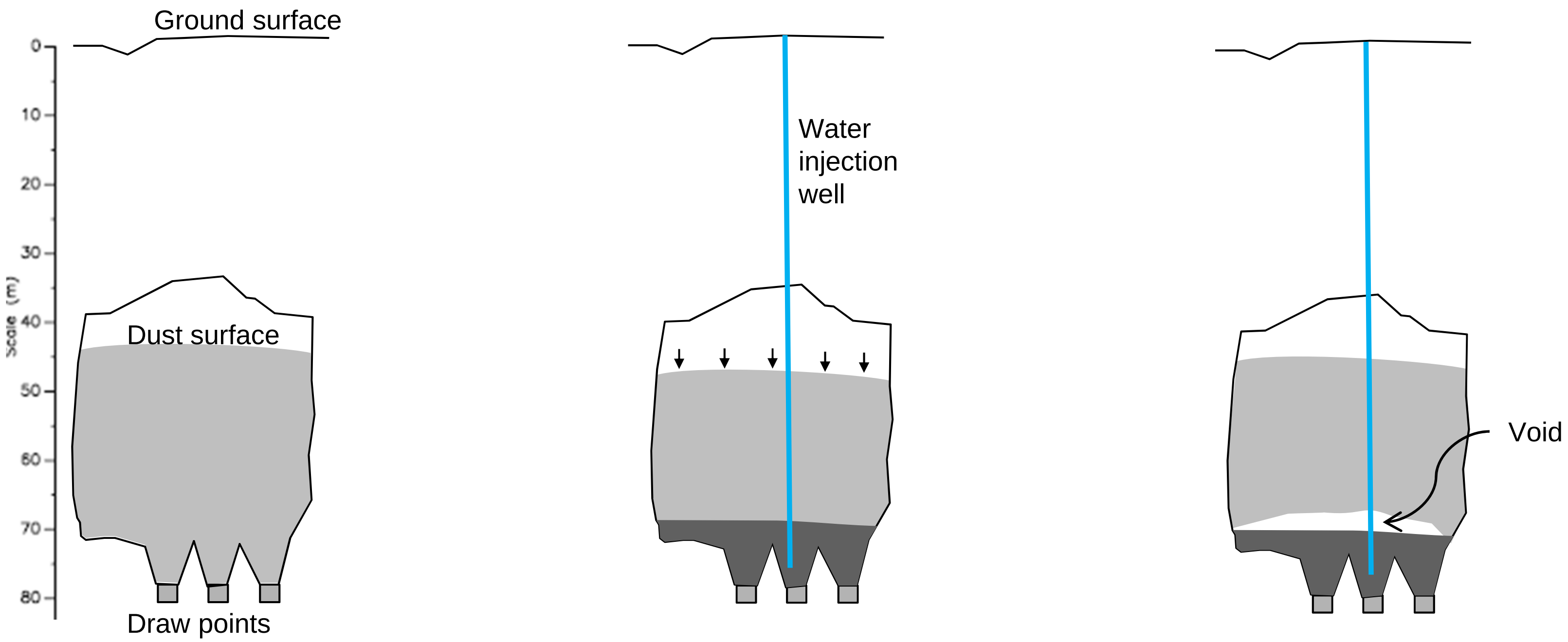
		Geometry for Comparing Wetting & Freezing Rates
Job No: 1CI001.026 Filename: FrozenBlockWettingStudyFigures.ppt	Giant Mine	Date: August 2012 / Approved: DH / Figure: 3



(a) Section showing dust geometry and estimated dust level in Chamber B233

(b) Saturation of base leading to slow and uniform settling of dust

(c) Saturation of base leading to arching and risk of collapse

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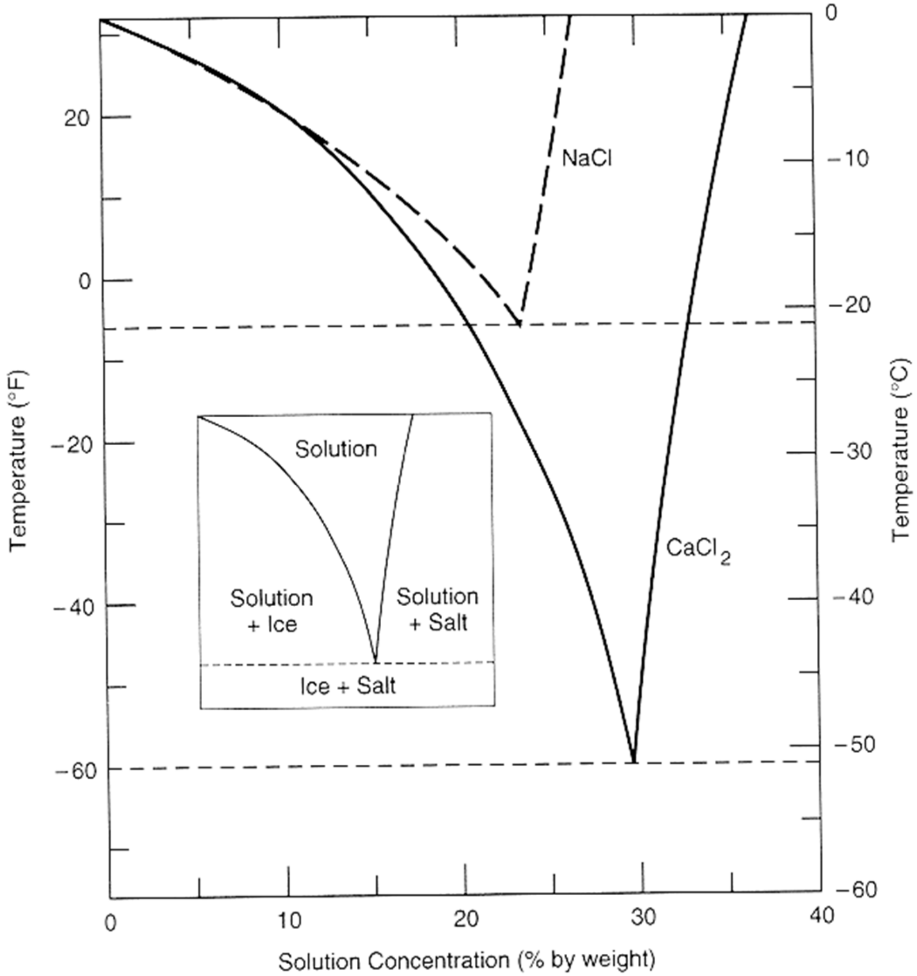
Job No: 1CI001.026 Filename: FrozenBlockWettingStudyFigures.ppt	Giant Mine	Date: August 2012 / Approved: DH / Figure: 4

(a) Phase diagrams for H_2O-NaCl and H_2O-$CaCl_2$ systems



(b) Empirical method from "Frozen Ground Engineering", Andersland and Ladanyi (1996)

$$\frac{Wu}{W} = \frac{Sn}{1000}\left(1 - \frac{54.11}{T}\right)$$

Wu = unfrozen water content
W = total water content
Sn = concentration of NaCL in g/L
T = temperature in ^{0}C

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		Methods for Salinity Exclusion Estimates
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