Red Dog Mine
Closure and Reclamation Plan

Supporting Document F
Reclamation and Revegetation

Red Dog Mine
Closure and Reclamation Plan

SD F1: Mine Area Closure Options – Summary of the Cover Studies

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Memo

To:	File 1CT006.000	**Date:**	December 19, 2005
cc:	Daryl Hockley	**From:**	Michel Noël
Subject:	Red Dog Mine Mine Area Closure Options Summary of the Cover Studies	**Project #:**	1CT006.000

This memo provides a summary of the cover studies that were performed in preparation for the closure and reclamation plan for the Red Dog Mine in Alaska. The cover for the tailings impoundment is not covered in this technical memo.

1 Potential Cover Materials

Cover materials can be of various origins, but generally, they consist of natural soils, processed rock, and synthetic materials. The following sections discuss the potential materials available for construction covers at the Red Dog Mine.

1.1 Natural Soils

Natural soils are usually comprised of clay, silt, sand and gravel. Cover strategies often require fine grained soils to reduce water and oxygen infiltration. Granular materials comprised of sand and gravel can be substituted by waste rock. Given the geological settings of the Red Dog Mine, there are practically no local sources of natural soils available for cover construction.

1.2 Waste Rock

Waste rock generally consists of blasted rock that is sometimes processed to obtain the proper particle size gradation. There are two geologic formations in the Red Dog area that could yield rock that will weather to relatively fine grained soil, namely the Kivalina shale and the Okpikruak shale.

Waste rock materials have been characterised in O’Kane Consulting (2004). The characterisation program focused on the physical properties of the waste rock types in relation to cover design. It included saturated hydraulic conductivity, soil-water characteristic curves, particle size, in-place bulk density and compaction tests. The testing program is discussed in a subsequent section.

1.2.1 Kivalina Shale

Kivalina shale is a calcareous shale with acid neutralization potential. It does not require crushing for coarse cover purposes. The Kivalina shale contains traces of orange sphalerite and may have a potential for zinc leaching. This potential for zinc leaching is not desirable for cover material because the contaminants could eventually be released in the environment.

1.2.2 Okpikruak Shale

The Okpikruak shale does not contain base metals, but has only traces of pyrite and is neutral in acid generating/consuming potential. The Okpikruak shale has similar physical properties as the Kivalina shale but its potential to release metals is much smaller, thus more suitable for cover material. This shale should also weather quickly to finer sizes.

1.2.3 Overburden Shale

The current Overburden Stockpile, located at the south end of the tailings impoundment, will be integrated into the Back Dam. Depending on the final design of the Back Dam, a portion of the stockpiled material may be available for other uses. Kivalina shale is the dominant material in this stockpile, and other mineralized materials are also present.

1.3 Synthetic Materials

Synthetic materials can also be used for covers. Several materials exist but the most common ones are high density polyethylene (HDPE), low density polyethylene (LDPE), polypropylene (PP) and geosynthetic clay liners (GCL). Bituminous geomembranes (BG) are also commonly used in Europe and have recently been introduced to North America. Site conditions, material availability, shipping cost and local experience are factors that influence the selection of the type of liner. The advantage of synthetic liner materials is the low hydraulic conductivity that can be achieved. However, these materials are often more expensive and less durable than soils and processed rock.

2 Soil Cover Test Program

The field program included 14 test pits excavated in the Main Waste Stockpile and another 9 test pits in the Overburden Stockpile. Bulk samples were recovered from these test pits for laboratory testing.

Paste pH and paste conductivity were measured during sampling. The pH and conductivity measurements indicate that the Overburden stockpile material contains sufficient oxidation products to impact the quality of the pore water.

In situ bulk density measurements were performed at various locations on the Main Waste and Overburden Stockpiles. The in situ bulk density was generally higher at or near the surface than at depths. This is indicative of the weathering properties of the shale present at the site, combined with the compaction effects from equipment traffic at the surface.

The laboratory program included particle size distributions, specific gravities, standard Proctor compaction curves, saturated hydraulic conductivities and water retention curves (soil-water characteristic curves).

The particle size distributions measured on Main Waste samples were relatively coarse-textured with a median diameter of approximately 11 mm. The material was relatively well graded from cobble down to silt and clay size particles, probably due to the weathering nature of the shale. The fine portion smaller than 0.075 mm in diameter ranges from 3 and 12 percent. Figure 1 shows the particle distribution curves obtained from bulk samples recovered from the Main Waste Stockpile.

The particle size distributions measured on the Overburden Stockpile material also indicate a relatively coarse textured material with a median diameter of approximately 7 mm as shown in Figure 2. Although the median is slightly smaller than the Main Waste material, the overburden material is within the same range obtained as the Main Waste samples. The Overburden material was also well graded, with fine particles smaller than 0.075 mm ranging from 7 to 27 percent.

The specific gravity was measured on three samples: two from the Main Waste Stockpile and one from the Overburden Stockpile. The tests were performed on fractions based on particle size but the results do not show any trend according to the particle sizes. One of the samples from the Main Waste Stockpile and the sample from the Overburden Stockpile have similar values, with values ranging from 2.43 to 2.74 and averaging 2.57. The other sample from the Main Waste Stockpile has higher values, ranging between 3.32 and 3.60 and averaging 3.46.

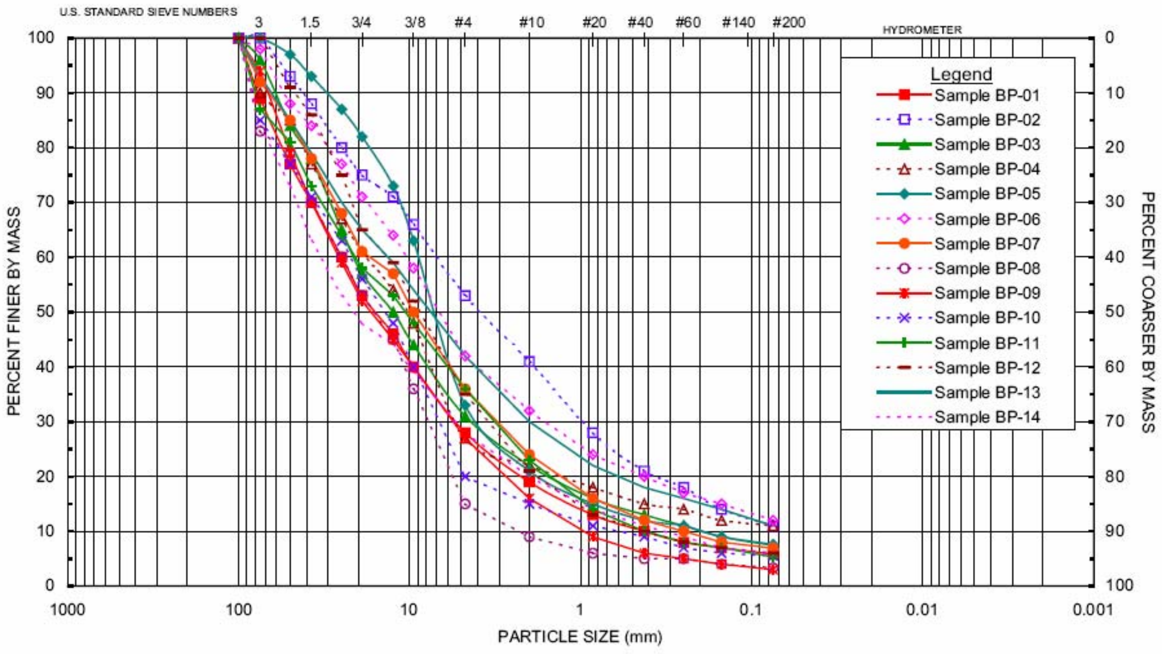

Figure 1: Particle size distribution curves, Main Waste Stockpile bulk samples (O'Kane 2004)

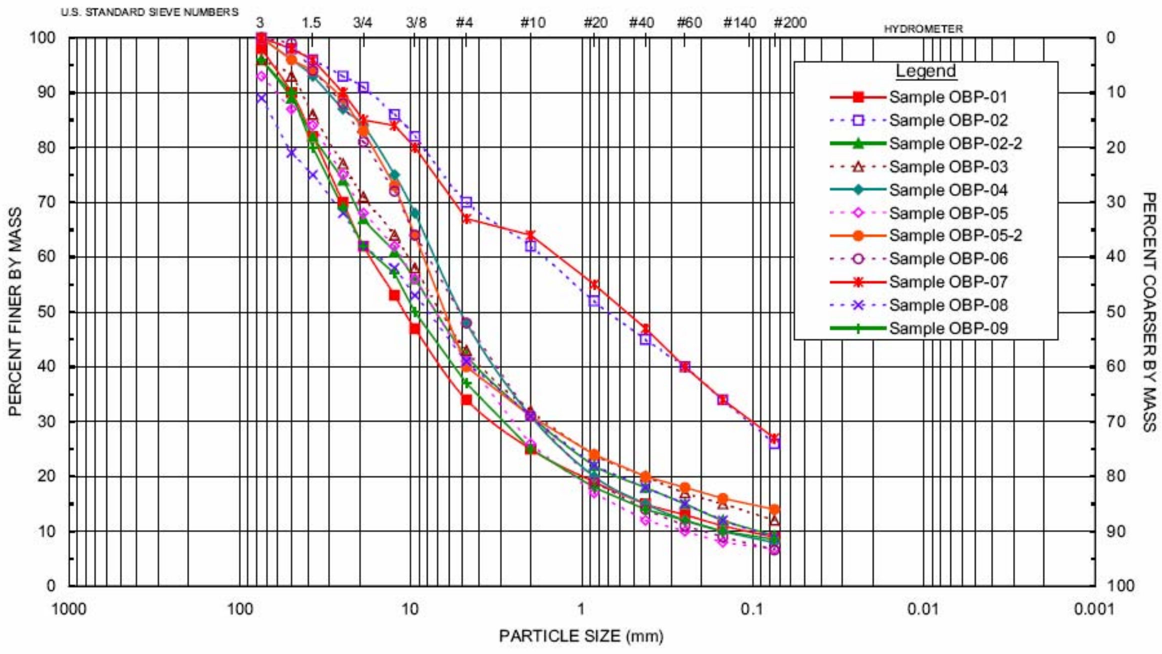

Figure 2: Particle size distribution curves, Overburden Stockpile bulk samples (O'Kane 2004)

The porosity, which is calculated using the dry bulk density and the specific gravity, varied from 0.20 to 0.43 for the combined Main Waste and Overburden Stockpile samples. The surface values were the lowest and there were no significant difference between the Main Waste and Overburden Stockpiles.

Proctor compaction curves were measured on three samples from the Main Waste Stockpile and two from the Overburden Stockpile. The test results are shown in Figure 3 and have the following range:

- Lower bound: Overburden Stockpile
  Optimum gravimetric water content: 13.6%
  Maximum dry bulk density: 1870 kg/m m^3
- Upper bound: Main Waste Stockpile
  Optimum gravimetric water content: 5.7%
  Maximum dry bulk density: 2872 kg/m^3

The maximum dry density is generally higher and the optimum water content lower as the coarse content increases.

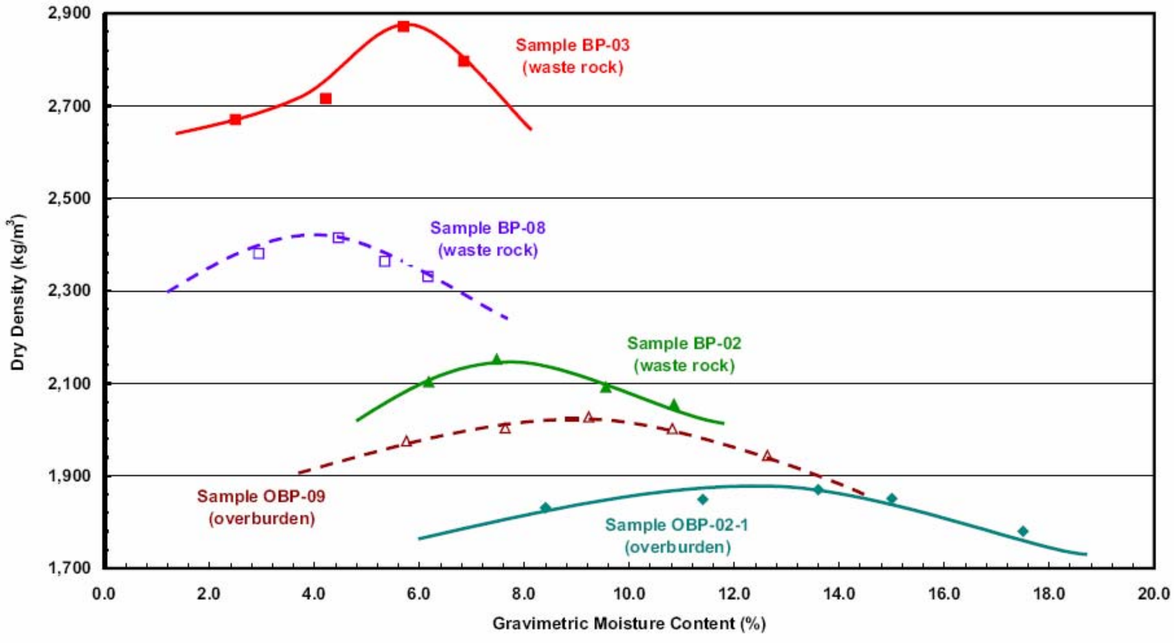

Figure 3: Standard Proctor compaction curves, Main Waste and Overburden Stockpile bulk samples (O'Kane 2004)

Saturated hydraulic conductivity was measured on selected samples using a 250 mm mould. The samples were prepared at initial densities and moisture contents representative of field conditions. The material from the Main Waste Stockpile gave values from 6.5 x 10^{-2} cm/s to 4.9 x 10^{-6} cm/s. The corresponding dry bulk densities were 2072 kg/ m^3 and 2207 kg/ m^3, respectively. These values indicate the influence of the dry bulk density on the hydraulic conductivity. Higher compaction efforts will induce lower hydraulic conductivity values. The saturated hydraulic conductivity values measured on samples from the Overburden Stockpile ranged from 2.0 x 10^{-3} cm/s to 1.0 x 10^{-5} cm/s. The corresponding dry bulk densities were 2012 and 2078 kg/m^3, respectively. Again, higher compaction will develop lower hydraulic conductivity values. Although the materials vary between the Main Waste and the Overburden Stockpiles, the saturated hydraulic conductivity values were similar.

Soil-water characteristic curves were measured on one sample from each the Main Waste and Overburden Stockpiles. The two curves are shown in Figure 4. This test characterises ability of the material to retain water. The relevant properties are known as the air entry value, the field capacity and the wilting point. In summary, the air entry value corresponds to the suction at which the material begins to de-saturate, the field capacity is the amount of water that can be stored by the soil under free drainage conditions, and the wilting point is the moisture content at which plants can no longer withdraw the stored moisture. The difference between the field capacity and the wilting point is a simple measure of the potential amount of water that can be stored and released by a unit volume of soil.

The sample from the Main Waste Stockpile show an air entry value of about 0.5 kPa and the sample from the Overburden Stockpile have a value of approximately 2 kPa, although it was not well defined. The test results show that both materials have a relatively low capacity to retain water under negative pressure (suction) conditions, thus having a low wilting point.

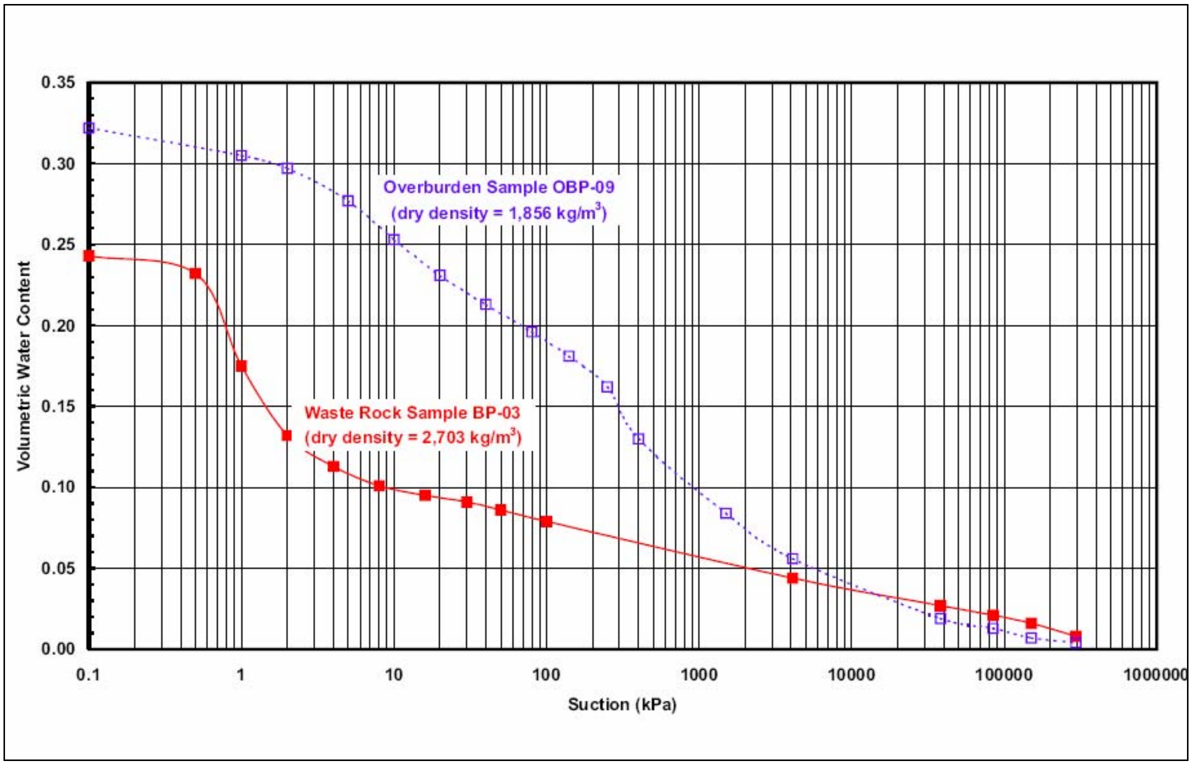

Figure 4: Water retention curves, Waste Rock and Overburden samples (O'Kane 2004)

3 Cover Options

Several options were considered for the closure and remediation of the waste rock at the Red Dog Mine. Five options were considered, namely compaction only, simple soil covers, complex soil covers, store and release covers, and geosynthetic covers. The covers options would all require resloping of the waste rock, regardless of the cover option selected. Consequently, resloping is practically independent of the cover option selected. Further details on resloping are discussed in SRK (2005). The sections below describe the cover options considered.

3.1 Compaction

The rock stockpiled at Red Dog is composed largely of shale that can be broken down by mechanical process such as compaction. Compaction will therefore reduce the saturated hydraulic conductivity of the waste rock, thus providing an opportunity to reduce infiltration if compaction is applied at the surface of the stockpile. The benefits of compaction in relation to infiltration were assessed by O'Kane Consultants (2004). The study indicated that compaction would provide limited reduction in net infiltration and that the runoff would become contaminated. These conclusions suggest that compaction is not sufficient as a stand-alone option.

3.2 Store and Release Covers

Store and release covers are designed to retain water until it can be taken up by plants and evapotranspired. The concept comes from "scientific irrigation" practices used in agriculture, which seek to add only as much water as the soil can store and then release for plant growth. In agriculture, the objective is to minimize the "loss" of water to the deeper soil. In our case, the objective would be to minimize the infiltration of water into the underlying waste rock and overburden materials.

Store and release covers are only possible in climates where there is a significant period of relatively low rainfall and high evaporation. The climate at the Red Dog Mine is such that precipitation is concentrated over a short period during August, which is after the period over which evaporation and plant uptake has peaked. For store and release covers to function, the precipitation should precede the evaporation and transpiration peaks. It is clear that the precipitation and the evapotranspiration balance at Red Dog are not favourable to a store and release cover system. This option was therefore eliminated.

3.3 Simple Soil Covers

Simple covers consist of a single layer cover that would isolate the stockpiled rock from runoff and direct access, provide a growth media for vegetation and maybe reduce infiltration. The reduction of the net infiltration will not only depend on the hydraulic conductivity at the surface of the cover, but also on the presence of a vegetative cover. The effectiveness of vegetative covers to remove pore water will depend on the growth condition, although the species present can sometimes be an important factor. In the case of the Red Dog Mine, the northern location of the site will restrict the selection of vegetative types and the short growth season will also limit the evapotranspiration.

Given the weathering properties of the local shale, the construction of the cover would be initiated about two years prior to closure to allow for the shale to weather prior to final grading, light compaction and seeding for the vegetation cover.

3.4 Complex Soil Covers

The purpose of the complex soil covers is to further reduce the net infiltration when compared to the simple soil covers. It is essentially a simple soil cover with a second layer placed on top. The base layer would be spread two years prior to closure to enable weathering. At closure, the surface of the base layer would be graded and heavily compacted prior to place the second layer. The surface would then be compacted and seeded to develop a vegetative surface.

3.5 Geosynthetic Covers

HDPE, PP and GCL covers have been used extensively to encapsulate landfills, to create ponds and to provide water barriers inside dams. There is however less experience with those materials for cover systems. BG liners are more recent and are gaining popularity because of their handling robustness and extended durability. There is no theoretical reason why geosynthetics will not be effective in covers. SRK has experience with the use of both GCL and HDPE in cover systems on northern Canadian projects. Polypropylene is also in use because it remains flexible in very cold conditions (where HDPE becomes brittle). Bitumen based geosynthetics have very recently been tested in the north.

The placement of geosynthetic liners becomes more difficult as the slope of the surface increases. Given the difficulty to place geosynthetic liners on sloped surfaces, its placement would be limited to flat surfaces and relatively flat slopes. The sloped surfaces would be covered with a complex soil cover.

Geosynthetic liners will require a base granular layer prior to place the liner. This is to protect the liner from punctuations caused by protruded rocks from the surface being covered. The base layer would typically consist of 150 mm (6 inches) of weathered shale that would be compacted. The geosynthetic liner would then be placed. Depending on the type of geosynthetic liner select, a non-woven geotextile may be required on top of the liner for protection. Another layer of weathered shale would then cover the liner. The final surface would then be lightly compacted and seeded to develop a vegetative surface.

The primary arguments against the use of geosynthetics in covers are cost and longevity. Typical installed costs are over \$10 per m^2, or \$100,000 per ha. Current estimates of longevity range to several hundred years for HDPE but frequently regulators require proponents set aside funds to test and replace the geosynthetic if it is used in longer term applications. For both these reasons, and because there may be better alternatives using locally available stockpiled materials, geosynthetics may be potentially practical for covering small areas that are stronger contaminant sources.

Another aspect to consider with some of the geosynthetic liners is the need to have effective joints/seams. With the exception of the GCL liners, the liners require a higher level of field quality control to assure that the seams does not contain leaks.

4 Soil Cover Modelling

Selected cover options were assessed using a numerical model to simulate the water transport that occurs through the cover and the underlying waste rock (O’Kane Consultants 2004). Soil cover modelling essentially estimates the water balance at the surface, which can be reduced to four components: runoff, evaporation and evapotranspiration, root uptake and net infiltration. Runoff is the amount of water that is shed from the surface of the stockpile and do not penetrate the surface. Evaporation, evapotranspiration and root uptake are processes that remove water from within the ground. The remaining portion of the water balance becomes the net infiltration. Net infiltration is often defined as the flux of water that reaches the base of the rock stockpile. The following sections provide an overview of the soil cover modelling that was carried out.

4.1 Model

The simulations were performed using VADOSE/W (Geo-Slope International Ltd. 2004), first in a one dimension (1D profile) and followed by simulations in two dimensions (2D geometry).

VADOSE/W requires climate data, soil properties and vegetation characteristics if they are included in the simulations. The climate and soil properties were based on data obtained at the site. The effects of climate change and heat generation from the oxidation of the waste rock were not incorporated in the simulations. The vegetation, when included, was considered as “poor” to reflect the limited growth capacity at the Red Dog Mine.

4.2 Climate

Climate is an essential component to perform soil cover modelling. O’Kane Consultants (2004) provides a summary of mean annual climate data for the mine site based on the Bons Meteorological Weather Station:

- Mean annual total precipitation: 467 mm (18.4 inches)
- Potential annual evaporation according to the Penman (1943) method: 580 mm (22.8 inches)
- Mean annual ambient temperature: -6 °C (21 °F)

The climate at the Red Dog Mine is sufficiently cold to support permafrost. Ground temperature measurements at the site indicate values in the order of -2 °C (28 °F).

4.3 1D Modelling

One dimensional simulations is equivalent to a large flat surface where there is no lateral water flow. The program consisted of reproducing the existing condition and then four cover system variants were modelled as listed in Table 1.

Table 1: Cover Profiles Modelled in 1D

Group	Description	Modelled Profile	Infiltration Fraction[a]	
			Range	Average
No compaction	Waste rock with no cover	0 to 10 m: Non-compacted waste rock	30%-52%	41%
	Thin Overburden cover (simple soil cover)	0 to 0.5 m: Non-compacted overburden 0.5 to 9.5 m: Non-compacted waste rock	17%-25%	23%
	Thick Overburden cover (simple soil cover)	0.0 to 1.0 m: Non-compacted overburden 1.0 m to 9.0 m: Non-compacted waste rock	10%-23%	17%
Compaction	Compacted waste rock with no cover	0 to 0.2 m: Compacted waste rock 0.2 to 10.0 m: Non- compacted waste rock	23%-31%	27%
	Compacted waste rock and overburden cover (complex soil cover)	0 to 1.0 m: Non-compacted overburden 1.0 to 1.2 m: Compacted waste rock 1.2 to 10 m: Non-compacted waste rock	6%-22%	14%

Source: O'Kane (2004)

Note: a: Infiltration fraction = (net annual infiltration) / (annual precipitation)
Overburden = material from the Overburden Stockpile
Waste rock = material from the Main Waste rock

Based on the characterisation work performed to date, the properties of the waste rock and the overburden materials are quite similar and vary over a range that is typical for that kind of material. The material from the Overburden Stockpile was usually within the range of the material from the Main Waste Stockpile. This is indicative of greater variability within the Main Waste Stockpile. If we consider that the stockpiled waste rock and overburden materials are not compacted, the 1D simulations effectively simulated three variants of uncovered stockpiles in relation to water transport. The remaining two variants represent covers that include compaction. The simulations listed in Table 1 are grouped accordingly.

The predicted annual net infiltration varies from 10% to 52% for the cases without compaction and 6% to 31% for the ones having compacted material. The corresponding four year averages ranged from 17% to 41% for the cases with no compaction and 14% to 27% where compaction was present. In comparison, it is our experience that uncovered and uncompacted waste rock piles typically have net infiltration in the order of 30% to 50% of the annual precipitation. Some of the low infiltration values obtained with uncompacted material may be questionable based on our experience with uncovered waste rock piles at other mine sites.

The predicted infiltration fractions are somewhat similar between the uncompacted and compacted cases, considering the uncertainties and approximation involved with water transport modelling. Consequently, the results do not demonstrate the benefit of having a compacted layer within the soil profile.

A sensitivity analysis was performed with the model by varying the saturated hydraulic conductivity of the materials and the coverage of the vegetation cover. The results show that both the hydraulic conductivity and the vegetation coverage can introduce important variations of the net infiltration. The vegetative cover would however reduce the net infiltration, although the development of the vegetative cover may be difficult to achieve given the conditions at the Red Dog Mine.

4.4 2D Modelling

Additional simulations were performed in 2D primarily to assess the influence of the slope on the net infiltration. These simulations were also used to assess other aspects of cover performance, such as:

- Estimate gaseous oxygen transport through the cover based on simplistic assumptions.
- Benefits of having a “poor” vegetative cover to reduce net infiltration.
- Sensitivity analysis of the saturated hydraulic conductivity of the materials.
- Influence of frozen ground on predicted net infiltration.

The material properties were the same as the 1D simulations and the boundary conditions were consistent with the 1D simulations. The selected slopes represent the potential range that may be implemented at closure. The steepest slope of 2 horizontal to 1 vertical (2H:1V) corresponds to the steepest slope that is considered adequate for long-term geotechnical and erosion stability. The flat slope of 4H:1V represents the slopes where high degree of compaction would be applied.

The results are reported as infiltration fractions in Table 2. The simulations did not demonstrate the benefit of compaction for reducing infiltration. The magnitude of the slope did not show any trend with the net infiltration, even if the soil profile included compacted materials. Additionally, the net infiltrations obtained with the 2D simulations were all larger than the equivalent 1D simulations. Those variations are indicative of the difficulties involved with numerical modelling.

Table 2: Cover profiles modelled in 2D

Description	Description	Modelled Profile	Side slopes modelled	Infiltration Fraction
No compaction	Thick Overburden cover (simple soil cover)	0.0 to 1.0 m: Non-compacted overburden 1.0 m to 9.0 m: Non-compacted waste rock	1D	9%
			2H:1V	14%
			3H:1V	15%
			4H:1V	10%
Compaction	Compacted waste rock And overburden cover (complex soil cover)	0 to 1.0 m: Non-compacted overburden 1.0 to 1.2 m: Compacted waste rock 1.2 to 10 m: Non-compacted waste rock	1D	24%
			2H:1V	29%
			3H:1V	31%
			4H:1V	23%
	Compacted waste rock with no cover	0 to 0.2 m: Compacted waste rock 0.2 to 10.0 m: Non- compacted waste rock	1D	8%
			2H:1V	13%
			3H:1V	13%
			4H:1V	6%

Source: O’Kane (2004)

Note: a: Infiltration fraction = (net annual infiltration) / (annual precipitation)
and (net infiltration without cover) = 41% of total precipitation
Overburden = material from the Overburden Stockpile
Waste rock = material from the Main Waste rock

The gaseous oxygen transport was also assessed as part of the 2D simulations for the 3H:1V slope. The oxygen flux was estimated by assuming that the gaseous oxygen is fully depleted immediately underneath the cover. This implies that the material underneath the cover is very reactive and that the reactant will never be depleted. Soil covers will implicitly reduce the oxygen flux reaching the underlying reactive waste rock, but the benefit of the cover should be measured in relation with the rate of oxidation. VADOSE/W is not capable of performing such predictions and the quantification of the oxygen flux as modelled with VADOSE/W should be interpreted with caution. However, it is probably not critical to perform more sophisticated modelling to assess gas transport and oxidation, since the main objective of the soil covers for the Red Dog Mine is to isolate the reactive and contaminated waste rock. Additionally, the soil materials available for covers do not have the capability of retaining high moisture contents under unsaturated conditions; a property required for effective control of oxygen transport through soil covers.

Some simulations included the effect of frozen ground on pore water movement through the system. According to estimates presented by O'Kane Consultants, the seasonal frozen ground can reduce the net infiltration. However, the movement of pore water under frozen condition is based on simple approximations; it did not consider the impact of climate change and did not include the influence of the heat generated by the oxidation of the waste rock. These factors could reduce considerably the effectiveness of maintaining adequate seasonal frozen conditions.

The inclusion of a "poor" vegetative cover in the simulation reduced the net infiltration. The amount of water extracted by the plants will be dependent on the plant varieties and their long-term sustainability. As mentioned earlier, the development of the vegetative cover may be difficult to achieve, given the conditions at the Red Dog Mine.

4.5 Discussion on Modelling

The cover modelling could not demonstrate any clear trend in the various cover options reproduced with the 1D and 2D simulations. The main variants were various cover configurations, the inclusion of compacted layers and the use of different slope surfaces. The wide range in the predicted infiltration rates obviously contains uncertainties and approximations. It highlights the importance of doing field trials to measure field performance, which could then be used in the final design at closure.

5 Covers for Further Consideration

The work carried out to date suggests that the minimum soil cover consist of a properly sloped and compacted surface where 0.45 m (1.5 ft) of material from the Overburden Stockpile would be placed on top. Given the contaminated nature of the Overburden stockpile material, the surface runoff would have to be intercepted and redirected to either the tailings impoundment or directly to the water treatment plant. The main criterion is to encapsulate and prevent direct contact with the stockpiled material. The thickness of this cover is limited and may not be sufficient to prevent root penetration through the cover if vegetation eventually develops over the cover.

The second option consists of compacting the waste rock surfaces and place 0.9 m (3 ft) of Okpikruak shale. This option appears to be a more efficient cover in relation to the net infiltration and surface water management. It achieves the goals of the "minimum cover", but it also prevents the migration of metals by using the Okpikruak shale. Additionally, the increase in the thickness should reduce the risk associated with the penetration of the roots through the cover.

The third option is to adopt a hybrid cover where a geosynthetic liner would be used to cover the flat surfaces and flat slopes. The steeper portions would be covered using 0.9 m (3 ft) of Okpikruak shale placed on top of compacted surfaces.

6 References

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