The Integrity of Cover Systems – An Update

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INTRODUCTION

Cover systems are generally constructed to prevent or reduce water infiltration to sulfide-bearing mine wastes and thus reduce acid generation. The application of cover systems has grown rapidly during the past decade. While cover systems have never been proposed as a walk-away solution, the use of cover systems is often attractive. The application of a cover system is one of the few remaining options available to reduce treatment costs where waste rock dumps or tailings impoundments have already been constructed and acid rock drainage has developed. In many cases, the objective of the design is to establish a system that will function for at least 100 years and ultimately into perpetuity. The desired design life extends well beyond most criteria accepted in engineering practice. Numerous mine operators have invested into a design technology for cover systems with the expectation that these covers will reduce long-term liability. Our experience with the long-term integrity of cover systems for mine waste management is limited to one or perhaps two decades at best.

The objective of this paper is to consider issues related to cover integrity.

CONCEPTS ASSOCIATED WITH COVER INTEGRITY

Soil cover systems function at the interface between the atmosphere, biosphere and the geosphere. The soil/atmosphere boundary is responsible for the partitioning of all incoming energy (ie short-wave solar and long-wave radiation) together with meteoric water. Fluctuations in temperature, soil water potential, and heat and mass transfer rates are the most extreme at this position within the soil–atmosphere profile. Engineered soil cover systems are essentially designed to control these variables. Technologies for the analysis, design and monitoring of cover systems have developed rapidly in recent times to meet the demand for the closure of municipal landfill systems, as well as mine waste management facilities. In general, the early approach to cover systems was based upon the same principles used for the design of liners (ie compacted clay liners or geomembranes at the base of solid waste profiles). Quite simply stated, liners are designed to form a physical barrier that isolates the flow of contaminated waters to groundwater and the receiving environment. In many cases, liners have been constructed using compacted low permeability clay. Extensive experience over the past several decades has shown this method of barrier construction to be successful. Therefore, the use of compacted clay to form a barrier in a soil cover profile was an obvious first choice. Unfortunately,

Table 1: Comparison of conditions imposed on liners and soil covers.

Parameter	Liners	Covers
Total Stress	High	Approaches Zero
Hydraulic Pressures	Positive 0 to 300 kPa	Negative 0 to –1500 kPa
Temperature	Constant 5 to 20°C	Highly Variable –50 to +60°C
Degree of Saturation	100%	1% to 100%
Water Phase	Liquid Only	Multiphase Vapour, Liquid, Ice
Hydraulic Regime	Downward Gradient	Infiltration Run-off Evapotranspiration Change in Storage
Environment	Isolated Engineered	Microbial Communities Plants Roots and Fibre Animals Living Systems

the physical environment and associated stresses for compacted clay liners situated deep within the soil profile are radically different from those at the soil surface. Table 1 summarises some of the several important differences between the operating environment of cover systems versus liners.

The most important variation in the operating environment for soil cover systems compared to liners is energy, which includes temperature and water potential. Fluctuations in temperature and/or water content in soil produces volume change. Of all the natural soils, clay-rich soils are the most sensitive to volume change. While highly plastic clay materials have proven to be successful in the construction of liners, they are not suitable for the construction of cover systems. Highly plastic clay, commonly referred to as expansive soil, is widely regarded as a problematic soil when used to construct highway pavements. Road builders have known this for decades. The design of pavement structures shares the same physical environment and climatic extremes as those for soil cover systems. In some ways, the approaches used in pavement/road design may have formed a better starting point for the development of cover design when compared to liner technology.

The design of pavement structures is rooted in material science. Clays and silts are problematic soils for road construction. The same can be said for the construction of cover systems. While highly plastic clay materials provide the lowest values of saturated hydraulic conductivity when compacted, they degrade rapidly in the active zone (ie the upper 0 – 3 m of the soil profile with seasonal variation in temperature and water content). Silt-rich soils are somewhat

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less susceptible to volume change, but are most susceptible to frost heave and dangerously susceptible to erosion. Sand and gravel soils offer high strength and are relatively incompressible compared to clay. However, granular materials have higher permeability with poor moisture retaining capacity and offer no benefit with respect to barrier or store/release covers. Well-graded materials have proven to be the best performers for the construction of the base and sub-grade layers in pavement structures. In general, this rule may be applied to cover systems.

Climatic conditions are paramount for cover design. Figure 1 shows annual precipitation and potential evaporation for several locations, and demonstrates the range of variations. Moisture availability will control the approach to cover design. It is widely known that current practice is to design covers to be barrier systems in wet climates and store/release systems in semi-arid regions. Store/release cover systems have been adopted as best practice for some parts of Australia. Barrier-type cover systems have been used extensively for landfill systems in the United States. Store/release covers and barrier covers rely on the physical properties of the soil within the different zones of their profile. Figure 2 illustrates the near surface profile of the soil cover environment. The profile consists of an active upper layer

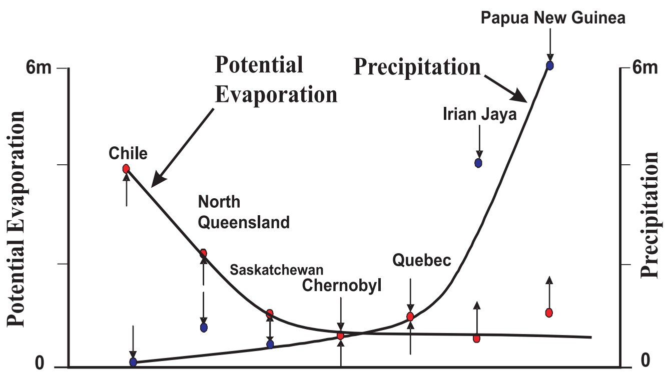

Figure 1: Global variation in annual precipitation and potential evaporation.

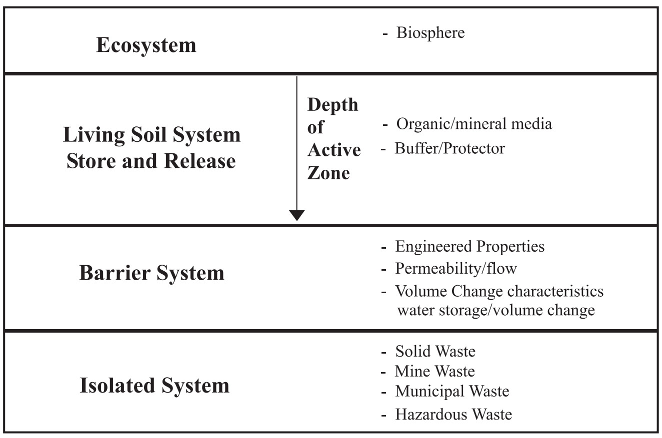

Figure 2: Appropriate concepts for the design of a soil cover system.

that supports the surface biosphere. This layer hosts biomass, organic nutrients and microbial communities. Large fluctuations in both temperature and water content prevail. The active layer is of greatest importance with respect to the performance of store/release covers as plant transpiration is critical to proper cover performance. In the case of barrier-type covers, which must maintain specific engineering properties with respect to permeability and high water retention, the barrier layer must be situated below the active zone.

The thickness of the active zone is dictated by climate, soil type and vegetation. The active zone may be less than 0.5 m thick, as in the temperate rain forests of British Columbia, Canada near White Rock, shown in Figure 3. Alternatively, the active zone may be greater than 3 m thick, as observed in the semi-arid region of southern Saskatchewan, Canada, shown in Figure 4. It is interesting to note that both soils shown in Figures 3 and 4 are a silty clay matrix glacial till located along the 49th parallel. Furthermore, the value of potential evaporation at both locations is approximately 1000 mm per annum. The difference in the thickness of the active zone occurs as a result of the difference in rainfall (1000 mm in White Rock versus 400 mm at the southern Saskatchewan location) together with differences in the mean annual temperatures of 15°C (ranging between 0°C and 30°C) versus 5°C (ranging between -40°C and + 40°C), respectively. It can be seen that the soil profile shown in Figure 4 exhibits extensive fracturing associated with desiccation and freeze/thaw cycling. Clearly, any attempt to construct a barrier layer within the upper 3 m of this profile would result in a failure. In general, the primary mechanism for failure of barrier-type cover systems is that the active zone penetrates the barrier layer. Repeated cycles of wetting and

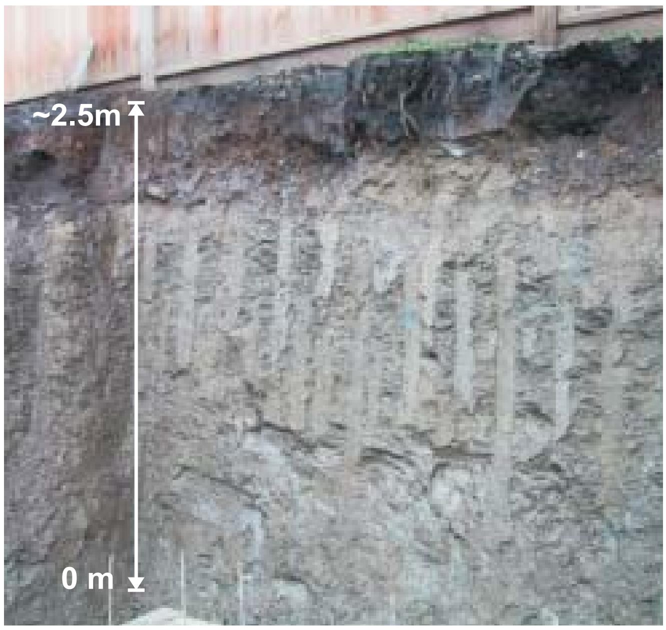

Figure 3: Near surface soil profile at White Rock, British Columbia, Canada.

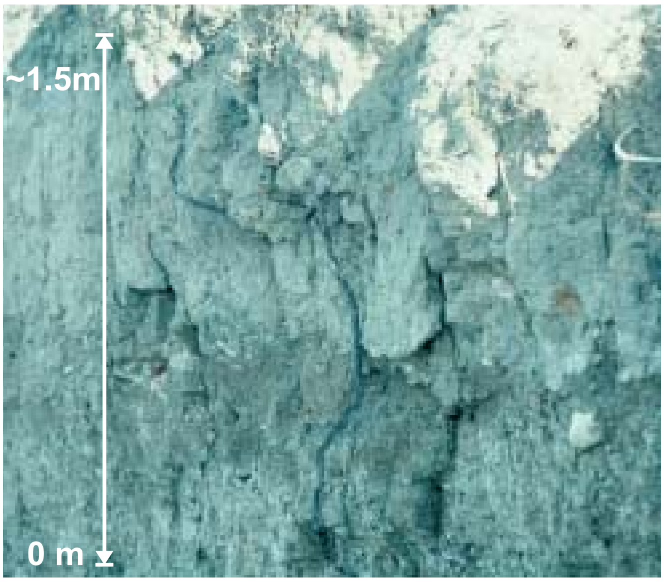

Figure 4: Near surface soil profile in southern Saskatchewan, Canada.

Figure 5: Highly plastic clay with nuggety fractured structure.

drying, as well as freezing and thawing produce environmental fatigue in the barrier layer. Highly plastic clays have the highest sensitivity to these stresses and develop a nuggety, fractured structure in the active layer, as shown in Figure 5, resulting in values of *in situ* hydraulic conductivity three and sometimes four orders of magnitude greater than the value measured in a compacted state in the laboratory.

Other mechanisms for failure of cover systems are known. Failure of store/release covers occurs less frequently than for barrier-type covers. In general, several primary mechanisms can be identified for failure in store/release covers. The first mechanism is lack of storage capacity. Storage capacity is controlled by the soil water characteristic curve of the cover profile in the active zone. In the same way that environmental stressing due to wetting and drying, freezing and thawing degrades hydraulic conductivity for barrier soils, these mechanisms also tend to reduce storage capacity. The primary objective of placing a store/release layer is to use the material with a high porosity and a gently sloping soil water characteristic curve (Wilson, 2000). Thus, the material is placed in a loose non-compacted state. Wetting and drying may cause the soil structure to consolidate and/or become aggregated with the formation of soil peds (particularly in the case where the soil contains clay). A significant reduction in porosity as well as an increase in density can be observed. In some cases, a reduction in storage capacity of up to 50 per cent may occur.

A more important consideration in the performance of store/release cover systems relates to the vitality and sustainability of the vegetation. Actual evaporation from a bare or non-vegetated soil cover will generally only be about ten per cent of the potential rate of evaporation available. High evapotranspiration can only be obtained with a fully developed plant canopy. Durham, Wilson and Currey (2000) demonstrated the influence of vegetation on the performance of the store/release cover system constructed at the Kidston Gold Mine, north Queensland. While the cover system was observed to provide excellent performance with lush grasses during the first year, the capacity to extract infiltration waters during the subsequent years was seen to diminish. It was determined that the decline in water transpiration rates was due to a lack of nutrients that reduced vegetation growth and vitality. While this reduction in performance was easily corrected with the addition of fertiliser, the need to monitor ongoing performance was demonstrated. This issue is likely one of the most critical with respect to the long-term performance of store/release covers, since the final performance will be determined by the ultimate vegetative canopy that develops through succession, which may require several decades. The long time periods required to establish vegetation leads to difficulty in assessing cover performance over the short term.

Erosion is a failure mechanism that may destroy the integrity of any cover. Figures 6 and 7 illustrate erosional damage of the barrier cover at the Equity Silver Mine, in British

Columbia, Canada and the store/release cover at Kidston gold mine respectively. A storm event at Equity Silver with a return of approximately 200 years caused a slump to occur in an over-steepened region of the cover (Figure 6). Fortunately, this minor failure occurred in an isolated over-steepened section of the cover, and was readily repaired. The erosional gully shown at the Kidston site occurred in a non-vegetated section of a test cover during a typical summer storm. While minor failures were easily remedied at the Equity and Kidston sites, they illustrate the type of damage that may occur in full-scale cover systems that are not properly designed. In general, the threat of severe erosion is considered of greatest risk to store/release cover systems on side slopes or where run-off may converge. This may be attributed to three key factors. Firstly, store/release covers are placed as loose, low-density materials. Secondly, the vegetative canopy is often stressed due to lack of rainfall and thus the surface of the cover becomes exposed and susceptible to erosion. Finally, the nature of semi-arid climate systems generally produces high intensity storms.

Figure 6: View of erosional slump failure in an over-steepened slope.

The concepts and mechanisms for failure or loss of cover integrity described above are largely subjective. For example, there are no theories available to describe or quantify the influence of weathering on the reduction in storage capacity for store/release covers, or to describe the change in saturated hydraulic conductivity due to wet/dry/freeze/thaw cycles. Furthermore, there is no comprehensive model available to describe root water uptake as a function of nutrients or to predict the progression and natural succession of plant communities. While numerous numerical models such as SoilCover (1997) are available for the design and analyses of soil cover systems, these models provide only a numerical description of ideal porous media and fall drastically short of predicting the performance of natural systems. Numerical models are useful design tools but should not be solely relied upon. Common sense and experience are the most useful design tools.

EXPERIENCE WITH COVERS

While hundreds of cover systems have been constructed worldwide, there appears to be only limited documentation available describing the success or failure with respect to long-term performance. A review of the current literature available for cover system performance on sulfide bearing mine wastes reveals only three well documented sites with a performance record longer than five years. These include: Rum Jungle, Equity Silver Mine, and Kidston Gold Mine.

Rum Jungle

Timms and Bennett (2000) provide a comprehensive overview of the performance of the cover system constructed at Rum Jungle in the Northern Territory, Australia. The climate regime at Rum Jungle may be classified as tropical with distinct wet/dry seasons having a total annual

Figure 7: Erosional gully in fine-grained soil due to high intensity storm.

precipitation of approximately 1400 mm. Performance data are available for 16 years. The cover system is classified as a barrier-type, designed to limit oxygen entry and water infiltration. The cover profile consists of 150 mm of gravelly sand and 250 mm of store/release sandy loam over 225 mm of compacted clay. Initial infiltration values less than three per cent of precipitation were observed during the first ten years following placement of the cover. Performance during the subsequent five years has been seen to degrade, with infiltration values climbing to ten per cent of total precipitation. This compares to infiltration of approximately 50 per cent to 60 per cent for the waste rock prior to the construction of the cover system. Oxygen concentrations were reported to drop to less than five per cent after cover placement; however long term data with respect to oxygen is not reported. In summary, the barrier cover system constructed at Rum Jungle provided excellent performance during the early years. Longer-term performance has shown the integrity of the cover system has declined with time.

Equity Silver Mine

Wilson *et al* (1997) describe the cover system constructed at Equity Silver Mine. The cover system was designed as a barrier cover to limit oxygen entry and reduce water infiltration. The climate at Equity Silver can be classified as humid alpine with a total precipitation of approximately 700 mm and potential evaporation equal to 500 mm producing a positive water balance. Approximately 60 per cent of the precipitation at Equity occurs as snow under freezing conditions, producing high run-off during the spring freshet. The cover system at the Equity Silver Mine consists of 300 mm of loose vegetated till over 500 mm of compacted till. The glacial till material is well graded, with gravel, cobbles and a silt and clay content greater than 30 per cent. Laboratory hydraulic conductivity tests for the till indicate values in the range of 1×10^{-10} m/sec when compacted at optimum water content. Cover design and analysis was based on a more conservative value of 1×10^{-9}m/s. SoilCover modeling suggested that infiltration rates would be decreased from 60 per cent to 80 per cent for uncovered waste rock to values less than five per cent. Early observations from field lysimeters confirmed this value of net infiltration.

Monitoring of performance for the cover system at Equity Silver Mine has continued since 1993. Continuous monitoring for water content at multiple locations in the compacted till barrier layer clearly shows the maintenance of high saturation. *In situ* hydraulic conductivity tests were completed in October 2002. The field-saturated hydraulic conductivity shows a range of values between 3×10^{-7} m/s and 2×10^{-9} m/s with the mean being less than 3×10^{-8} m/s. A reduction in oxygen concentrations can be seen at select locations while seasonal fluctuations are measured at other locations.

In general, lime loads for treatment of ARD have dropped by more than 50 per cent between 1993 and 2000. The observed performance for the cover system at Equity suggests satisfactory performance during the early years. However, abnormally high precipitation occurred during the 2001 and 2002 winter and spring. The excess precipitation, run-off and seepage exceeded the design capacity of the water collection and treatment system requiring further design modifications to be implemented. It is difficult to determine the source of all waters discharging to the drainage ditch around the perimeter of the main waste rock dump at the present time; however an excess of water above the five per cent value initially predicted due to cover infiltration is being measured in the drainage ditch. The source of this additional water is not yet clearly understood. The potential for excess infiltration is being investigated together with the assessment of other sources of flow such as groundwater discharge. In summary, it is not yet possible to make conclusive statements on the full-scale performance of the cover system at Equity Silver Mine.

Kidston Gold Mine

Two large-scale test cover systems were constructed at Kidston Gold Mine in 1995/96. The Kidston Gold Mine is situated in a semi-arid tropical climate with distinct wet/dry seasons. Average annual precipitation is approximately 700 mm with potential evaporation exceeding 2000 mm. In general, all rainfall occurs during the summer months between December and March. The first test cover profile consisted of approximately 2000 mm of store/release oxide material while the second profile is 1500 mm of store/release oxide material over a 500 mm compacted low permeability oxide barrier. Williams *et al* (2003) describe the long-term performance of this cover system. In short, the performance of this store/release system has proven to be very good with no significant infiltration measured in deep lysimeters installed at the base of the test cover profiles.

The primary concerns with the long-term integrity of the store/release covers relates to the development and sustainability of the vegetative canopy along with erosion control. The influence of vegetation and storage capacity of the cover together with the results of SoilCover modeling are described in detail by Durham *et al* (2000). Williams *et al* (2003) describe the novel approach to control of erosion at the Kidston Gold mine. The surface of the storage layer was left with a hummocky topography to trap and retain run-off. High intensity rainfall events frequently occur during the summer months producing extreme surface flows with high potential to cause erosion (Figure 7). The hummocky design has proven successful in preventing erosion associated with breaches in the cover. The application of the store/release hummocky design was restricted to the flat surfaces on the waste rock dumps since it is not possible to construct erosion-resistant covers with loose material on side slopes. Clean waste rock was placed around the outer batters of the waste rock dumps. In summary, the observations to date indicate the store/release cover system installed at the Kidston Gold mine is providing good performance. Long-term performance will ultimately be determined by the performance of the successional vegetative canopy.

Alternate Covers Assessment Program

One of the most comprehensive studies currently underway for the assessment of long-term field scale cover performance is the Alternative Covers Assessment Program (ACAP) being conducted by the United States Environmental Protection Agency (Benson, 2002a). The 'alternative covers' being investigated are essentially store/release covers. The purpose of the study is to compare the performance of store/release systems with compacted clay or complex cover systems with barrier layers. Only preliminary results for one to 2.5 years are available. Complex and alternative test covers have been constructed in six arid and semi-arid climates in the southern and western regions of the United States. A further four sites were selected for the construction of conventional compacted clay, monolithic or composite multilayer covers in humid regions in the eastern regions of the United States. It has been shown that infiltration into the alternative covers constructed in arid and semi-arid locations is typically less than one per cent of precipitation. Composite covers appear to be performing well in all climates with less than one per cent infiltration in semi-arid climates and less than five per cent infiltration in humid climates. Compacted clay covers are performing much worse than expected. Excessive leakage greater than 50 per cent of infiltration has been measured in humid climates.

The integrity and value of cover systems will now be discussed in view of the concepts, failure mechanisms and observed performance/experience outlined above.

THE INTEGRITY OF COVER SYSTEMS

The construction of cover systems for the permanent closure and reclamation of waste rock dumps and tailings impoundments requires high capital investment. The clear objective for the construction of any closure tool is to reduce long-term liability and risk. Closure must be defined in terms of time scale. Clearly, perpetuity can be argued to be one measure of appropriate time frame. However, engineering practice has no precedent for design at this level. Cover systems function within natural environments and the natural environment is, by definition, transient. Behaviour and function changes constantly with time and natural systems must adapt to changes in the prevailing environment. It is thus difficult to define the integrity of cover systems for the long-term closure of mine waste management systems, when it is understood that the cover system must satisfy engineering criteria with respect to heat and mass transfer, and at the same time integrate into the behaviour of natural systems. The comments and recommendations outlined here on the integrity and value of cover systems will not attempt to describe methods for ensuring long-term integrity, but will simply draw conclusions based on observed performance over brief time scales.

A key issue that must always be considered in the evaluation of performance, risk, benefit and integrity, is of course, cost. The range of capital investment required for the construction of soil cover systems is considerable. Figure 8 presents a simple plot for the approximate cost per hectare for typical cover systems. Experience with construction costs for cover systems has generally indicated that construction costs for covers built within the United States when counted in United States dollars are similar to construction costs for covers built within Australia when counted in Australian dollars. The same is true for Canadian construction. Dollar figures in this paper therefore represent costs for construction within Australia, Canada or the United States in the local currency. It can be seen the cost for the simplest cover intended to provide a base for re-vegetation only, is about $10 000 per hectare. The barrier-type cover system constructed at the Equity Silver Mine was approximately $35 000 per hectare. The store/release cover at the Kidston Gold mine was in the order of $50,000 per hectare. These covers can be considered to be among the least expensive to construct relative to most other cover systems. In the case of both Equity Silver and Kidston, an abundant source of suitable construction material was locally available. Furthermore, both cover systems were monolithic with respect to material type. The cost per hectare increases sharply with the number of layers and skill required to construct more sophisticated covers. In general, for most multilayer covers, whether

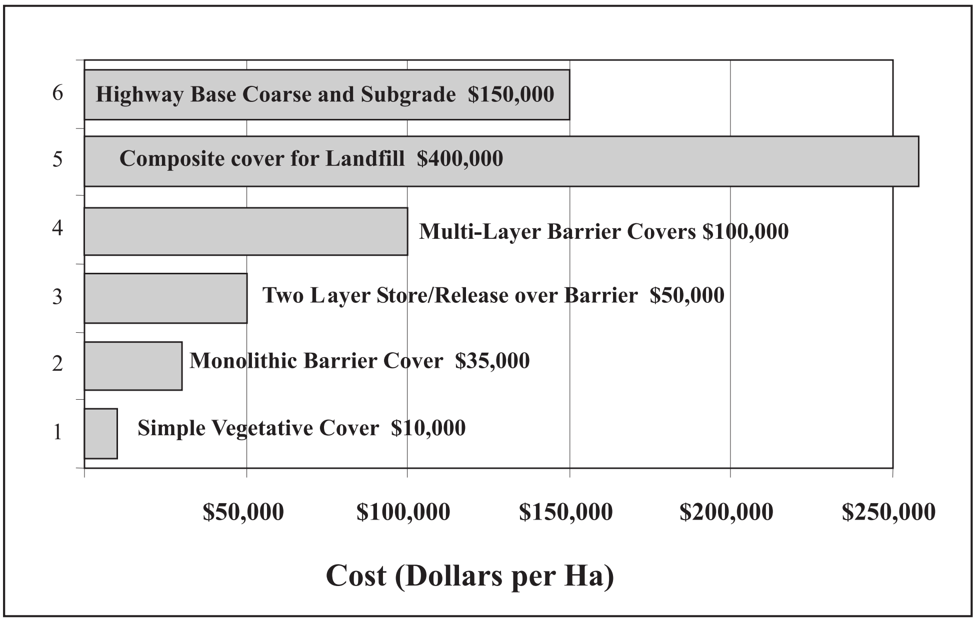

Figure 8: Indicative costs for cover construction. Dollar amounts are approximate for construction in Australia, Canada and the United States, in local currency.

constructed with compacted layers, storage layers, or capillary barriers, the cost usually rises to $100 000 per hectare (Aubertin, 2002). The cost for composite covers, with the inclusion of a geosynthetic clay liner (GCL) and internal drainage layers may rise even further to $400 000 per hectare (Benson, 2002b). Clearly, the value of any cover system must be addressed in terms of cost.

In general, compacted clay barrier-type covers are known to provide the poorest performance. At the same time, there is no reason to select this type of cover on the basis of cost. Compacted clay covers provide the poorest performance of all cover systems and thus are given a rank of low integrity versus high cost. Alternatively, the store/release covers, such as that constructed at the Kidston Gold Mine, have shown excellent performance over an extended period of time. Additional observation and experience of store/release cover systems in the arid and semi-arid regions of the United States have also shown excellent performance with respect to the reduction of water infiltration to values approaching zero. Store/release cover systems depend on the natural cycles within the active zone, hence long-term integrity for properly designed covers may be expected. Construction costs for store/release cover systems are reasonably low. Given the high performance and low cost, store release covers appear to provide good value.

The construction of barrier-type covers raises serious questions. There appears to be no proven precedent that conclusively demonstrates barrier-type cover systems can be relied upon to provide high performance; even when considered over relatively brief time scales. The primary difficulty with the construction of barrier-type covers is the thickness of the cover versus the depth of the active zone. In most cases, cover systems are constructed with a thickness less than 1500 mm and the depth of the active zone exceeds the thickness of the cover. Continuous cycles of environmental stress eventually lead to environmental fatigue of the barrier layers. It is believed the integrity of composite covers must be drawn into even greater scrutiny, given their high cost, relatively thin dimensions and the depth of the active zone. The only way to ensure that barrier-type covers will perform successfully over the long term is to place the barrier structures below the depth of active wet/dry/freeze/thaw cycles. In the case of most mine sites, this will require cover thicknesses of 2 m to 3 m or greater, hence, costs of more than $100 000 to $150 000 per hectare should be expected.

The selection of materials used for the construction of cover systems is paramount. Cover systems constructed with poorly graded, homogeneous soils are destined to fail. Well-graded soils with a broad grain size distribution of cobble, gravel, sand, silt and clay provide the best performance. The well graded glacial till material placed for the barrier-type cover system at the Equity Silver Mine has provided outstanding performance given its relative thickness and harsh climate. The total cover thickness for the Equity Silver cover system is only 800 mm. This cover system is constructed completely within the active zone and is subject to full depth freezing each winter. Even under these extreme conditions, values of hydraulic conductivity as low as 1×10^{-8} to 2×10^{-9} m/s have been measured after a period of a decade. The primary reason this cover system performs so well is that the well-graded, dense material undergoes minimal volume change with changes in water content. Given the relatively low cost of $35 000 per hectare, this cover system can be given a relatively high rank in terms of cost-effectiveness and integrity.

QA/QC has not been discussed in this paper. For the present discussion it is assumed the covers are constructed according to good standards with construction control. Obviously, poor construction techniques produce poor performance and failure.

A final comment should be considered in view of long-term cover integrity compared to pavement structures for highway construction. The design life of most pavement structures is ten to 15 years. In other words, reconstruction can be expected every one to two decades. A new breed of highway pavement design has recently been introduced. This new system is referred to as 'perpetual pavements'. The principal philosophy behind perpetual pavements is to maximise service life and reduce reconstruction costs. The design life for these high performance structures is in the order of 50 to 60 years. Figure 8 shows the cost of a high performance sub-grade and base structure for a highway system to be approximately $150 000 per hectare (typical cost for a standard 500 mm thick base and sub-base structure is in the range of $80 000 per hectare). The primary advantage of this high capital investment is that the serviceability of the roadway is not interrupted with frequent reconstruction. Only minimal maintenance in terms of replacing the surface concrete is required and the roadway can usually remain in service during maintenance. The greater initial cost can be justified with high service. In the case of cover systems, it generally appears that high performance does not correlate with high cost. Furthermore, it is apparent that high cost covers will not perform satisfactorily over the long term. The best value versus performance appears to be in the range of $40 000 to $50 000 per hectare. It is also concluded that high investment into high performance cover systems may not be warranted. Low cost cover systems may provide the best value, provided some of the savings are retained for long-term maintenance. ■

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