A Field-Scale Performance Evaluation of Erosion Control Measures for Slopes of Mine Tailings Dams

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ABSTRACT

Erosion is a serious problem at mine tailings disposal sites, particularly if the surface is left unprotected. Dust from the tailings dams can be harmful to human, animal, and plant life. Water erosion of the slopes of tailings dams is a considerable and costly maintenance and pollution problem. At present, erosion prevention and control in the short term is very often a process of trial and error and very little information exists on performance of erosion protection measures for long periods. The purpose of this study was to conduct a field-scale investigation into effectiveness of different erosion control measures. This involved creating erosion control panels on a typical slope of tailings dam with surface treatments ranging from simple vegetative techniques to fairly civil engineering erosion protection covers using fragments of rock. A series of measurement of erosion rates were made using measurement of sediment trapped in catchment paddocks and measurement by means of steel pegs to provide a quantitative basis for identifying effective and more economical erosion protection measures. Results of the erosion measurement have shown that erosion from the unprotected slope for the period of the experiment ranged from 257 to 316 tons/ha/year. These losses are alarmingly high and the surface loses its aesthetic appeal with time. On the other hand, any forms of vegetative and physical stabilization of the slopes can significantly reduce erosion of tailings and minimize environment problems at the tailings storage facility. The results of the field experiment have demonstrated that a protective treatment for slope surface takes a number of years to show its value. It has been shown that non-vegetative treatments such as fragments of rock are very effective in resisting erosive forces of nature, providing long-term stability and keeping maintenance to minimum.

Key words: Mine waste, tailings dams, erosion protection, rock fragments, vegetative techniques

INTRODUCTION

Mining and mineral processing result in generation of large quantities of waste such as overburden, waste rock, and tailings. These large volumes of mine waste are expensive to manage, and are frequently cited as an obstacle in the environmental sustainability of mining. Tailings are finely ground rock and mineral waste products of mineral processing operations. The tailings are usually mixed with water to form slurry which is then transported hydraulically into tailings ponds or dams.

Mine tailings are potentially subject to wind and water erosion, acid generation and the release of heavy metals. Dust generated from tailings dams on windy days can be a major problem especially where such dams are located near population centres (Fahey & Newson, 1997). Besides the visual impact of such dust clouds, there are also many potential public health and environmental problems associated with dust. Erosion of the slopes of tailings dams by rainwater runoff is a considerable and costly maintenance and pollution problem (Blight & Steffan, 1979). Cumulative and subsequent erosion down the slope of waste deposits results in gullies that can damage embankment and subsequently lead to instability of part of a slope (Bromhead, 1986). Gullies are also difficult to control and arrest and are not aesthetically pleasant, especially for unprotected slopes. The cost of repairing damages caused by erosion processes can be very high and of great concern to the mining industry.

A major environmental issue facing the mining industry is the rehabilitation options for tailings dams. Successful rehabilitation of mine waste deposits is a major problem, particularly in arid and semi-arid climates, and cannot be attained without substantial outlays of effort, money and innovative techniques (Stiller, Zimpfer & Bishop, 1980). Experience has shown that, of all the rehabilitation purposes, stabilising the impoundment against long-term wind and water erosion is often the most technically problematic and difficult to achieve (Vick, 1983). The need to prevent pollution, improve safety and the appearance of the environment has led to the use of various control and stabilisation techniques.

In South Africa, establishment of grass cover is by far the most common and usually the preferred stabilisation option for tailings impoundments. Vegetation not only serves to reduce wind and water erosion, it also stabilises slopes and results in improvement in the aesthetics of a tailings area. However, mine tailings are generally inhospitable medium for growth and are difficult to vegetate due to their characteristics such as the presence of acid and metals, deficiency in nutrients, lack of agglomerating material and extremes of moisture content (Gorber *et al*., 1978). In arid climates and for tailings having high concentrations of heavy metals or salts, establishment of vegetation may be a lengthy, difficult, and costly process.

It should be possible to identify potential rehabilitation options for a particular site well before the actual rehabilitation programme is implemented based on experience of long-term monitoring of alternatives and comparing their performance. This approach to rehabilitation assessment will provide more assurance that the rehabilitation programme will be successful. In this regard, a large-scale field experiment was designed and constructed to monitor the performance of various slope protection options.

RESEARCH METHODS

Experimental design

The experimental site was a south-facing slope with a slope angle of 16^o over the lower two-thirds of the slope length of 20 m and 28^o over the upper one-third. The slope was divided into 11 panels each measuring 20 m long (upslope) by 10 m wide. Each panel was separated from its neighbour by means of a 0.5 m metal sheet partly dug into the tailings surface to form a low vertical wall. The toe of each panel terminates in a catchment paddock to capture and hold solids removed from the slope by water erosion. Figure 1 shows a plan of part of the experiment.

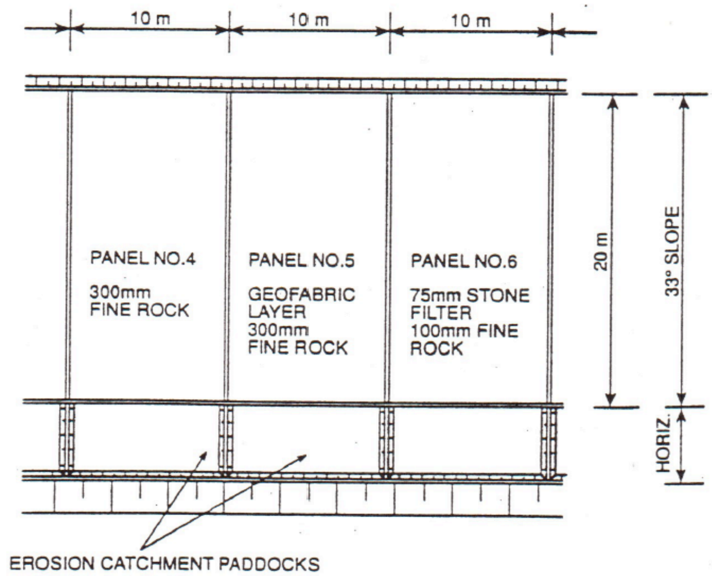

Figure 1 Part layout of erosion protection experiment

Design considerations of slope protection methods

The major design objectives were to utilise simple and low-cost control measures that prevent wind and water erosion, provide long-term stability, and require minimal maintenance to assure performance. A number of options identified for this experiment were rock armouring, revegetation and a combination of these two to take advantage of the benefits of each approach. These erosion protection methods range from very simple changes in vegetative methods to fairly civil engineering works. For any alternative surface treatment to be accepted, it will have to be demonstrated to have long-term durability.

Vegetation is by far the most common and usually the preferred stabilisation option for tailings impoundments. Vegetative stabilisation involves establishment of vegetation on top of a deposit, either by planting directly into the tailings material or by first covering the surface with a layer of top soil of suitable thickness. According to Blight (1989), where continuously maintained, fertilised and watered as needed, a good growth can establish. Physical stabilization involves covering the top and slopes of embankment of tailings dams with suitable thickness of soil, sand or broken waste rock or other restraining material to prevent and control erosion. The use of soil often has a dual advantage in that effective cover is obtained and a habitat is provided for local vegetation to encroach. Crushed rock for stabilisation purposes may be readily available at many mine sites in the form of mine waste or stripped overburden.

Cost estimation of erosion control options

The cost of erosion protection methods was determined only in terms of initial capital outlay without any maintenance cost component. This was to enable the most resilient surface treatment over the long-term without any maintenance to be determined. The cost components considered were: raw materials, direct labour and earthwork activities such as levelling and compacting. Raw materials (such as grass seed, rocks, soil fertiliser, and geofabric) are those materials that actually become part of the product which is the control measure. The cost of labour is the straight wages paid to the employees during construction of the control measure. Some of the surface treatments required levelling and compacting whilst others needed levelling only.

Erosion assessment of slope protection methods

Two methods were used for determination of erosion rates from the erosion protection panels. These were measurement of sediment trapped in catchment paddocks and measurement by means of steel pegs. Each panel was originally equipped with a sprinkler irrigation system to simulate rain, 3 rain gauges and a set of 10 surface pegs. Simulated rain was used to obtain initial results and for the next five years the slopes were exposed to natural weather. It should be noted that the erosion rates were measured differently for phases I to 2 and 3 to 5 of the experiment.

Phase 1 involved a five-week period of simulated rain during the dry winter season of the first year of the experiment. The sprinkling periods were carefully controlled by observation of the rain gauges, thereby ensuring an equal distribution of simulated rain on each of the panels. At the end of the five-week period, all eroded material captured in the catchment paddocks was extracted and weighed. Phase 2 comprised of measurements taken for two wet seasons. At the end of each wet season all eroded material accumulated in the catchment paddocks was measured by determining the in situ volume and unit weight of the captured material.

During phase 3 (cumulative erosion for 4 wet seasons), an unusually heavy rainstorm caused tailings to be washed onto the test slopes from above, thus rendering the origin of the mass of caught material questionable (Blight & Amponsah-Dacosta, 1999a). For this reason, erosion for phases 3 to 5 was assessed by measuring the retreat of the slope surface against the surface level pins. According to Toy (1983), this erosion pin technique is the most extensively used erosion measurement technique. It is also a more reliable method of measurement of soil losses from constructed slopes and gives an indication of the distribution of the soil loss from the slope. From the average measured surface retreat on the selected slopes and measured dry density of the material of the slope surface, the annual rate of erosion in tons/ha was determined. It should be noted that phase 4 and phase 5 represent cumulative erosion for 6 wet seasons and 8 wet seasons respectively.

Cost-effective evaluation of erosion control alternatives

The erosion control measures were assessed in terms of cost and likely effectiveness. This assessment is based on combination of considerations, including reported experience gained and relevant work undertaken by the contractors.

RESULTS AND DISCUSSION

Table 1 records the type of surface protection and its relative cost, actual erosion rates in tons/ha/year, relative erosion rates and a cost effectiveness number represented by the product of relative cost (C) and relative erosion rate (E). The most cost-effective treatment would be the one with the least value of the cost-effective number.

Table 1 Cost-effectiveness evaluation of slope protection methods

Panel Number	Treatment	Level & compact	Level only	Relative Cost/ha C %	Erosion Rate (tons/ha/year)			
					Phase 2	Phase 3	Phase 4	Phase 5
1	Conventional grassing	√	—	100	164	164	164	192
2	100 mm ballast (50 mm size)	√	—	67	105	32	35	23
3	300 mm coarse rock	√	—	62	170	12	23	23
4	300 mm fine rock	√	—	62	38	96	70	63
5	Geofabric + 300 mm fine rock	√	—	120	22	15	70	65
6	75 mm of 6mm stone + 100 mm fine rock	√	—	66	42	82	61	69
7	300 mm fine rock	—	√	54	118	75	67	53
8	250 mm open pit overburden	—	√	64	203	161	175	175
9	250 mm soil + Ag Lime +grass sods	—	√	120	19	72	78	74
10	100 mm soil + Ag Lime +grass sods	—	√	96	21	15	36	10
11	Zero control (no treatment)	—	—	0	276	257	316	261

Table 2 Cost-effectiveness evaluation of slope protection methods (continued)

Panel No.	Relative Erosion Rate E (%)				Cost-Effectiveness C X E (%)				Cost-Effectiveness Ranking			
	Phase 2	Phase 3	Phase 4	Phase 5	Phase 2	Phase 3	Phase 4	Phase 5	Phase 2	Phase 3	Phase 4	Phase 5
1	59	64	52	72	59	64	52	72	10	10	10	10
2	38	12	11	9	25	8	7	6	7	4	2	2
3	62	5	7	9	38	3	5	6	8	1	1	2
4	14	37	22	24	9	23	14	15	3	7	6	5
5	8	6	22	25	10	7	27	30	4	3	7	7
6	15	32	19	26	10	21	13	17	4	6	5	6
7	43	29	21	20	23	16	11	11	6	5	3	4
8	74	63	55	67	47	40	35	43	9	9	9	9
9	7	28	25	28	8	34	30	34	2	8	8	8
10	8	6	11	4	7	6	11	4	1	2	3	1
11	100	100	100	100	0	0	0	0	11	11	11	11

Rates of erosion from unprotected slopes of tailings dams can be frighteningly large. Erosion from the unprotected slope for the period of the experiment ranged from 257 to 316 tons/ha/year. According to COMSA (1996), losses of tailings from unprotected gold tailings dams in South Africa of over 500 tons/ha/year are quite common. Blight & Amponsah-Dacosta (1999b) have also recorded erosion exceeding 1000 tons/ha/year on some unprotected slopes of tailings dams in South Africa. Results of the erosion measurement also shows that protecting the slope, by armouring it with crushed rock or covering it with vegetation, increases the surface shear strength and this helps to reduce erosion considerably by dissipating the energy of the erosive forces of wind and water.

On the basis of cost-effectiveness for phase 2, conventional grassing ranks just above no treatment at all and a soil layer covered with grass sods (Panel 10) rated top. However, the grass sods have visibly deteriorated with time and most of the grass has now died. Only the presence of the grass roots has maintained the effectiveness of the treatment. Although establishment of grass cover is the most common means of stabilising tailings disposal sites in South Africa, there are several situations where vegetation is relatively or completely ineffective in protecting a slope from erosion. An important factor, which must be considered in any vegetation programme, is the related equipment necessary to neutralise, fertilise and seed the tailings. According to Gober et al. (1978), the finer fractions of the tailings when wet, is not capable for supporting the heavy equipment normally used for these purposes, and special techniques are required to vegetate these areas. Blight (1989) has also pointed out that grassing does reduce wind erosion but has much less effect on water erosion.

On panel 9, which has a thicker soil layer, and was expected to perform better than Panel 10, the grass has died and the panel rating has dropped from 2 to 8. The conditions of the surface of the various panels after six years are shown in Figures 2 to 4.

Figure 2 Devastating effect of erosion on unprotected slope (Panel 11)

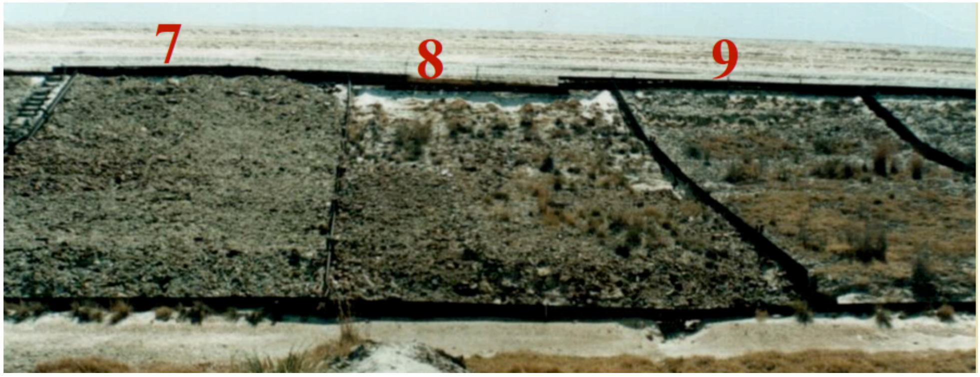

Figure 3 Slope protection panels 7 – 8

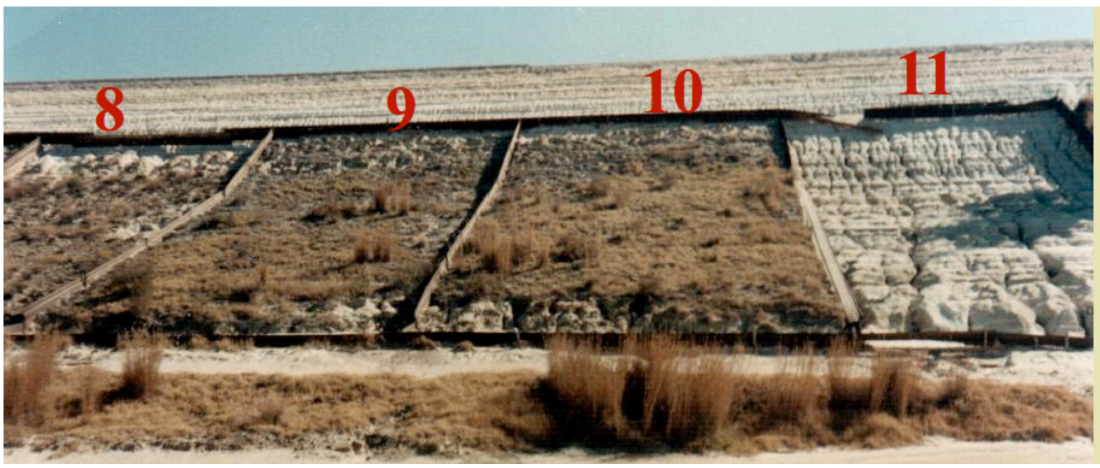

Figure 4 Slope protection panels 8 – 11

It is observed that unprotected panel shown in Figure 2 is highly eroded compared to the other panels which have some form of surface cover. Thus, physical roughness in the form of vegetation and crushed rock play an extremely important role in controlling erosion. Bare slopes of tailings dams experience accelerated erosion whilst any measure that provides cover significantly retards tailings loss and minimise erosion. These qualitative results reinforces the results of the quantitative erosion assessment by repeated measurements of surface elevation using pins driven into the slope surface as reference points and by sediment collection from paddocks that surface cover plays an extremely important role in controlling erosion from slopes of tailings dams.

Table 1 shows that non-vegetative treatments occupy 6 of the first 9 places in the ranking, and should therefore be seriously considered for use in future. The presence of riprap, coarse fragments of rock, on the tailings surface act as mulch. The size and mass of the riprap material absorbs the impact energy of rain drops, while the gaps between the riprap traps and slows the flow of water, lessening its ability to erode the tailings. Rock mulches significantly reduce erosion potential when a large percentage of the tailings surface is covered but this can be an expensive undertaking. The effectiveness of riprap to stabilise soil against erosion is evidenced in nature by the development of a desert pavement, a surface layer of pebbles that forms an effective erosion-resistant surface for long periods of time (Vick, 1983).

This experiment has demonstrated that a protective treatment for a slope surface takes a number of years to show its true value. According to Waugh & Richardson (1995), when earthen materials are placed in an environment that is not harmonious with the surrounding system, rapid changes in characteristics of the placed material occurs as nature begins to bring the entire system into equilibrium. This point is further illustrated by Figure 5 which shows how the performance of six of the panels has changed with time, with the performance of some remaining relatively static, some improving and others deteriorating with time. It should be noted that season 1 represents application of irrigation and 100% corresponds to erosion of unprotected panel.

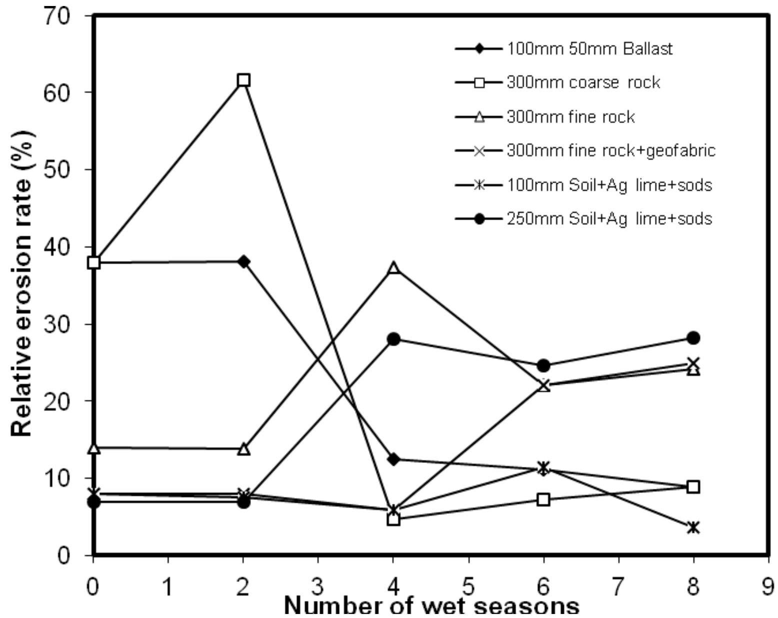

Figure 5 Variation of erosion rate with time (in wet seasons)

The successful long-term stabilization of mine tailings dams is a difficult and complicated process. Erosion prevention and control measures selected must be based on a thorough understanding of the characteristics of the tailings, site-specific properties, how they will react to various treatments, and how the erosion protection covers will change with time. The fundamental principle currently used associates erosion control of tailings dams with revegetation. However, erosion control of tailings dams by means of grassing or revegetation alone has indeed proved challenging to the mining industry. The actual amount of vegetation cover required for adequate erosion protection depends on several factors, including the amount and intensity of rainfall, length and angle of the slope to be stabilized, and erodibility of the tailings material.

This field experiment has shown that rock fragments over slopes of tailings dams are very effective in resisting erosive forces of wind and water. Tailings covers designed with crushed rock, gravel/cobble mixtures, or riprap have several advantages over vegetative covers. Large particle sizes are more resistive to movement by water and wind and have higher shear strengths compared with the smaller soil particles required for revegetation. However, the rock to be used for erosion protection should be geochemically analysed to ensure that it does not cause environmental pollution and evaluated to determine its suitability for providing the necessary long-term erosion protection.

CONCLUSION

Tailings and other mine residues are potentially subject to wind and water erosion. Unprotected surfaces of tailings dams offer little or no resistance to erosive forces and therefore experience accelerated erosion with time. Slope surfaces without cover are aesthetically unpleasant. From mechanics of the detachment and transport of tailings by rainsplash, runoff and wind, it follows that the best way to minimise the potential adverse effect of tailings erosion on the surrounding environment and hasten the restoration of the area is to cover the surfaces of the tailings dams to protect it from raindrop impact and increase surface roughness to reduce the velocity of the runoff and the near-surface velocity wind.

The need to prevent pollution, improve safety and the appearance of the environment has led to the use of various control and stabilisation techniques. Observation of the various erosion protection panels indicates that nature is attempting to alter some panels in the short time they have been in existence. Some of the panels intended to protect tailings for long time periods experienced severe deterioration over only six years of the cover performance monitoring. Nevertheless, the experiment has enabled continual performance data to be compiled.

It is evident from the results that cost-effective slope protection can be achieved using non-vegetative methods. The rock fragments have potential field applications to mitigate erosion on tailings dams for longer-term period. However, guidelines need to be developed for system design and potential applications, taking into consideration the size of the fragments, the thickness of the cover and the durability of the material. Research to determine the optimum percentage of materials such as boulders, cobbles, gravels, and coarse sands for erosion resistance for a given slope gradient and length also need to be conducted.

REFERENCES

Blight, G. E. (1989) Erosion losses from the surfaces of gold tailings dams, Journal of South African Inst. Mining and Metallurgy, 89 (1), 23 - 29.

Blight, G. E. and Amponsah-Dacosta, F. (1999a) In search of the 1000 year tailings dam slope, Civil Engineering, Oct. 1999.

Blight, G. E. and Amponsah-Dacosta, F. (1999b) Improving the erosional stability of tailings dam slopes, Tailings and Mine Waste '99, 6th International Conference on Tailings and Mine Waste, Balkema, Fort Collins, Co. USA, 197 – 206.

Blight, G. E. and Steffen, K. H. (1979) Geotechnics of gold mining waste disposal, in Current Practice in Mine Waste Disposal, Committee on Embankment Dams and Slope of the Geotechnical Engineering Division, ASCE, New York, pp. 1- 52.

Bromhead, E. N. (1986) The Stability of Slopes, Blackie & Sons/Surrey University Press, London.

COMSA (1996) The Design, Operation and Closure of Metalliferous and Coal Residue Deposits, Handbook of Guidelines for Environmental Protection, Vol.1., Chamber of Mines of South Africa.

Fahey, M. and Newson, T. A. (1997) Aspects of the geotechnics of mining wastes and tailings dams, in Proceedings of the 1st Australia-New Zealand Conference on Environmental Geotechnics – GeoEnvironment 97, Bouazza, A., Kodikara, J. and Parker, R. (eds.), Melbourne/Victoria, Australia, 26 – 28 November, pp. 115 - 134.

Gorber, D. M., Ibbotson, B. G. and Knapp, R. A. (1978) Trends in uranium mining waste management, in Proceedings of the International Symposium on Waste Treatment and Utilisation, University of Waterloo, Waterloo, Ontario, Canada, July 5 – 7.

Stiller, D. M., Zimpfer, G. L. and Bishop, M. (1980) Application of geomorphic principles to surface mine reclamation in the semiarid West, Journal of Soil and Water Conservation, Nov./Dec., pp. 274 - 277.

Toy, T. J. (1983) A linear erosion/elevation measuring instrument (LEMI), Earth Surface Processes and Landforms, 8, 313 – 322.

Vick, S. G. (1983) Planning, Design, and Analysis of Tailings Dams, John Wiley & Sons Inc., New York, USA.

Waugh, W. J., and Richardson, G. N. (1995) Ecology, design, and long-term performance of waste-site covers: Applications at a uranium mill tailings site, in Proceedings of National Academy of Sciences Workshop on Barriers for Long-Term isolation, 13 Aug. 1995, Denver, Colorado.