Revegetation research on hard rock mining disturbances in north-central Montana
by Michael Jerome Spry

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Rehabilitation
Montana State University

Abstract:

Hard rock mining developments in Montana are subject to regulation under the 1972 Montana Metal Mine Reclamation Act. Many mine operators are unfamiliar with revegetation techniques and are unable to develop reclamation plans, as required by the Act. The purpose of this study was to develop revegetation techniques for hard rock mining disturbances near Zortman, Montana. The disturbances included a waste rock dump, abandoned tailings, and a clay pit. Environmental conditions at these sites were characterized using physicochemical analyses of surface materials, soil water monitoring, and water retention analyses. Research plots were established at each site to study seeded and transplanted species. Germination percentage was measured to evaluate establishment of seeded species.

Results of site characterizations indicated low water availability was the main limiting factor at all sites. The effect of low water availability on seedling establishment and growth was evident during the 1984 growing season. Plant performance was poor at the clay pit and tailings site. At the waste rock dump, however, seeded species remained healthy and produced some growth, in spite of severe drought. These results indicate that successful revegetation of the clay pit and abandoned tailings will require enhanced water availability and surface stabilization. Further research is needed on these sites and on the waste rock dump to identify appropriate seed and fertilizer rates, timing, and seeding methods, so that plant establishment is maximized.

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A thesis submitted in partial fulfillment
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APPROVAL

of a thesis submitted by

Michael Jerome Spry

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citation, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Hard rock mining developments in Montana are subject to regulation under the 1972 Montana Metal Mine Reclamation Act. Many mine operators are unfamiliar with revegetation techniques and are unable to develop reclamation plans, as required by the Act. The purpose of this study was to develop revegetation techniques for hard rock mining disturbances near Zortman, Montana. The disturbances included a waste rock dump, abandoned tailings, and a clay pit. Environmental conditions at these sites were characterized using physicochemical analyses of surface materials, soil water monitoring, and water retention analyses. Research plots were established at each site to study seeded and transplanted species. Germination percentage was measured to evaluate establishment of seeded species.

Results of site characterizations indicated low water availability was the main limiting factor at all sites. The effect of low water availability on seedling establishment and growth was evident during the 1984 growing season. Plant performance was poor at the clay pit and tailings site. At the waste rock dump, however, seeded species remained healthy and produced some growth, in spite of severe drought. These results indicate that successful revegetation of the clay pit and abandoned tailings will require enhanced water availability and surface stabilization. Further research is needed on these sites and on the waste rock dump to identify appropriate seed and fertilizer rates, timing, and seeding methods, so that plant establishment is maximized.

INTRODUCTION

Increases in precious metal prices over the past decade have resulted in new hard rock mining developments throughout Montana. These developments are subject to regulation under the Montana Metal Mine Reclamation Act of 1972, which mandates the reclamation of hard rock disturbances. In order to comply with the provisions of the Act, hard rock mine operators must submit a reclamation plan which defines the proposed post-mine land use and describes the type of vegetation cover to be established.

Because mine operators are often unfamiliar with revegetation methods, they are unable to develop a reclamation program that satisfies the requirements of the Act. This problem has come to the attention of the Montana Department of State Lands (DSL), which administers the Act. In order to ensure that hard rock disturbances are reclaimed to the extent required by the Act, the DSL, in cooperation with mine operators, is sponsoring research on the revegetation of hard rock disturbances. This research will be used to develop recommendations for mine operators who are attempting to reclaim hard rock disturbances throughout Montana.

The purpose of this study was to develop revegetation techniques for disturbances associated with a large open-pit gold and silver mine near the town of Zortman, Montana. Disturbances at this mine include waste rock dumps, leach pads, abandoned tailings, and clay pits. In order to develop revegetation techniques for these disturbances, representative sites were chosen for study. Unfortunately, this study did not include a leach pad site because all leach pads were active when the research was initiated. Therefore, recommendations for leach pad revegetation are not included here.

The objectives of this study were to: (1) characterize environmental conditions at each site, including physical and chemical properties of the root zone materials, (2) identify environmental factors which limit revegetation potential, (3) demonstrate revegetation techniques using trial plots, and (4) develop recommendations for the revegetation of the disturbances, based upon site characterizations and the results of revegetation trials.

LITERATURE REVIEW

Revegetation of Hard Rock Mining Disturbances

Most research on the revegetation of hard rock disturbances has involved alpine environments. Brown and others have intensively studied the revegetation of alpine mine disturbances on the Beartooth Plateau in southern Montana (Brown et al., 1976; Brown and Johnston, 1976, 1978, 1980; Brown et al., 1984). Alpine revegetation research has also been conducted on molybdenum mines in Colorado (Brown, 1974; Guillaume, 1980; Jackson, 1982).

Results of this research indicate that native species are better suited for alpine revegetation than are introduced species. Although introduced species may establish rapidly (Richardson, 1980), native species are adapted to harsh climatic conditions and provide a stable plant community (Brown et al., 1976).

Successful alpine revegetation may require amendment of mine spoils, including the addition of lime, fertilizer, organic matter, or surface mulch (Brown and Johnston, 1978). Liming of acidic spoils reduces heavy metal toxicity and enhances the availability of some nutrients (Johnston et al., 1975). Fertilizer application overcomes inherent nutrient deficiencies and stimulates organic matter production (Richardson, 1980). Direct addition of organic matter, such as manure, improves water holding capacity, aeration, and nutrient availability (Brown et al., 1976). Finally, surface mulches can be used to enhance plant establishment. Mulches improve infiltration, hold seed in place, retain water for plant uptake, and ameliorate surface temperatures (Kay, 1978).

In addition to amendments, coversoil has been considered for use on hard rock spoils. Parady (1981) assessed the suitability of alluvial overburden for use as a coversoil on acidic waste dumps. Use of the alluvium required amendment with organic matter to reduce crusting. Lawson (1984) reported better establishment of three grass species on the alluvium amended with manure than amendment with hay mulch or fertilizer. Both studies were conducted at the Berkeley Pit Complex near Butte, Montana, where alluvial overburden is relatively abundant. Use of coversoil has received little attention elsewhere because suitable topsoil or overburden is scarce near hard rock mines, especially in alpine environments (Brown et al., 1976).

Revegetation of Mill Tailings

Mill tailings are a common disturbance associated with hard rock mining. Revegetation of these materials poses unique problems because of severe environmental conditions. Factors which hinder revegetation efforts include high salinity, heavy metal toxicity, acidification, and nutrient deficiencies (Nielson and Peterson, 1978). Vegetation on tailings also is subject to desiccation and scouring by wind (Deckler, 1982). Water stress which results from desiccation is exacerbated by low available water holding capacity of most tailings. Moreover, plants may be subject to excessive solar radiation because of high reflectivity of tailings surfaces (Dean et al., 1973).

Some of these limiting factors have been addressed in revegetation attempts. Nielson and Peterson (1978), who worked with tailings produced by copper smelting operations, leached the tailings to remove salts. This treatment and fertilizer applications resulted in high establishment and survival rates for *Agropyron elongatum, Medicago sativa,* and *Melilotus officinalis.* Dean et al. (1973) demonstrated two methods for desalinization of copper tailings in Utah. One method involved the stratification of sand and "slime" layers to reduce upward migration of salts. For the second method, mounds of tailings were oriented in an east-west direction to reduce evaporation and upward salt migration on north-facing sides. Both methods reduced salinity; vegetation was healthier and more dense on north-facing slopes and on stratified tailings than on unaltered tailings.

In addition to desalinization, successful tailings reclamation may require surface stabilization to reduce wind erosion, seed loss, and scouring of seedlings (Deckler, 1982). Nielson and Peterson (1978) recommended the use of chemical soil binders or plant residue mulches to reduce wind erosion. Dean et al. (1973) demonstrated the use of asphalt and synthetic polymers to agglomerate tailings particles. Compost and sewage sludge also were used to improve aggregation and reduce erosion. They concluded that revegetation, aided by application of a chemical or organic stabilizer, would assure long-term stabilization of tailings.

Minesoils with High Rock Fragment Content

Rock fragments in mineoils often are considered to inhibit revegetation. Inhibitory characteristics include excessive drainage, instability on steep slopes, and heat injury to vegetation (Down, 1975). However, the presence of rock fragments can benefit revegetation. High rock fragment content concentrates soil water in the <2 mm fraction, which makes water more available for plant uptake. Plants compensate for the reduced amount of soil by extending roots vertically and horizontally around fragments (Ashby et al., 1984).

Rock fragments can be especially beneficial to tree establishment. Successful establishment of *Pinus resinosa* has been reported on Pennsylvania coal mine spoils containing 60 to 80% coarse fragments (Aharrah and Hartman, 1973). Kolar et al. (1981), who studied tree establishment in Illinois mine spoils, reported that growth of deciduous species on coarse spoils was nearly double the growth on topsoiled spoils and on undisturbed silt loam.

Tree establishment on coarse minesoils in the Northern Great Plains is less documented. Stark (1982) investigated establishment of *Pinus ponderosa* on surface-mined lands in southeastern Montana. Stark suggested that *Pinus ponderosa* establishment can be enhanced by constructing minesoils with large rock fragments on the surface. These fragments would simulate natural rocky outcrops where *Pinus ponderosa* thrives.

According to Stark (1982), surface rock fragments enhance water availability to trees by a "distillation-condensation" process. The rocks conduct heat into the soil during the day, which vaporizes soil water. At night, the vapor moves toward the surface where it condenses under cooling rocks. Although this process may enhance tree establishment, successful establishment using surface rock fragments has not been documented in the Northern Great Plains.

Other research in the Northern Great Plains has involved shrub establishment on coarse materials. In 1971, twelve shrub species and two tree species were seeded on scoria fill in southeastern Montana (Hodder and Sindelar, 1972; Dollhopf and Majerus, 1975). After four years, density measurements revealed that only *Atriplex canescens, Sarcobatus vermiculatus,* and *Artemisia nova* survived in moderate to high numbers (DePuit and Dollhopf, 1978). Poor performance of several species native to scoria outcrops could not be explained. DePuit and Dollhopf concluded that interspecific site requirements required further study.

Stabilization and Revegetation of Steep Waste Dumps

Stabilization and revegetation of steep waste dumps are difficult because dump slopes often are characterized by severe erosion and mass instability. Erosion and mass movement occur because traditional dump construction consists of dumping spoils downslope and allowing gravity to sort the materials. Dumping results in stratification of materials, with smaller rock fragments and the <2 mm fraction overlying larger rock fragments. This stratification promotes slippage between disparate fragment sizes and along the base of the dump where water accumulates. Erosion occurs because dump surfaces mainly consist of the <2 mm fraction, which is readily displaced by runoff on steep slopes (Riddle and Saperstein, 1978).

The head-of-hollow or valley fill is an alternative dump construction method which may reduce erosion and instability. This method involves placement of spoil in lifts which are constructed from the bottom of the drainage toward the top. Head-of-hollow fills are more stable than traditional dumps because the lifts are not stratified. The fills also are constructed with drains, which reduce erosion and water accumulation. Thus, by controlling erosion and instability, the head-of-hollow fill method creates a stable environment for revegetation (Ramani and Grim, 1978).

Use of the head-of-hollow fill has been successfully demonstrated at phosphate mines in Idaho (Farmer and Richardson, 1980). These dumps are constructed on steep mountain slopes and graded to conform to the original topography. Grading and shaping enhance surface stability and allow safe operation of reclamation equipment (Farmer and Blue, 1978).

After grading, the phosphate dumps are sometimes covered with topsoil, subsoil, or shale parent materials. The dumps are ripped and harrowed to improve the seedbed. Heavy fertilizer applications are used to promote biomass production which provides soil organic matter (Farmer and Blue, 1978). These procedures have yielded highly productive stands of native and introduced species on the dumps (Farmer and Richardson, 1980).

Effects of Water Stress on Germination and Seedling Growth

Germination

Germination of grass species is inhibited with decreasing matric potential. McGinnies (1960) reported that germination of six grass species was significantly reduced at potentials between -7.5 and -15 bar. Germination of *Agropyron smithii* may be inhibited below -7 bar (Bokhari et al., 1975). Knipe (1973) reported reduced germination of the same species at -1 bar. Germination of some warm season grasses may be reduced at potentials below -0.3 bar (Knipe and Herbel, 1960).

Germination is delayed or inhibited by water stress because seeds are unable to imbibe sufficient water. Imbibition is slowed with decreasing potential. As the soil dries, the potential gradient steepens at the seed-soil interface (Currie, 1973). Eventually, the potential gradient may be too steep to allow imbibition to continue, so that germination is inhibited.

Large seeds may be more susceptible to water stress than small seeds. Large seeds have more surface exposed to the air than in contact with water. As the soil dries, large seeds may evaporate more water than they can take up (Harper and Benton, 1966). In contrast, small seeds have a larger wetted surface to total surface area ratio; they are less affected by drying and may germinate at higher rates in dry soil than do large seeds.

The effect of water stress also may vary with seed position in the soil. Nelson et al. (1970) reported significantly lower germination of six *Agropyron* species on broadcast plots than on drill-seeded plots. Broadcast plots had lower germination because rapid drying reduced soil water content and potential at the surface (Wilson et al., 1970).

Seedling Growth

Water stress slows or suspends growth of grass seedlings. Initial effects of water stress are reduced shoot and root growth because of reduced turgor pressure (Brown, 1977). Eddleman and Nimlos (1972) reported shoot growth cessation in *Agropyron smithii* seedlings when matric potentials reached -30 bar at 4 to 12 cm depth. Root growth ceased at -7.5 bar at the same depth. Leaf growth cessation has also been observed in *Agropyron inerme*; growth cessation in this species may be associated with photosynthetic dormancy (DePuit and Caldwell, 1975).

MATERIALS AND METHODS

Experimental Design and Statistical Analyses

Revegetation research plots were constructed on a waste rock dump, abandoned tailings, and a clay pit. At the waste rock dump, nine blocks were placed in three rows on two adjacent benches. Each block consisted of six 1 m^2 plots for six seeded species. Blocks were not randomized; an order of species was established for each row of three blocks and repeated three times. Plot configurations are depicted in Figure 1.

The same numbers of blocks and plots were used at the tailings site. Blocks at this site were placed close together in an area of uniform tailings depth. Blocks were arranged in three groups; each group consisted of two blocks placed in parallel and a third block placed downslope. An order of species was established and repeated three times in each group of three blocks. Plot configurations are depicted in Figure 2.

At the clay pit, three blocks were constructed at three locations which differed in slope and aspect. Each block consisted of three replicate 1 m^2 plots for each of four species. An order of species was established and repeated three times in each block. Plot configurations are depicted in Figure 3.

The species seeded in the research plots are listed in Table 1. All the species, except *Pinus contorta*, are adapted to semi-arid environments and are commonly used in the reclamation of mine disturbances in the Northern Great Plains. Seeding rates used in this study were based on rates commonly used in mineland reclamation.

All species were broadcast seeded at all sites in late October 1983, except for *Agropyron spicatum*, which was seeded at the waste rock dump in early May and at the tailings

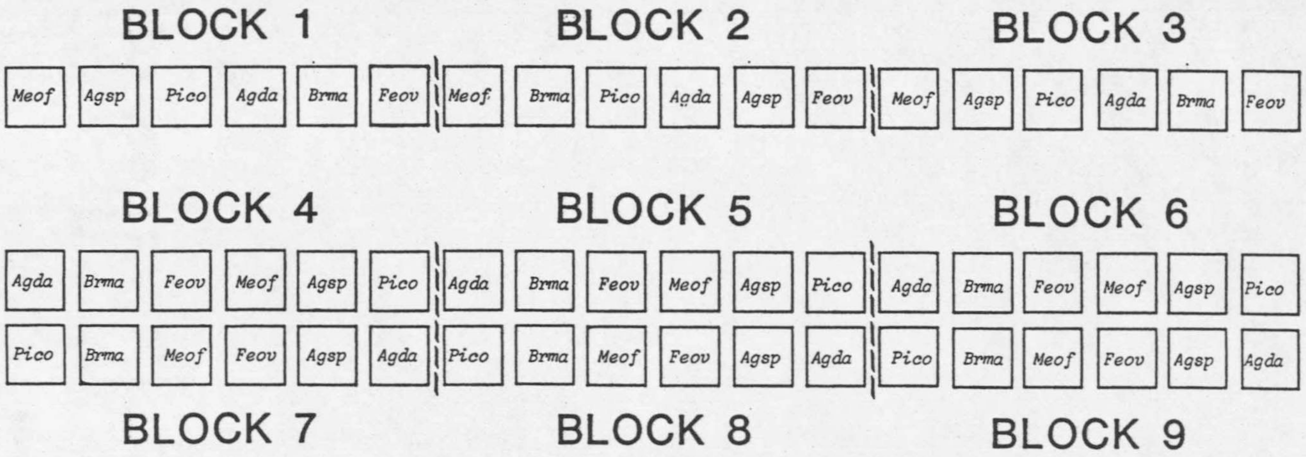

Figure 1. Plot configuration used at the waste rock dump.
(Agda: *Agropyron dasytachyum,* Agsp: *Agropyron spicatum,* Brma: *Bromus marginatus,* Feov: *Festuca ovina,* Meof: *Melilotus officinalis,* Pico: *Pinus contorta*).

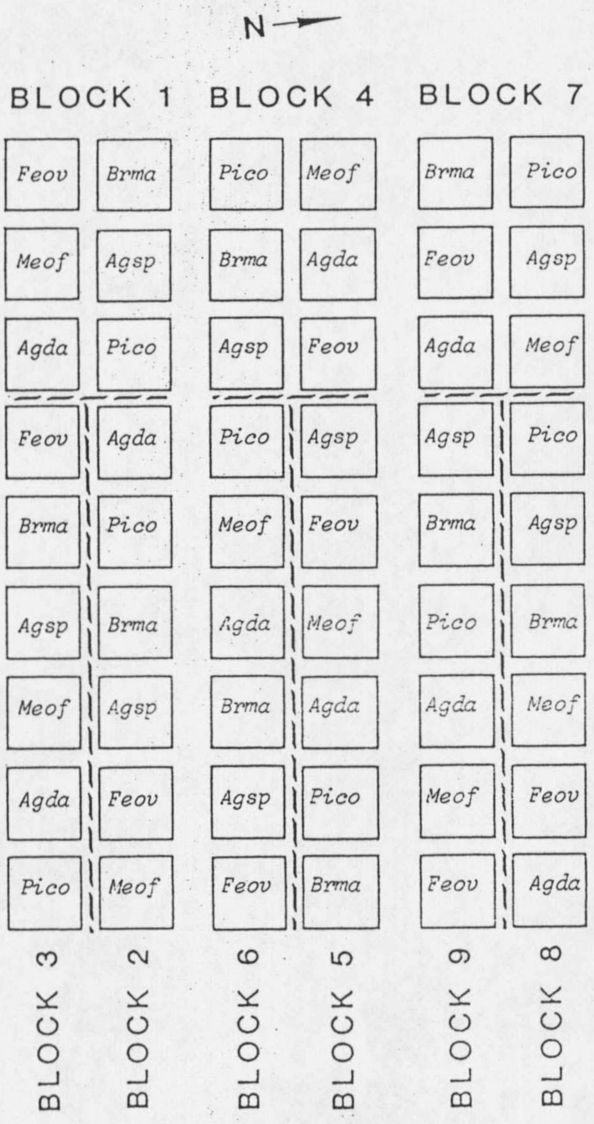

Figure 2. Plot configuration used at the tailings site.
(Agda: *Agropyron dasystachyum*, Agsp: *Agropyron spicatum*, Brma: *Bromus marginatus*, Feov: *Festuca ovina*, Meof: *Melilotus officanalis*, Pico: *Pinus contorta*)

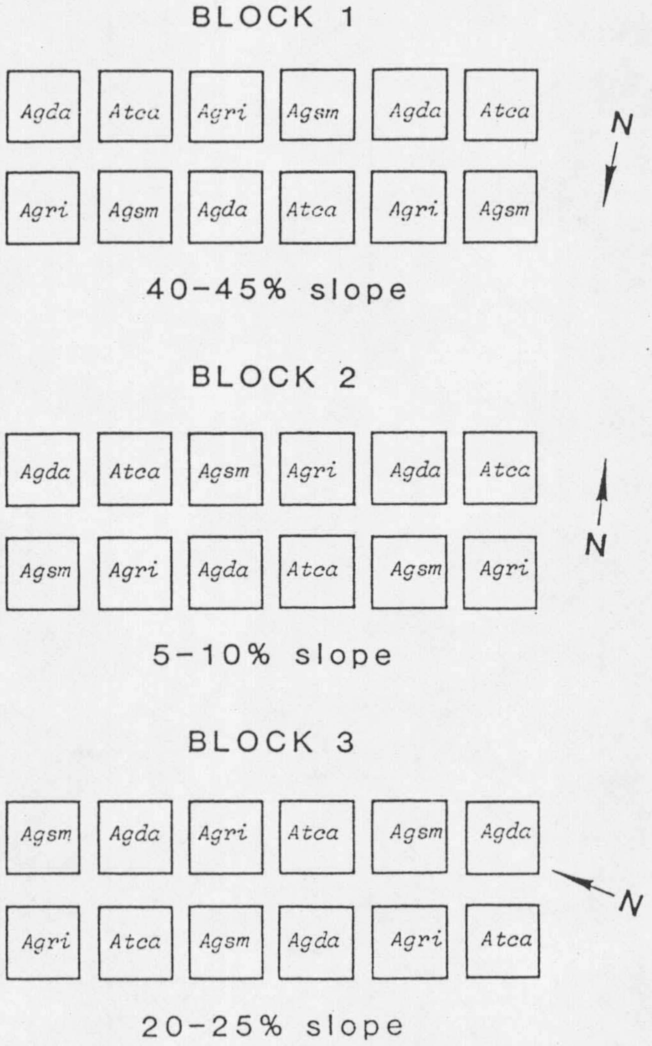

Figure 3. Plot configuration used at the clay pit.
(Agda: *Agropyron dasystachyum,* Agri: *Agropyron riparium,* Agsm: *Agropyron smithii,* Atca: *Atriplex canescens*)

Table 1. Species List and Seeding Rates Used on Revegetation Research Plots.

Species	PLS/m² *	kg/ha
Waste Rock and Tailings Sites		
Agropyron dasystachyum (Hook.) Scribn.** 'Critana' thickspike wheatgrass	430	15.0
Agropyron spicatum (Pursh.) Scribn. and Smith 'Secar' bluebunch wheatgrass	430	15.6
Bromus marginatus Nees. 'Bromar' mountain brome	160	15.0
Festuca ovina L. 'Covar' sheep fescue	430	11.0
Melilotus officinalis (L.) Lam. yellow sweetclover	215	12.0
Pinus contorta Dougl.*** lodgepole pine	10	1.1
Clay Pit		
Agropyron dasystachyum	430	15.0
Agropyron riparium Scribn. and Smith 'Sodar' streambank wheatgrass	430	15.0
Agropyron smithii Rydb. 'Rosana' western wheatgrass	430	22.0
Atriplex canescens (Pursh.) Nutt. fourwing saltbush	100	10.0

*Pure live seeds/m².

**Scientific names taken from Hitchcock and Cronquist (1973).

***Locally collected.

site in early June 1984. Seeding of *Agropyron spicatum* was delayed because seed was not available in October 1983.

The research plots were fertilized to enhance initial vegetation establishment. Diammonium phosphate (18-46-0) fertilizer was applied at a rate of 112 kg/ha. The fertilizer was broadcast on the plots at the waste rock dump and clay pit in May 1984 and at the tailings site in June 1984.

In addition to seeding of species, the study included transplanting native trees and shrubs. Ten *Pinus contorta* Dougl. and ten *Pinus ponderosa* Dougl. seedlings were transplanted on the waste rock dump in May 1983. At the clay pit, ten *Symphoricarpos occidentalis* Hook. and ten *Juniperus horizontalis* L. plants were transplanted around block 1 in October 1983. All transplants were taken from adjacent undisturbed areas. Survival of trees and shrubs was monitored during the course of the study.

Establishment of seeded species was evaluated by germination percentage. Measurement consisted of live and dead seedling counts in a .25 m^2 frame. Two counts were taken on each 1 m^2 plot, averaged, and multiplied by four to obtain seedling density in the whole plot. Seedling density was divided by seed rate (seeds/m^2) to obtain a germination percentage for each plot. Although no additional vegetation measurements were taken, overall growth and survival were monitored during the growing season.

Statistical analyses of germination data included analysis of variance (ANOV) and calculation of least significant differences (LSD) among overall mean germination percentages of blocks and species. All statistical analyses were performed using MSUSTAT statistical package (Lund, 1983). Statistical analyses did not include germination data for *Melilotus officinalis* or *Pinus contorta*.

Sampling and Analysis of Surface Materials

The waste rock, tailings, and clay were sampled and analyzed to identify factors which limit revegetation potential. These materials were sampled in May and October 1983. Samples weighing approximately 200 g were taken at two depth increments: 0 to 5 cm and 15 to 30 cm. The surface (0 to 5 cm) samples were taken to characterize the soil environment of germinating seeds and young seedlings. The subsurface samples were taken to characterize the materials in the zone of primary root activity. Two surface and subsurface samples were taken at each of three block locations at the clay pit. At the waste rock dump, a surface and subsurface sample were taken from each of three waste rock types:

porphyry, gneiss, and mixed porphyry and gneiss. Two surface and subsurface samples were taken at the tailings site.

Samples were analyzed to evaluate the physical and chemical properties of the materials at each site. Analytical parameters, laboratory procedures, and references are summarized in Table 2. Coarse fragment content in the tailings and clay samples was determined by calculating the percentage, by weight, of materials which did not pass a #10 (2 mm) sieve. Coarse fragment content in the waste rock was estimated by a combination of visual volume estimates and weight measurements (see Appendix A).

The physical and chemical properties were evaluated by comparison with two sets of soil guidelines: National Soils Handbook (SCS, 1983) guidelines, and Montana DSL 1983 guidelines. Parameter levels were considered unsuitable if the SCS rating was poor or the DSL rating was unsuitable. The guidelines are listed in Tables 29 and 30, Appendix G.

Clay mineral analysis was performed on the six 15 to 30 cm samples taken at the clay pit. The X-ray diffraction technique of Whittig (1965) was used to identify clay minerals present in the samples. Semiquantitative analysis (Klages and Hopper, 1982) was used to estimate relative proportions of the clay minerals.

Water Availability Measurements

Because water availability was assumed to be critical to successful revegetation of the disturbances, samples of the materials were taken during each month of the growing season to monitor changes in soil water content. Samples were taken at two depth increments: 10 to 20 cm and 21 to 30 cm. It was assumed that these increments encompassed the portion of the profile where water was available to seedlings. Four samples taken at each depth were composited at the waste rock and tailings sites and at each of the three block locations at the clay pit. The samples, which were placed in sealed plastic bags, were oven-dried at 105°C to determine gravimetric water content (Gardner, 1965).

Table 2. Laboratory Procedures Used for Analysis of Waste Rock, Tailings, and Clay.

Parameter	Procedure	Reference
Particle size distribution	8-hour hydrometer	Day (1965)
Saturation percentage	saturated paste	Bower and Wilcox (1965)
pH	saturated paste extract	Peech (1965)
Electrical conductivity (EC)	saturated paste extract	U.S. Salinity Staff (1954)
Ca, Mg, Na	saturated paste extract	Sandoval and Power (1977)
Sodium absorption ratio (SAR)	$Na/[(Ca+Mg)/2]^{1/2}$ (meq/l)	U.S. Salinity Staff (1954)
Nitrate-N	phenoldisulfonic acid	Bremner (1965)
Phosphorus	Olsen ($NaHCO_3$) extractable	Sandoval and Power (1977)
Potassium	ammonium acetate	Sandoval and Power (1977)

In order to determine the availability of soil water measured during the growing season, water retention analyses were performed on materials from each site. Samples were taken at a depth of 15 to 30 cm and assumed to be representative of materials throughout the first 30 cm of the profile. Five replicate samples weighing approximately 2000 g were taken at the waste rock and tailings sites. At the clay pit, three replicate core samples were taken at each block location. The core samples, which were taken with a Uhland sampler, weighed approximately 400 g each.

The samples taken for water retention analyses required preparation to ensure that adequate results would be obtained. The waste rock and tailings samples were air-dried, disaggregated with a mortar and pestle, and sieved to remove coarse fragments. The core samples taken at the clay pit consisted of loose, coarse aggregates. It was assumed that large pore spaces between these aggregates would reduce contact between the clay and the pressure plate. Therefore, to ensure good contact, the core samples were flailed and passed through a #10 sieve.

Retentivity was determined at five tension levels using procedures described by Richards (1965). A five-bar pressure chamber was used to determine retentivity at -0.1, -0.33, and --1 bar; a 15-bar pressure plate apparatus was used to determine retentivity at -3 and -15 bar. Ceramic plates were used in all determinations. Water content at each tension level was determined by oven-drying at 105°C.

Water retention curves were constructed for the waste rock and tailings and for clay materials from each of the block locations at the clay pit. The curves were used to determine the availability of the soil water measured during the growing season at the three sites. The water content at -15 bar was assumed to be the permanent wilting point of seedlings; when soil water levels were less than the -15-bar percentage, that water was assumed to be unavailable to seedlings.

Available water was determined by subtracting 15-bar percentage from field capacity (FC) (Peters, 1965). For the clay, 0.33 bar was used as FC; for the waste rock and tailings, 0.1 bar was used. To convert available water by weight to a volume, the weight percentage was multiplied by an assumed bulk density of 1.35 g/cc. The water volume percentage was then multiplied by the volume percentage of the <2 mm fraction, because coarse fragments were assumed to hold no water. The result of this conversion was available water holding capacity in cm per cm of soil.

Water balance calculations were performed for each site to predict water availability over the growing season, given average climatic conditions. The Thornthwaite method (Thornthwaite and Mather, 1955, 1957) was used to calculate potential evapotranspiration and the water balance. The Thornthwaite method is discussed in greater detail in Appendix B.

In addition to retention analyses and water balance calculations, infiltration tests were performed at the clay pit to further evaluate water availability. Infiltration rates were determined with a rain simulator developed by Meeuwig (1971). Water was applied at a rate of 12.5 mm/hr for 30 minutes. Runoff was collected and measured at three-minute intervals. The procedure was repeated three times on two slopes at the clay pit. The infiltration rates for the three replicate tests were averaged to obtain mean infiltration rates.

SITE DESCRIPTIONS

Geology, Climate, and Vegetation

The mine disturbances which are the subject of this study are located in the Little Rocky Mountains of north-central Montana. The Little Rockies are a group of dome-shaped buttes separated by steep, narrow drainages. Surrounding the buttes are remnant terraces and rolling plains. Elevation ranges from 1100 to 1750 m. The Little Rockies were formed in the early Tertiary Period when igneous rock intruded Mesozoic and Paleozoic sedimentary rocks. The igneous rocks mainly consist of syenite porphyry; the sedimentary rocks consist of limestones, sandstones, and shales. In addition to igneous and sedimentary rocks, Precambrian metamorphic rocks are also found in the Little Rockies (Knechtel, 1959).

The climate of the Little Rockies is distinct from that of the surrounding plains. Average annual precipitation ranges from 40 to 56 cm in the mountains, as compared to 25 to 36 cm for the plains (Ross and Hunter, 1976). The Zortman weather station, which is at 1207 m altitude, receives 46.4 cm average annual precipitation. Over 50% of the annual precipitation occurs from May through August. Mean monthly precipitation and temperature are given in Table 21 (Appendix E).

Distribution of plant communities in the Little Rockies reflects climatic patterns. *Pseudotsuga menziesii, Pinus contorta, Agropyron spicatum, Calamagrostis rubescens,* and *Carex* spp. dominate at altitudes above 1400 m and on north-facing slopes where moisture is less limiting. *Pinus ponderosa, Agropyron spicatum, Stipa viridula,* and *Symphoricarpos occidentalis* are dominant at altitudes below 1400 m and on south and west-facing slopes (Ross and Hunter, 1976).

Waste Rock Dump

The waste rock site was located on one of several waste dumps located at the mine. The dumps consist of rock fragments removed from open pits to expose ore-bearing rock. Fragments range in size from boulders to gravel and constitute 70 to 90% of the total volume. Syenite porphyry and gneiss are the dominant rock types.

The dumps, which are placed in drainages lying downslope from pits, are constructed in a series of benches and lifts. Exposed benches are up to 3 meters wide; lifts vary from two to four meters high. Overall slopes of the dumps range from 45 to 60%. The dump used in this study has an approximate slope of 55%, although the benches on which the demonstration plots were placed are nearly level. The dump faces south.

Tailings Site

Several drainages in the Little Rockies contain tailings dumped from older mine workings. The tailings used in this study probably were dumped in the 1930s (Bryant, 1953). The drainage in which the tailings were deposited begins below Goldbug Butte and runs north toward Peoples Creek. The drainage is concave in profile, steep, and narrow. The slope of the east side of the drainage, on which plots were located, ranges from 25 to 35%.

The tailings consist of unconsolidated sand and gravel. Some large coarse fragments are present in the material because of mixing with colluvium. The mixing probably occurred when the current mine operator spread and compacted the tailings in an attempt to reduce erosion. Much of the tailings was spread along one side of the drainage. As a result, the tailings vary in depth from 10 cm on the slope to 30 cm nearer the bottom of the drainage. Coarse colluvium underlies the tailings.

The tailings probably are similar to the waste rock in geologic origin and mineralogy because the ore bodies mined in the Little Rockies usually are found in syenite porphyry (Emmons, 1907; Bailey, 1974).

Clay Pit

The clay pit was located off the mine site on federal land leased by a local rancher. Clay was mined from an open cut for use as a liner under ore leaching pads constructed at the mine. The cut was made in a steep hillside, which resulted in a three-sided pit. The pit wall nearest the toe of the hillside has a slope of 25% and faces south-southeast. An adjacent wall has the same slope and faces west-southwest. The third wall, which abuts the hillside, has a slope of 40 to 45% and faces north-northwest. In addition to the pit walls and floor, an additional disturbed area exists above the south-facing wall. This area, which may be a small spoil pile, has a slope of 5 to 15%.

Some areas of the pit have been colonized by annual weeds, perennial grasses, and shrubs. *Melilotus officinalis* had become established on much of the pit surface when this study was initiated in October 1983. However, little vegetation has become established on the 40 to 45% slope. A large slump indicates that this slope is unstable.

The clay mined at the pit probably was derived from a shale of the late Cretaceous Period (Knechtel, 1959). Varied clay content on the pit surface may indicate that several geologic strata were disturbed. Although no bentonitic materials were observed in the pit, a bentonite stringer which has been located nearby (Berg, 1969) may have been mined in the pit.

RESULTS AND DISCUSSION

Waste Rock Dump

Site Characterization

Results of physical and chemical analyses of the waste rock are given in Table 17 (Appendix D). Evaluations of physical and chemical properties are presented in Table 3. The evaluations identify low saturation percentage, low available water, and high coarse fragment content as characteristics which render the waste rock unsuitable for use in minesoil reconstruction or as a soil substitute. Based on the evaluations, low water holding capacity may be considered a factor which limits the potential for revegetation of the waste rock.

Table 3. Evaluations of Physical and Chemical Properties of Waste Rock Using Two Sets of Guidelines.

Parameter	Level	Rating	
		DSL	SCS
pH	7.5*	acceptable	good
EC (mmhos/cm)	0.25*	acceptable	good
SAR	0.49*	acceptable	good
Saturation %	22.0*	suspect	––
Available water (cm/cm)**	0.04	––	poor
Textural class	sl*	acceptable	good
Coarse fragments (% by wt.)	83.1***	suspect	––

*Levels given are means of six values.

**AW = (FC-WP)/100 × 1.35 × (100-CF)/100.

***Fragments >2 mm and < 5 cm in largest dimension.

Infertility is another limiting factor. Because the waste rock lacks nutrients and little organic matter exists in the dumps, nitrogen, phosphorus, and potassium levels are low. Successful revegetation of the waste rock dumps will require fertilization.

Germination Results

Survival of transplanted *Pinus* spp. seedlings at the waste rock dump was difficult to assess because mining operations destroyed seven *Pinus ponderosa* seedlings. Two of three remaining *Pinus ponderosa* seedlings and three of ten *Pinus contorta* seedlings survived the 1984 growing season.

Mean germination percentages (MGP) and ranges for species seeded at the waste rock dump are presented in Table 4. The ranges indicate that germination percentages varied considerably from block to block, although ANOV indicated no significant differences existed among blocks (Table 14, Appendix C). Significant differences were found among MGP of grass species; LSD analysis indicated MGP of *Agropyron spicatum* was significantly higher than that of the other three grasses. MGP of *Festuca ovina* was significantly higher than that of *Bromus marginatus* and *Agropyron dasystachyum*. No significant difference existed between MGP of the latter two grasses.

Table 4. Mean Germination Percentages (MGP) and Ranges for Six Species Seeded at the Waste Rock Dump (n = 9).

Species	MGP	Range (%)
Agropyron dasystachyum	6.9	1.9 - 7.7
Agropyron spicatum	33.8	21.4 - 60.0
Bromus marginatus	3.1	0.6 - 6.5
Festuca ovina	13.5	5.6 - 19.6
Melilotus officinalis	9.5	1.9 - 24.2
Pinus contorta	8.9	0.0 - 30.0

Higher germination of *Agropyron spicatum* may have been the result of spring seeding. The species was seeded in the first week of May 1984, whereas the other species were seeded in late October 1983. Spring seeding may have been advantageous to *Agropyron spicatum* because the other species probably were subject to seed loss over winter.

Seed loss may have been the result of depredation. Nelson et al. (1970) reported that avian and rodent depredation significantly reduced the effectiveness of broadcast seeding on rocky slopes. Rodents caused 98% seed loss in six weeks after a fall seeding. Where rodents were controlled, birds caused 93% seed loss. It is important to note that Nelson and his associates conducted their study on depleted rangeland; study plots were adjacent to plant communities which provided cover for wildlife. In contrast, the portion of the waste rock dump used in this study was not directly adjacent to wildlife habitat. Therefore, although depredation on the waste rock dump may have been significant, seed loss rates probably were lower than those reported by Nelson et al. (1970).

Germination of fall-seeded species may have been reduced by depredation; however, their relatively poor performance also may indicate that *Agropyron spicatum* is better adapted to conditions at the dump.

Germination of all seeded species was less than optimal and probably was reduced by a lack of soil water at the dump surface. Available water held near the surface probably was rapidly lost to evaporation. Because seeds could not imbibe sufficient water before the surface dried, many seeds did not germinate.

Water Relations and Seedling Survival

A severe drought occurred during the 1984 growing season. Records for the Zortman weather station indicated that precipitation for the period of 1 May to 31 August was 47% below normal (Table 21, Appendix E). Results of soil water monitoring indicate that available water appeared to have been depleted early in the growing season. Figure 4 depicts the availability of soil water at three monitoring dates in the growing season. Permanent wilting point (PWP), which was assumed to be 15 bar, was reached sometime after 13 June and before 6 July. On the latter date, samples taken at the waste rock dump held water well below PWP. On 26 August, water remained unavailable at 10 to 20 cm depth, but was

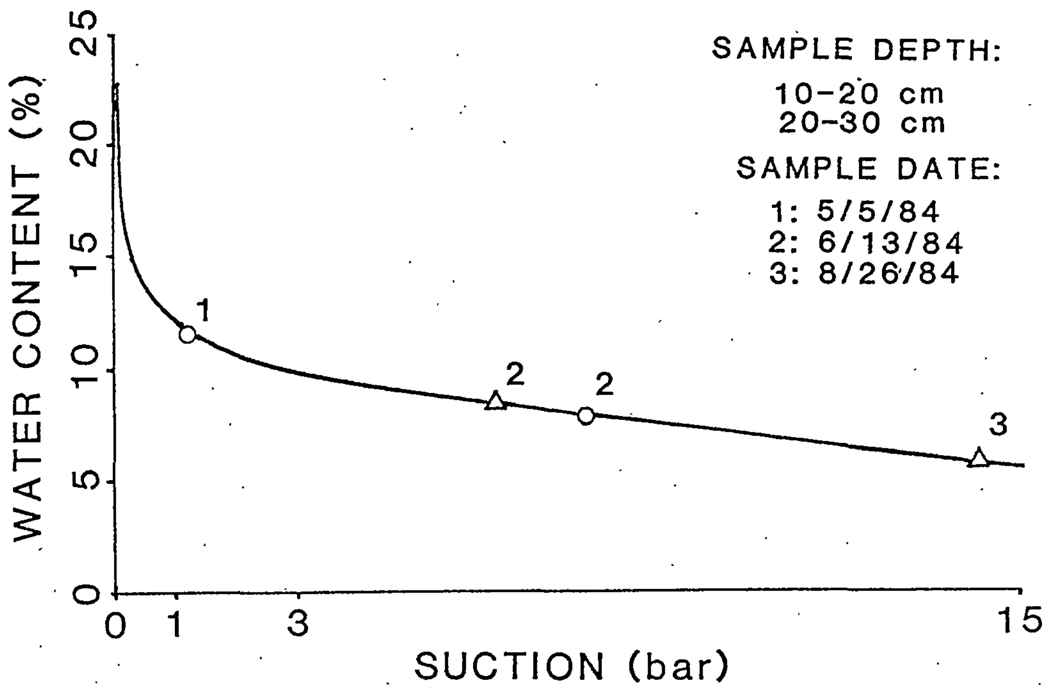

Figure 4. Water retention curve for waste rock depicting soil water status during the growing season at the waste rock dump.

above PWP at 20 to 30 cm depth. Retention and soil water monitoring data are summarized in Tables 22 and 23 (Appendix F).

Although soil water monitoring results shown in Figure 4 indicate that water became unavailable early in the growing season, seedling survival and growth did not appear to be affected by water stress. No indications of stress were observed when the site was visited in late August 1984; nearly all plants were green and vigorous. *Agropyron dasystachyum* and *Agropyron spicatum* produced growth between 5 July and 26 August, although only 2 cm of rain fell in Zortman during that period. Seedheads produced by *Bromus marginatus* and the emergence of several *Pinus contorta* seedlings also were observed in August. Continued growth of seedlings indicated that water availability may not have become limiting during the growing season.

The seedlings may have used water sources which were not measured by retention analysis or soil water monitoring. One source may have been rock fragments which were not included in retention analysis because it was assumed they held no water.

This assumption was tested by determining the water holding capacity of the fragments. Water holding capacity was determined with a method used by Coile (1953), who studied field stones. Five fragments from the dump were soaked in water for 8 days, blotted, and then oven-dried to a constant weight. The fragments, which ranged from 4 to 7 cm in largest dimension, held 1.7 to 5.0% water by weight. Although these results are not conclusive, they indicate that rock fragments in the dump may hold significant amounts of available water.

Several other climatic and edaphic factors also may have enhanced water availability in the waste rock. The amount of precipitation received at the site probably was higher than that which was recorded at the Zortman weather station, because the dump is at a higher elevation. Several mountain rain showers were observed during the growing season; some of these showers may have occurred at the dump but were not recorded in Zortman. This precipitation may have helped to maintain seedling growth and vigor.

Most precipitation became readily available to seedlings because of the unique structure of the dump profile. The profile consists of large fragments separated by smaller fragments and the <2 mm fraction. Presumably, precipitation rapidly infiltrated the profile with downward flow concentrated between rock fragments. It can also be assumed that roots of seedlings grew between fragments. Therefore, the seedlings were able to take up water which was concentrated between rock fragments.

In addition to concentrating infiltrating water, the unique profile structure may have enhanced water availability by reducing evaporative loss. The unconsolidated mixture of sandy loam and small fragments near the surface was susceptible to rapid drying. After initial losses, however, further evaporation may have been reduced as a dry layer formed at the surface. Upon drying, the conductivity of pores near the surface may have been reduced, so that upward diffusion through the dry layer could not keep pace with evaporative demand. Reduced evaporative loss may have prolonged water availability after precipitation events at the dump. Other investigations have measured similar phenomena (Gardner, 1959; Hanks et al., 1967).

Water availability also may have been enhanced by solar heating of surface rock fragments. Water held by the fragments may have been vaporized and driven out by heating. In vapor form, water moves from warm to cold areas in the profile (Ward, 1975). In soils with rock fragments at the surface, vapor moves downward during the day when surface rocks are heated. When the surface radiates heat at night, vapor moves upward and condenses under cooling rocks (Jury and Bellantuoni, 1976; Stark, 1982). Such a process may have benefited seedlings by concentrating water under fragments for plant uptake.

Although each of the factors discussed above could have enhanced water availability, the exact conditions which enabled the seedlings to avoid water stress are not known. Seedling survival probably was due to a combination of climatic and edaphic factors which enhanced water availability.

The Water Balance

Successful revegetation of the waste rock dump will require good seedling survival during the first growing season. Because water availability affects seedling survival, the water balance of the upper 30 cm of the waste rock profile is critically important.

Figure 5 depicts the water balance for the upper 30 cm of the waste rock dump. According to the calculations (Table 10, Appendix B), seedlings use precipitation as "surplus" water until June, when potential evapotranspiration exceeds precipitation. At that time, soil water "use" begins. Soil water is used through June and into July, when

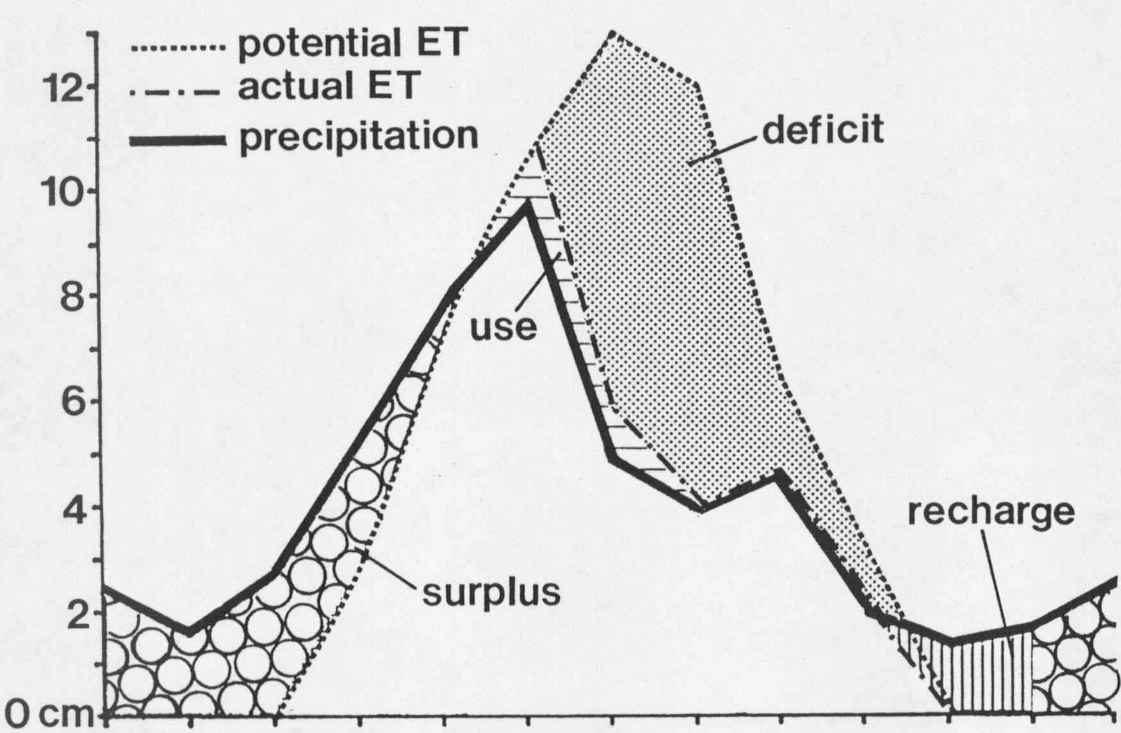

Figure 5. Water balance diagram for the waste rock dump.

it is depleted. From that point in July on, available water is inadequate and seedling growth is slowed or suspended; seedling mortality may also occur. The "deficit," as shown in the diagram, represents the amount of water which would be needed to maintain seedling growth. Following the growing season, soil water "recharge" occurs until field capacity is reached.

The theoretical water balance depicted in Figure 5 is in obvious conflict with the observations made during the 1984 growing season. Although the water balance calculations indicate that soil water is depleted with average precipitation, seedlings survived the 1984 growing season with much less precipitation. This discrepancy exists because the water balance calculations did not account for the previously discussed factors which may have enhanced water availability in 1984.

Most importantly, the water balance calculations did not include water which may be held by rock fragments. The calculation of available water, as shown in Appendix B, excluded the volume occupied by coarse fragments from the volume of soil which holds water. If the rock fragments hold significant amounts of water, part of their volume should be included in the water-holding volume of soil. The entire volume occupied by rock fragments could not be included, however, because some fragments or parts of fragments may not hold water.

If part of the rock fragment volume is included in available water calculations, the amount of available water in the waste rock profile would be increased. In effect, the depletion of soil water would occur later than July. If the amount of water held by fragments is sufficiently large, soil water may not be depleted during the growing season. In that case, the water balance would reflect what may have occurred during the 1984 growing season.

In summation, the water balance in the waste rock dump may be favorable for seedling survival if rock fragments hold significant amounts of available water. Adequate prediction of water availability for seedling establishment will require determination of the importance of rock fragments to the water balance in the waste rock dump.

Tailings Site

Site Characterization

Results of physical and chemical analyses of the tailings are shown in Table 18 (Appendix D). Evaluations of physical and chemical properties are given in Table 5. The evaluations identify low saturation percentage and coarse texture as characteristics which render the tailings unsuitable for use in minesoil reconstruction or as a soil substitute. Poor water holding capacity, because of coarse texture, is a factor which limits successful revegetation of the tailings.

Table 5. Evaluations of Physical and Chemical Properties of Tailings Using Two Sets of Guidelines.

		Rating	
Parameter	Level	DSL	SCS
pH	7.5*	acceptable	good
EC (mmhos/cm)	1.96*	acceptable	good
SAR	0.11*	acceptable	good
Saturation %	19.1*	suspect	––
Available water (cm/cm)**	0.08	––	fair
Textural class	ls*	suspect	fair
Coarse fragments (% by wt.)	27.6*	acceptable	––

*Levels given are means of four values.
**AW = (FC-WP)/100 X 1.35 X (100-CF)/100.

Erosion also is a limiting factor. Much of the erosion may be due to runoff from upslope. Most of the rills observed in the tailings began on an abandoned road which runs parallel to the drainage. This road meets a haul road which crosses the head of the drainage. During the 1984 growing season, it appeared that runoff from the compacted haul road followed the abandoned road down the drainage and onto the tailings. Erosion caused by runoff from a rainstorm in June 1984 produced extensive rilling of the tailings surface, including a gully 2 m deep and 1 m wide.

Strong winds also may cause erosion of the tailings. Extremely windy conditions were observed at the site in May, July, and August. The effect of wind and water erosion was evident as dozer tracks which covered the tailings in May became nearly invisible by August. Erosion hinders vegetation establishment because seed and seedlings may be buried or carried away as the tailings erode.

A third limiting factor is infertility. Because the parent materials of the tailings lacked nutrients and little organic matter has accumulated, nitrogen, phosphorus, and potassium levels are low.

Germination Results

Mean germination percentages (MGP) and ranges for species seeded at the tailings site are given in Table 6. ANOV indicated no significant differences among MGP of the nine blocks (Table 15, Appendix C). Significant differences were found among MGP of grass species; LSD analysis revealed that MGP of *Bromus marginatus* was significantly higher than that of the other three grasses. No significant difference was found between MGP of *Festuca ovina* and *Agropyron dasystachyum;* both species had higher MGP than *Agropyron spicatum.*

Table 6. Mean Germination Percentages (MGP) and Ranges for Six Species Seeded at the Tailings Site (n = 9).

Species	MGP	Range (%)
Agropyron dasystachyum	15.4	7.9 - 26.5
Agropyron spicatum	3.3	0.0 - 5.2
Bromus marginatus	22.1	6.3 - 47.5
Festuca ovina	15.0	7.9 - 25.2
Melilotus officinalis	8.0	0.0 - 25.1
Pinus contorta	1.1	0.0 - 10.0

Germination of all species at the tailings site was low. Severe erosion of the tailings during snowmelt and rainstorms in May and June probably removed significant amounts of seed from plots near the top of the slope. At the same time, deposition of eroded tailings near the bottom of the slope may have inhibited emergence of seedlings. In addition, seed loss may have occurred over the winter as a result of depredation. Plots at the tailings site were adjacent to a forested slope which provided cover for birds and rodents.

Germination at the tailings site also was reduced by a lack of available soil water. Because the tailings have a poor water holding capacity, little available water may have been retained near the surface against gravitational flow. Thus, water near the surface was scarce and available only for a short time before the surface dried. Only those seeds which were able to rapidly imbibe sufficient water were able to germinate.

Water Relations and Seedling Survival

Low water availability also affected seedling growth and vigor during the growing season. Symptoms of water stress became apparent in July. Leaves of *Agropyron dasystachyum* and *Agropyron spicatum* became strongly involuted; the only *Pinus contorta* seedling which emerged on the plots and many *Melilotus officinalis* seedlings wilted. *Festuca ovina* seedlings did not appear to be stressed, but produced no growth after emergence. Only *Bromus marginatus* seedlings appeared to maintain vigor and produce significant growth during the growing season.

Although low water availability reduced germination and seedling growth, results of retention analyses indicated that water may have been available for uptake by seedlings throughout the growing season. Figure 6 depicts the availability of soil water measured on four days during the growing season. According to the retention curve, permanent wilting point (PWP) was not reached during the growing season. Soil water was readily available for plant uptake at 20 to 30 cm depth. At 10 to 20 cm, water became less available in July

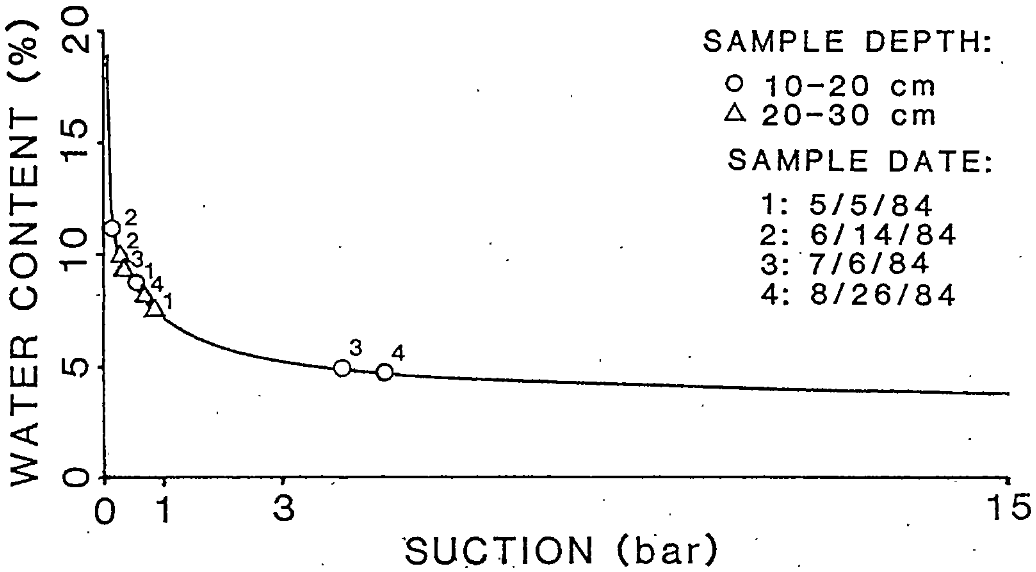

Figure 6. Water retention curve for the tailings depicting soil water status during the growing season at the tailings site.

and August, as the tailings surface dried. Retention and soil water monitoring data are summarized in Tables 24 and 25 (Appendix F).

The discrepancy between soil water monitoring results and field observations may be attributed to possible errors associated with soil water monitoring. The retention curve for the tailings is relatively flat; the difference between water contents at -1.0 and -15 bar is 3.5%. Small errors in the measurement of water content in tailings samples may have resulted in erroneous positions on the curve for some samples.

Another possible explanation involves poor conductivity of the tailings. With continued drying, the hydraulic conductivity of the loamy sand may have been reduced so that the nascent root systems of seedlings could not take up water fast enough to keep pace with transpiration. Therefore, although some water may have been available, seedlings may have become stressed because they could not take up water rapidly enough.

The Water Balance

The water balance for the tailings is depicted in Figure 7. According to the calculations (Table 11, Appendix B), seedlings begin to use soil water in June. Soil water is depleted in early August, which may be too early for seedlings which are active throughout the growing season. However, some cool-season grasses which become semi-dormant in August may not be affected by water stress following depletion of available soil water. *Bromus marginatus* and *Festuca ovina* are two such species which appeared to have survived the 1984 growing season on the tailings. In years of average precipitation, the water balance may favor seedlings of these species. Other species may become established on the tailings in years of above-normal precipitation.

Clay Pit

Site Characterization

Results of physical and chemical analyses of the clay are given in Table 19 (Appendix D); evaluations of physical and chemical properties are given in Table 7. For purposes of evaluation, data from samples taken at the three block locations were averaged.

The evaluations identify high clay content as a characteristic which renders the material unsuitable for use in minesoil reconstruction or as a soil substitute. High clay content inhibits plant growth because of poor permeability and poor aeration (Brady, 1974).

Results of mineralogical analyses revealed varied mineralogy in the clay (Table 20, Appendix D). Illite and kaolinite were dominant clay minerals in all analyzed samples; levels of smectite and vermiculite were varied for the three locations sampled. Because smectite was not a primary constituent of the clay minerals in the samples, shrinking and swelling may not significantly inhibit revegetation. However, smectite may be dominant in other areas of the pit that were not sampled; in these areas, shrinking and swelling

Figure 7. Water balance diagram for the tailings site.

Table 7. Evaluations of Physical and Chemical Properties of Clay Using Two Sets of Guidelines.

Parameter	Level	Rating	
		DSL	SCS
pH	8.1*	acceptable	good
EC (mmhos/cm)	2.09*	acceptable	good
SAR	1.64*	acceptable	good
Saturation %	68.7*	acceptable	––
Available water (cm/cm)**	0.21	––	good
Textural class	sic*	suspect	poor
Coarse fragments (% by wt.)	0.9*	acceptable	––

*Levels given are means of twelve values.

**AW = (FC-WP)/100 X 1.35 X (100-CF)/100.

may be inhibitory. Some additional shrinking and swelling of the other minerals also may occur.

The effects of high clay content and swelling clay minerals were evident during infiltration tests at the clay pit. As water was applied by a rainfall simulator, swelling of the clay caused cracks to close on the surface. Simulated precipitation did not infiltrate more than a few centimeters below the surface. Much precipitation may evaporate from the surface or run off before it reaches roots.

The effect of low permeability on water availability is exacerbated by the steep slopes of the pit walls. The effect of slope also was demonstrated with the rain simulator. On a slope of 40 to 45%, the infiltration rate was reduced from 12.5 mm/hr to 5.1 mm/hr after one half hour of application. In contrast, the infiltration rate was only reduced from 12.5 mm/hr to 12.3 mm/hr on a 5 to 10% slope (Table 28, Appendix F). These results indicate that less infiltration and more runoff occurred on the steeper slope. The combination of high clay content and steep slopes reduces infiltration so that little precipitation becomes available to plants. Poor infiltration is a limiting factor at the clay pit.

Infertility is another limiting factor, as nitrogen and phosphorus levels are low. Vegetation establishment will require fertilization.

Germination Results

One of the two shrub species transplanted at the clay pit had a high survival rate while the other species failed to become established. All ten *Symphoricarpos occidentalis* plants survived the 1984 growing season; one *Juniperus horizontalis* plant survived through August but appeared to be dead in May 1985. These results indicate that *Symphoricarpos occidentalis* is suitable for revegetation of the clay pit.

Mean germination percentages (MGP) and ranges for seeded species are given in Table 8. ANOV indicated significant differences existed among MGP of grass species (Table 16, Appendix C). LSD analysis indicated that MGP of *Agropyron riparium* was significantly higher than that of *Agropyron dasystachyum* and *Agropyron smithii*; no significant difference was found between MGP of the latter two grasses.

Table 8. Mean Germination Percentages (MGP) and Ranges for Four Species Seeded at the Clay Pit (n = 9).

Species	MGP	Range (%)
Agropyron dasystachyum	4.7	0.0 - 12.6
Agropyron riparium	19.5	1.4 - 35.3
Agropyron smithii	0.7	0.0 - 3.3
Atriplex canescens	0.0	— ——

ANOV also revealed significant differences among overall MGP of the three blocks. Overall MGP of block 1 was significantly lower than that of blocks 2 and 3; no significant difference was found between MGP of blocks 2 and 3.

Differences existed among MGP of the three blocks because the blocks were located on differing slopes. Block 1, which had the lowest MGP of the three blocks, was located on a slope of 41%; blocks 2 and 3 were located on slopes of 11% and 26%, respectively. Germination in block 1 was reduced because the steep slope increased runoff and reduced water storage. The effect of slope on infiltration was demonstrated in infiltration tests previously discussed. Blocks 2 and 3 produced higher germination percentages because more water was available for imbibition on the flatter slopes.

Germination in all blocks was poor, probably because of severe drought. The surface of the pit was dry and cracked in May and June; little water appeared to be available to seeds on the soil surface. Germination was measured four days after 3.3 cm of precipitation was recorded at the Zortman weather station. If this precipitation fell at the clay pit, it may have been enough to allow some seed to germinate. Additional germination may have been inhibited as the surface dried following the precipitation events.

Water Relations and Seedling Survival

The seedlings produced little growth because little precipitation fell after emergence. Moreover, soil water levels were low. Figure 8 depicts the availability of soil water at the three block locations during the growing season. Water content during the growing season was below PWP in all but one of the samples. A sample from 20 to 30 cm depth which was taken at block 1 in May 1984 held available water. Retention and soil water monitoring data are summarized in Tables 26 and 27 (Appendix F).

Results of retention analyses should be considered with respect to error associated with preparation of the clay samples for desorption. The core samples were flailed and sieved; error associated with disturbing the structure may have been significant. Broadfoot (1954) reported that the amount of water held at -15 bar in disturbed silty clay samples was significantly higher than that held in core samples. Disturbed samples of silty clay and silt loam also retained more water at tensions greater than -1 bar. Elrick and Tanner (1955) reported similar results for silty clay loam and silt loam at low tensions. However, they suggested that disturbed samples may be used at tensions from -1.0 to -15 bar with an error of 10% of the percentage value.

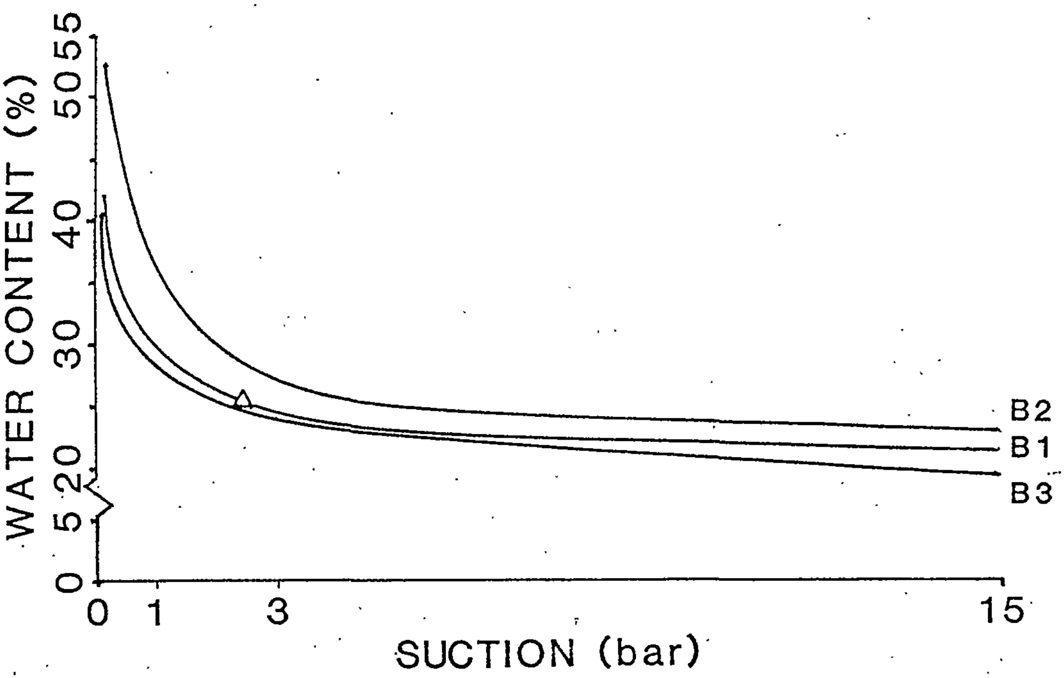

Figure 8. Water retention curves for clay materials depicting soil water status during the growing season at three block locations in the clay pit.

A more significant error may have resulted from the small sample size which was used to obtain retention curve points. Three samples from each block location were used to determine retentivity at five tension levels; the mean water content of the three samples was used for the points on the curve. Although the standard deviation of the mean 15-bar percentage was less than one for block 2, standard deviations for blocks 1 and 3 were 5.75 and 2.9, respectively (see Table 26, Appendix E). Because of the variability associated with the small sample size, values for 15-bar percentage may not represent the permanent wilting point. Therefore, water content values which were obtained in May and June and were close to the 15-bar percentages may not have been below PWP. However, values obtained in July and August were more than two standard deviations below the 15-bar percentages. Soil water probably was unavailable in July and August.

Although soil water may have been available for part of the growing season, poor plant performance indicated that little water was available to seedlings. No seedling growth was observed after June; in July, seedling leaves became necrotic and, in August, some seedling mortality was evident. Water stress also affected species which were colonizing the clay pit. *Melilotus officinalis* seedlings began to wilt in June and were brown and necrotic in July. Only mature, established grasses and shrubs remained vigorous through the growing season. Presumably, these plants had well-developed root systems which enhanced water uptake.

Vegetation establishment in the blocks at the clay pit was inhibited by severe drought. Because little water was available early in the growing season, germination was reduced; seedling growth also was retarded. The seedlings, which had poorly developed roots, could not take up enough water to meet transpiration demand. High seedling mortality resulted as the drought extended through the growing season.

The Water Balance

The water balance for the upper 30 cm of the clay pit profile is depicted in Figure 9. The calculations (Table 12, Appendix B) indicate that soil water remains available throughout the growing season which should favor seedling survival during years of average precipitation. Soil water is not depleted by evapotranspiration because of the high water holding capacity of the clay material.

The water balance for the clay pit must be interpreted with caution because the calculations do not account for poor infiltration into the clay. The Thornthwaite method was developed with the assumption that all precipitation infiltrates the profile until the soil is saturated. At the clay pit, however, infiltration tests which were previously discussed demonstrated that infiltration was impeded by high clay content and steep slopes. Therefore, much precipitation may not become available to seedlings because it is lost to runoff.

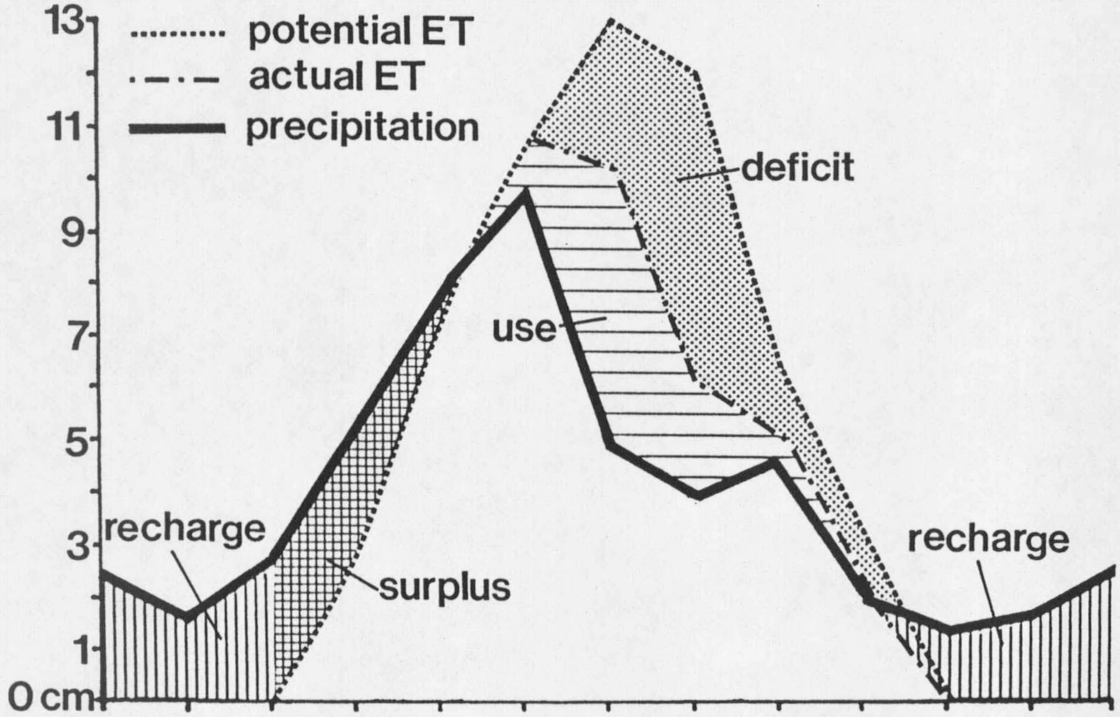

Figure 9. Water balance diagram for the clay pit.

Because actual stored soil water may be less than the ideal amount used in water balance calculations, soil water may not remain available through the growing season. The favorable conditions depicted in Figure 9 may not occur at the clay pit unless water availability is enhanced by improving infiltration.

CONCLUSIONS AND RECOMMENDATIONS

Waste Rock Dump

Results of the revegetation demonstration at the waste rock dump are not conclusive because species performance was not measured after germination. The results which were obtained are significant, however, because they indicate that revegetation of the waste rock is feasible. Adverse environmental conditions are apparent on the dumps; evaluations of waste rock characteristics indicated that low water availability may be a limiting factor. However, the survival of seedlings through the drought indicates that water availability should not inhibit successful revegetation of the dumps.

The species which have the most potential for revegetation of the dumps are *Agropyron spicatum* and *Festuca ovina.* Germination of the other species was poor in comparison. *Agropyron dasystachyum* and *Bromus marginatus* probably should not be considered for use in revegetation; growth of these species was poor. *Melilotus officinalis* should be included because a legume is needed to enhance nitrogen availability in the waste rock. Although other legumes may be considered, *Melilotus officinalis* may be better suited to the harsh environment on the dumps.

Establishment of *Pinus contorta* from seed was largely unsuccessful. Seedlings showed little growth after emergence. No seedlings appeared to have survived the winter when the site was visited in May 1985. Transplants of *Pinus contorta* and *Pinus ponderosa* fared better, but tree establishment by transplanting may be too labor-intensive to be economical. Development of an effective method of tree establishment on the dumps will require further study.

Selection of appropriate species and seeding rates also will require further study. *Poa compressa*, which has invaded the dumps in large numbers, should be studied. Higher seed rates should be tested to overcome poor germination because of reduced seed-soil contact. Spring and fall seeding should be compared to determine when water availability for germination can be maximized. Spring seeding may improve germination by reducing seed loss.

Results of chemical analyses of the waste rock indicated that fertility is a limiting factor in revegetation. Although long-term fertilizer requirements on the waste rock dumps may require further study, a tentative recommendation can be made: 100 kg/ha nitrogen, 67 kg/ha phosphorus, and 224 kg/ha potassium. These rates, which are based on analysis results and accepted fertility levels, should be adequate for plant establishment.

Large-scale revegetation of the dumps will require an efficient and effective means of seeding and fertilizing. The rough and steep dump surfaces prevent the use of conventional implements. The dumps could be broadcast seeded and fertilized on foot, although walking on the steep dumps can be dangerous. Aerial application may be safer, but more expensive. Finally, hydroseeding may be effective, but access roads would have to be built on the dump faces to ensure complete coverage with seed and fertilizer.

Tailings Site

Germination of all species seeded at the tailings site was poor. *Agropyron spicatum* and *Pinus contorta* had the lowest MGP; these species may not be suitable for revegetation of the tailings. The seeded species also produced little seedling growth. *Bromus marginatus* was an exception, however, as it continued to grow until late August and produced some seed heads. *Bromus marginatus*, which also became established on other areas on the tailings, should be suitable for revegetation. *Agropyron dasystachyum, Festuca ovina,* and

Melilotus officinalis may be suitable, but may require improved water availability to become established.

Enhancement of water availability and erosion control may be essential for successful revegetation of the tailings. However, application of mulches or other treatments to improve conditions may not be economically feasible to the mine operator, who is not obligated to reclaim the abandoned tailings. Therefore, low-cost revegetation techniques must be developed.

One such technique is the use of a rapidly growing species as a "nurse crop" for other species. *Bromus marginatus,* which appeared to become established on the tailings in 1984, could be used to stabilize the tailings surface. This temporary cover could reduce erosion and improve infiltration. Following successful establishment of *Bromus marginatus,* other species, such as *Agropyron dasystachyum* and *Festuca ovina,* could be interseeded.

The tailings should be seeded in fall instead of spring because snow remains in the drainage until late spring. Drill seeding is preferable to broadcast seeding, although the drainage may be too steep and narrow to allow efficient operation of a drill.

Based on results of chemical analyses of the tailings, tentative fertilizer recommendations can be made: 100 kg/ha nitrogen, 56 kg/ha phosphorus, and 112 kg/ha potassium. These rates should be adequate for plant establishment, but long-term fertilizer requirements may need further study.

Clay Pit

Performance of all seeded species at the clay pit was poor. *Agropyron riparium* had fair germination, but seedlings of the species had high mortality. *Agropyron dasystachyum* and *Agropyron smithii* also had high mortality; *Atriplex canescens* did not germinate on any of the seeded plots. Transplanted shrub species produced mixed results. Only one

Juniperus horizontalis transplant survived, but all ten *Symphoricarpos occidentalis* transplants survived.

The species could not be completely evaluated because the drought reduced germination and inhibited plant growth. Further study is needed to identify suitable species. *Stipa viridula* and *Agropyron spicatum* have invaded the clay pit and should be considered for use in revegetation. Although *Agropyron riparium* and *Symphoricarpos occidentalis* appear to be the only species used in this study which may be suitable for revegetation, the other species may be more suitable if water availability is enhanced.

Water availability must be enhanced to ensure successful revegetation of the clay pit. Water storage may be enhanced by incorporation of wood chips to improve infiltration. This treatment has been effective in improving water availability and vegetation establishment on bentonite spoils (Smith, 1984). Incorporation of 90 t/ha wood chips and 2.5 kg/t nitrogen is recommended for bentonite spoils. Further study will be required to identify appropriate application rates for the clay pit.

Application of a wood chip mulch may not be feasible on the 40 to 45% slope because the slope may be too steep for equipment used to incorporate the chips. An alternative to mulching may be dozer basins, which would retain runoff. Basins in clayey material may not allow infiltration to occur, however, and ponded water may be lost to evaporation (Dollhopf et al., 1977).

The steep slope may require stabilization to prevent further slumping. Construction of terraces may help stabilize the slope while retaining runoff. However, successful stabilization of the slope may require engineering applications which lie beyond the scope of this study.

Mulch application and seeding operations should be performed in late fall because wet conditions following snowmelt may hamper such operations in spring. Drill seeding is recommended, but may not be feasible on steep slopes. If the pit is broadcast seeded, the seed should be covered by harrowing or hand-raking.

Results of chemical analyses of the clay materials indicated that nitrogen and phosphorus are low. Tentatively recommended fertilizer rates are 90 kg/ha nitrogen and 56 kg/ha phosphorus. The recommended rate for nitrogen does not include nitrogen which is required when wood chips are applied.

The clay pit and surrounding area was heavily grazed in 1984, although vegetation in the pit was sparse. Fencing of the pit following seeding is recommended to reduce grazing pressure on young vegetation.

LITERATURE CITED

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Aharrah, E. C., and R. T. Hartman. 1973. Survival and growth of red pine on coal spoil and undisturbed soil in western Pennsylvania. *In* R. J. Hutnik and G. Davis (eds.), Ecology and reclamation of devastated land, vol. 1. Gordon and Breach, New York. pp. 439-444.

Alexander, E. B. 1984. Volume estimates of coarse fragments in soils: A combination of visual and weighing procedures. J. Soil Water Cons. 36:360-361.

Ashby, W. C., W. G. Vogel, C. A. Kolar, and G. R. Philo. 1984. Productivity of stony soils on strip mines. *In* D. L. Kral (ed.), Erosion and productivity of soils containing rock fragments. Special Publication 13, Soil Sci. Soc. Am., Madison. 103 pp.

Bailey, R. L. 1974. Geology and ore deposits of the Alder Gulch area, Little Rocky Mountains, Montana. M.S. Thesis, Montana State University, Bozeman, MT. 81 pp.

Berg, R. B. 1969. Bentonite in Montana. Montana Bur. Mines and Geol. Bull. 74. Montana College of Mineral Sci. and Tech., Butte, MT. 34 pp.

Bokhari, U. G., J. S. Singh, and E. M. Smith. 1975. Influence of temperature regimes and water stress on the germination of three range grasses and its possible ecological significance for a shortgrass prairie. J. Appl. Ecol. 12:153-163.

Bower, C. A., and L. V. Wilcox. 1965. Soluble salts. *In* C. A. Black (ed.), Methods of soil analysis, part 2. Agron. Monogr. 9, Am. Soc. of Agron., Madison. Chapt. 62.

Brady, N. C. 1974. The nature and properties of soils. Macmillan Publishing Co., Inc., New York. 8th ed. 639 pp.

Bremner, J. M. 1965. Inorganic forms of nitrogen. *In* C. A. Black (ed.), Methods of soil analysis, part 2. Agron. Monogr. 9, Am. Soc. of Agron., Madison. Chapt. 84.

Broadfoot, W. M. 1954. Core vs. bulk samples in soil-moisture tension analysis. Southern Forest Exp. Stat. Occasional Paper 135, U.S.D.A. Forest Service.

Brown, J. A. 1974. Cultural practices for revegetation of high-altitude disturbed lands. *In* W. A. Berg, J. A. Brown, and R. L. Cuany (eds.), High-altitude revegetation workshop no. 1. Colo. Water Res. Research Inst. Information Series No. 10, Colorado State University, Fort Collins, CO. pp. 59-63.

Brown, R. W. 1977. Water relations of range plants. *In* R. E. Sosebee (ed.), Rangeland plant physiology. Society for Range Management Range Science Series No. 4, Society for Range Management, Denver, CO. 290 pp.

Brown, R. W., and R. S. Johnston. 1976. Revegetation of an alpine mine disturbance: Beartooth Plateau, Montana. Int. Forest and Range Exp. Stat. Res. Note INT-206. U.S.D.A. Forest Service, Ogden, UT.

Brown, R. W., and R. S. Johnston. 1978. Rehabilitation of a high-elevation mine disturbance. *In* S. T. Kenney (ed.), High-altitude revegetation workshop no. 3. Colo. Water Res. Research Inst. Information Series No. 28, Colorado State University, Fort Collins, CO. pp. 116-129.

Brown, R. W., and R. S. Johnston. 1980. An assessment of revegetation techniques for alpine disturbances. *In* C. L. Jackson and M. A. Schuster (eds.), High-altitude revegetation workshop no. 4. Colo. Water Res. Research Inst. Information Series No. 42, Colorado State University, Fort Collins, CO. pp. 126-146.

Brown, R. W., R. S. Johnston, and J. C. Chambers. 1984. Responses of seeded native grasses to repeated fertilizer applications on acidic alpine mine spoils. *In* T. A. Colbert and R. L. Cuany (eds.), High-altitude revegetation workshop no. 6. Colo. Water Res. Research Inst. Information Series No. 53. Colorado State University, Fort Collins, CO. pp. 200-214.

Brown, R. W., R. S. Johnston, B. Z. Richardson, and E. E. Farmer. 1976. Rehabilitation of alpine disturbances: Beartooth Plateau, Montana. *In* R. H. Zuck and L. F. Brown (eds.), High-altitude revegetation workshop no. 2. Colo. Water Res. Research Inst. Information Series No. 21, Colorado State University, Fort Collins, CO. pp. 58-71.

Bryant, F. B. 1953. History and development of the Landusky Mining District, Little Rocky Mountains, Montana. *In* J. Parker (ed.), Fourth Ann. Field Conf. Guidebook, Billings Geological Society, Billings, MT. 93 pp.

Coile, T. S. 1953. Moisture content of small stones in soil. Soil Sci. 75:205-207.

Currie, J. A. 1973. The seed-soil system. *In* F. Heydecker (ed.), Seed ecology. Macmillan Publishing Co., Inc., New York. 534 pp.

Day, P. R. 1965. Particle fractionation and particle size analysis. *In* C. A. Black (ed.), Methods of soil analysis, part 1. Agron. Monogr. 9, Am. Soc. of Agron., Madison. Chapt. 43.

Dean, K. C., R. Havens, K. T. Harper, and J. B. Rosenbaum. 1973. Vegetative stabilization of mill mineral wastes. *In* R. J. Hutnik and G. Davis (eds.), Ecology and reclamation of devastated land, vol. 2. Gordon and Breach, New York. pp. 119-134.

Deckler, J. H. 1982. Characterization of four inactive hard rock mines in western Montana. M.S. Thesis, Montana State University, Bozeman, MT 188 pp.

DePuit, E. J., and M. M. Caldwell. 1975. Gas exchange of three cool semi-desert species in relation to temperature and water stress. J. Ecol. 63:835--858.

DePuit, E. J., and D. J. Dollhopf. 1978. Revegetation research on coal surface-mined lands at West Decker Mine, Decker, Montana: progress report 1975. Montana A. Exp. Stat. Res. Report 133, Montana State University, Bozeman. 30 pp.

Dollhopf, D. J., and M. E. Majerus. 1975. Strip mine reclamation research located at Decker Coal Company, Decker, Montana. Montana Ag. Exp. Stat. Res. Report 83, Montana State University, Bozeman, MT. 42 pp.

Dollhopf, D. J., I. B. Jenson, and R. L. Hodder. 1977. Effects of surface configuration in water pollution control on semi-arid mined lands. Montana Ag. Exp. Stat. Res. Report 114, Montana State University, Bozeman, MT. 179 pp.

Down, C. G. 1975. Soil development on colliery waste tips in relation to age. J. Appl. Ecol. 12:613-637.

Eddleman, L., and T. Nimlos. 1972. The response of native Montana grasses to soil water stress: Completion report. Montana Univ. Joint Water Res. Research Project No. A-046MONT. 30 pp.

Elrick, D. E., and C. B. Tanner. 1955. Influence of sample pretreatment on soil moisture retention. Soil Sci. Soc. Am. Proc. 19:279-282.

Emmons, W. H. 1907. Gold deposits of the Little Rocky Mountains, Montana. U.S.G.S. Bull. No. 340, part 1.

Farmer, E. E., and W. G. Blue. 1978. Reclamation of lands mined for phosphate. *In* F. W. Schaller and P. Sutton (eds.), Reclamation of drastically disturbed lands. Am. Soc. of Agron., Madison. 742 pp.

Farmer, E. E., and B. Z. Richardson. 1980. Phosphate mine dump stability and revegetation. *In* Symposium on watershed management, proceedings, vol. 2. Am. Soc. Civil Engineers, New York. pp. 888-897.

Gardner, W. H. 1965. Water content. *In* C. A. Black (ed.), Methods of soil analysis, part 1. Agron. Monogr. 9, Am. Soc. of Agron., Madison, Chapt. 7.

Gardner, W. R. 1959. Solutions of the flow equation for the drying of soils and other porous media. Soil Sci. Soc. Am. Proc. 23:183–187.

Guillaume, M. 1980. Alpine revegetation research at the Climax molybdenum mine. *In* C. L. Jackson and M. A. Schuster (eds.), High-altitude revegetation workshop no. 4. Colo. Water Res. Research Inst. Information Series No. 42, Colorado State University, Fort Collins, CO. pp. 185-203.

Hanks, R. J., H. R. Gardner, and M. L. Fairbourn. 1967. Evaporation of water from soils as influenced by drying with wind or radiation. Soil Sci. Soc. Am. Proc. 31:593-598.

Harper, J. C., and R. A. Benton. 1966. The behaviour of seeds in soil: II. The germination of seeds on the surface of a water-supplying substrate. J. Ecol. 54:151-166.

Hitchcock, C. L., and A. Cronquist. 1973. Flora of the Pacific Northwest. University of Washington Press, Seattle. 892 pp.

Hodder, R. L., and B. W. Sindelar. 1972. Coal mine reclamation research located at Decker, Montana. Montana Ag. Exp. Stat. Res. Report 20, Montana State University, Bozeman. 29 pp.

Jackson, C. L. 1982. An update of Urad mine reclamation. *In* R. L. Cuany and J. Etra (eds.), High-altitude revegetation workshop no. 5. Colo. Water Res. Research Inst. Information Series No. 48, Colorado State University, Fort Collins, CO. pp. 79-105.

Johnston, R. S., R. W. Brown, and J. Cravens. 1975. Acid mine rehabilitation problems at high elevations. *In* Watershed management symposium proceedings. Am. Soc. Civil Engineers, New York. pp. 66-79.

Jury, W. A., and B. Bellantuoni. 1976. Heat and water movement under surface rocks in a field soil: II. Moisture effects. Soil Sci. Soc. Am. J. 40:509-513.

Kay, B. L. 1978. Mulches for erosion control and plant establishment on disturbed sites. *In* S. T. Kenney (ed.), High-altitude revegetation workshop no. 3. Colo. Water Res. Research Inst. Information Series No. 28. Colorado State University, Fort Collins, CO. pp. 181-203.

Klages, M. G., and R. W. Hopper. 1982. Clay minerals in Northern Plains coal overburden as measured by x-ray diffraction. Soil Sci. Soc. Am. J. 46:415-419.

Knechtel, M. M. 1959. Stratigraphy of the Little Rocky Mountains and adjacent foothills. U.S.G.S. Bull. No. 1072-N.

Knipe, O. D. 1973. Western wheatgrass germination as related to temperature, light, and moisture stress. J. Range Manage. 26:68-69.

Knipe, O. D., and C. H. Herbel. 1960. The effects of limited moisture on germination and initial growth of six grass species. J. Range Manage. 13:297-302.

Kolar, C. A., W. C. Ashby, and G. R. Philo. 1981. Differential performance of trees planted on reclaimed surface-mined land. *In* Symposium on surface mining hydrology, sedimentology, and reclamation. University of Kentucky, Lexington. pp. 271-278.

Lawson, J. A. 1984. Suitability of an alluvial overburden material as a plant growth medium at the Berkeley Complex in Butte, Montana. M.S. Thesis, Montana State University, Bozeman, MT. 110 pp.

Lund, R. E. 1983. MSUSTAT statistical package, version 2.20. Montana State University, Bozeman, MT.

McGinnies, W. J. 1960. Effects of moisture stress and temperature on the germination of six grasses. Agron. J. 52:159-162.

Meeuwig, R. O. 1971. Infiltration and water repellancy in granitic soils. Int. Forest and Range Exp. Stat. Res. Paper INT-111. U.S.D.A. Forest Service, Ogden, UT.

National Oceanic and Atmospheric Administration. 1966-1984. Monthly precipitation and temperature data from recording stations: Montana. U.S. Dept. of Comm., Env. Data and Information Service, National Climatic Center, Asheville, NC.

Nelson, J. R., A. M. Wilson, and C. J. Goebel. 1970. Factors influencing broadcast seeding in bunchgrass range. J. Range Manage. 23:163-169.

Nielson, R. F., and H. B. Peterson. 1978. Vegetating mine tailings ponds. *In* F. W. Schaller and P. Sutton (eds.), Reclamation of drastically disturbed lands. Am. Soc. of Agron., Madison. pp. 645-652. ✓

Parady, F. E. 1981. Investigation of selected Berkeley Pit overburden as a medium for plant growth. M.S. Thesis, Montana State University, Bozeman, MT. 83 pp.

Peech, M. 1965. Hydrogen-ion activity. *In* C. A. Black (ed.), Methods of soil analysis, part 2. Agron. Monogr. 9, Am. Soc. of Agron., Madison. Chapt. 60.

Peters, D. B. 1965. Water availability. *In* C. A. Black (ed.), Methods of soil analysis, part 1. Agron. Monogr. 9, Am. Soc. of Agron., Madison. Chapt. 19.

Ramani, R. V., and E. C. Grim. 1978. Surface mining: A review of practices and progress in land disturbance control. *In* F. W. Schaller and P. Sutton (eds.), Reclamation of drastically disturbed lands. Am. Soc. of Agron., Madison. pp. 241-270.

Richards, L. A. 1965. Physical condition of water in the soil. *In* C. A. Black (ed.), Methods of soil analysis, part 1. Agron. Monogr. 9, Am. Soc. of Agron., Madison. Chapt. 20.

Richardson, B. Z. 1980. Reclamation of acid-producing spoils on a western surface mine. *In* C. L. Jackson and M. A. Schuster (eds.), High-altitude revegetation workshop no. 4. Colo. Water Res. Research Inst. Information Series No. 42, Colorado State University, Fort Collins, CO. pp. 101-111.

Riddle, J. M., and L. W. Saperstein. 1978. Premining planning to maximize effective land use and reclamation. *In* F. W. Schaller and P. Sutton (eds.), Reclamation of drastically disturbed lands. Am. Soc. of Agron., Madison. pp. 223-240. ✓

Ross, R. L., and H. E. Hunter. 1976. Climax vegetation of Montana. U.S.D.A. Soil Conservation Service, Portland, OR. 64 pp.

Sandoval, F. M., and J. F. Power. 1977. Laboratory methods recommended for chemical analysis of mined-land spoil and overburden in western United States. Ag. Handbook 525. U.S.D.A., Washington, D.C. 31 pp.

Smith, J. A. 1984. Wood residue and fertilizer amendments for reclamation of orphan bentonite spoils. M.S. Thesis, University of Wyoming, Laramie, WY. 106 pp.

Soil Conservation Service. 1983. National Soils Handbook. U.S. Govt. Printing Office, Washington, D.C.

Stark, N. 1982. The soils and ecology of establishing ponderosa pine on reclaimed mine lands. *In* Symposium on surface mining in the Northern Great Plains, Billings, MT. Montana Ag. Exp. Stat. Res. Report 194, Montana State University, Bozeman, MT.

Thornthwaite, C. W., and J. R. Mather. 1955. The water balance. Publications in climatology, vol. 8, no. 1. Drexel Inst. of Tech., Centerton, NJ. 104 pp.

Thornthwaite, C. W., and J. R. Mather. 1957. Instructions and tables for computing potential evapotranspiration and the water balance. Publications in climatology, vol. 10, no. 3. Drexel Inst. of Tech., Centerton, NJ. 311 pp.

U.S. Salinity Staff. 1954. Diagnosis and improvement of saline and alkali soils. Ag. Handbook 60. U.S.D.A., Washington, D.C. 160 pp.

Ward, R. C. 1975. Principles of hydrology. McGraw-Hill Publishing Co., Ltd., London. 2nd ed. 367 pp.

Whittig, L. D. 1965. X-ray diffraction techniques for mineral identification and mineralogical composition. *In* C. A. Black (ed.), Methods of soil analysis, part 2. Agron. Monogr. 9, Am. Soc. of Agron., Madison. Chapt. 92.

Wilson, A. M., J. R. Nelson, and C. J. Goebel. 1970. Effects of environment on the metabolism and germination of crested wheatgrass seeds. J. Range Manage. 23:283-288.

APPENDICES

APPENDIX A

ESTIMATION OF COARSE FRAGMENT CONTENT IN WASTE ROCK

Coarse fragment content in the waste rock could not be determined by sieving because most of the fragments were too large to be included in samples. Volume estimates could have accounted for these large fragments, but visual estimation of the volume of smaller fragments and the <2 mm fraction was difficult. Because of the wide range of fragment size in the waste rock dumps, neither the weight nor volume method could produce reliable estimates of fragment content. To adequately estimate fragment content, visual volume estimates were combined with weight measurements. Volume estimates were used for large fragments, and weight measurements were used to separate small fragments from the <2 mm fraction.

Five 1 m profiles were dug on the faces of two lifts at the dump. Coarse fragments were visually estimated and separated into categories. Fragments larger than 5 cm were estimated to occupy 40% of the total volume. Fragments less than 5 cm and the <2 mm fraction were estimated to occupy 50%; the remaining 10% was large voids between fragments. The <5 cm fraction was sampled for sieving; the five samples weighed 900 to 1200 g.

Coarse fragment content in these samples was calculated as a percentage by weight. These weight percentages for <5 cm fragments were converted to volume percentages so that small and large fragment volumes could be combined. The following formula, which was devised by Alexander (1984), was used for the weight-to-volume conversion:

$$V_{cf} = \frac{100\ W_{cf}}{W_{cf} + (100\text{-}W_{cf})/(BD_s/BD_{cf})}$$

where: V_{cf} = % volume of coarse fragments

W_{cf} = % weight of coarse fragments (decimal)

BD_s = soil bulk density

BD_{cf} = bulk density of coarse fragments

For purposes of this study, the ratio of soil bulk density to bulk density of coarse fragments was assumed to be 0.5.

The volume percentages were then multiplied by .50, which was the estimated fraction of the total volume occupied by <5 cm material. The product obtained from this multiplication was added to 40%, which was the estimated percentage of fragments larger than 5 cm. The resulting percentage was the estimate of total rock fragments by volume. The volume estimate calculations are summarized in Table 9.

Table 9. Calculation of Coarse Fragment Content.

Sample No.	Fragments 2 mm to 5 cm			Fragments > 5 cm	Total (%)
	% by wt.	% by vol.	% of total vol.		
1	89.5	81.0	40.5	40	80.5
2	82.5	70.2	35.1	40	75.1
3	83.8	71.5	35.8	40	75.8
4	81.5	68.8	34.4	40	74.4
5	78.1	64.1	32.1	40	72.1
$\overline{x}$	83.1	71.1	35.6	40	75.6

The total coarse fragment volume estimates range from 72.1 to 80.5%, with a mean of 75.6%. The remaining volume consists of 10% large voids and the <2 mm fraction.

APPENDIX B

WATER BALANCE CALCULATIONS

The Thornthwaite method was used to calculate potential evapotranspiration and the water balance for the waste rock dump, tailings, and clay pit. The method uses empirical formulae which predict potential evapotranspiration (PET) based upon air temperature:

$$PET = 1.6(10T_m/I)^a$$

$$a = 6.75 \times 10^{-7}(I^3) - 7.71 \times 10^{-5}(I^2) + .01792(I) + .49239$$

$$i = (T_m/5)^{1.514}$$

where PET = potential evapotranspiration (cm/month)

T_m = mean monthly air temperature (°C)

I = sum of monthly heat indices (i)

For purposes of this study, mean monthly air temperature and precipitation data from the Zortman weather station were used. These data were obtained from monthly climatic summaries published by the National Oceanic and Atmospheric Administration (NOAA, 1966–1985).

The water balance calculations involve simple accounting and the use of tables generated by Thornthwaite and Mather (1957). Monthly PET is subtracted from mean monthly precipitation (P). The negative P-PET values are cumulatively summed to obtain a monthly accumulated potential water loss (APWL) which represents the potential water deficit. The monthly APWL value is used to determine the amount of soil water retained by the soil after a given amount of PET has occurred. This value is obtained from a table which corresponds to the water holding capacity of the soil. The table value which corresponds to the APWL value is the amount of soil water (SW) which is retained at the end of the month. The change in soil water (CSW) value represents the month-to-month fluctuation in soil water retention.

The amount of actual evapotranspiration (AET) represents the amount of water loss which can occur, given the amount of precipitation and soil water which is available. When

P exceeds PET, AET equals PET. When PET exceeds P, soil water use begins, and AET equals P plus the absolute value of CSW. The deficit (D) represents the amount of water needed to maintain a constant soil water level, which is of value in irrigation planning. The deficit equals PET minus AET.

The water balance calculations for each site are shown in Tables 10, 11, and 12. These calculations are for a soil depth of 30 cm, nm, which was assumed to be the maximum depth of primary root activity for seedlings. The available water holding capacities of the materials and the corresponding soil water retention tables which were used are shown in Table 13. The AWC of the materials were calculated using the following formula:

$$\mathrm{AWC} = (\mathrm{FC} - \mathrm{WP})/100 \times \mathrm{BD} \times (100\,\mathrm{CF}/100) \times 300\,\mathrm{mm}$$

where: FC = % gravimetric water at field capacity
WP = % gravimetric water at permanent wilting point
BD = bulk density (assumed to be 1.35)
CF = % coarse fragments by volume

Table 10. Water Balance Calculations for the Waste Rock Dump (AWC = 12 mm).

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
P (mm)	22	14	24	47	72	94	53	43	47	19	12	16
PET	0	0	0	28	70	102	128	121	67	33	0	0
P–PET	22	14	24	19	2	-8	-75	-78	-20	-14	12	16
APWL	–	–	–	–	–	-8	-83	-161	-181	-195	–	–
SW	12	12	12	12	12	5	0	0	0	0	12	12
CSW	0	0	0	0	0	-7	-5	0	0	0	+12	0
AET	0	0	0	28	70	101	58	43	47	19	0	0
D	0	0	0	0	0	1	70	78	20	14	0	0

Table 11. Water Balance Calculations for the Tailings Site (AWC = 25 mm).

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
P (mm)	22	14	24	47	72	94	53	43	47	19	12	16
PET	0	0	0	28	70	102	128	121	67	33	0	0
P–PET	22	14	24	19	2	-8	-75	-78	-20	-14	12	16
APWL	–	–	–	–	–	-8	-83	-161	-181	-195	–	–
SW	25	25	25	25	25	17	1	0	0	0	12	25
CSW	0	0	0	0	0	-8	-16	-1	0	0	+12	+13
AET	0	0	0	28	70	102	69	44	47	19	0	0
D	0	0	0	0	0	0	59	77	20	14	0	0

Table 12. Water Balance Calculations for the Clay Pit (AWC = 75 mm).

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
P (mm)	22	14	24	47	72	94	53	43	47	19	12	16
PET	0	0	0	28	70	102	128	121	67	33	0	0
PnPET	22	14	24	19	2	-8	-75	-78	-20	-14	12	16
APWL	–	–	–	–	–	-8	-83	-161	-181	-195	–	–
SW	55	69	75	75	75	67	23	8	6	5	17	33
CSW	22	14	6	0	0	-8	-44	-15	-2	-1	12	16
AET	0	0	0	28	70	102	97	58	49	20	0	0
D	0	0	0	0	0	0	31	63	18	13	0	0

Table 13. Available Water Holding Capacities (AWC) and Corresponding Soil Water Retention Tables Used in Water Balance Calculations.

Material	AWC	Table
Waste rock	11.2 mm	12 mm
Tailings	23.9 mm	25 mm
Clay	62.1 mm	75 mm

The water balance data were depicted graphically by plotting P, PET, and AET (Figures 5, 7, and 9). Data were converted from mm to cm to simplify the diagrams.

APPENDIX C

STATISTICAL ANALYSES OF GERMINATION DATA

Table 14. ANOV and LSD Analysis for Mean Germination Percentages for the Waste Rock Dump.

Source	D.F.	S.S.	M.S.	F
Blocks	8	.03291	.004114	.7099
Species	3	.5038	.1679	28.98*
Error	24	.1391	.005795	
Total	35			

Species	MGP
Bromus marginatus	3.11 a**
Agropyron dasystachyum	6.89 a
Festuca ovina	13.46 b
Agropyron spicatum	33.77 c

*Significant at the 0.05 level.

**MGP values followed by the same letter are not significantly different at the 0.05 level.

Table 15. ANOV and LSD Analysis for Mean Germination Percentages for the Tailings Site.

Source	D.F.	S.S.	M.S.	F
Blocks	8	.0643	.008037	1.701
Species	3	.1648	.05494	11.63*
Error	24	.1134	.004724	
Total	35			

Species	MGP
Agropyron spicatum	3.30 a**
Festuca ovina	15.02 b
Agropyron dasystachyum	15.42 b
Bromus marginatus	22.10 c

*Significant at the 0.05 level.

**MGP values followed by the same letter are not significantly different at the 0.05 level.

Table 16. ANOV and LSD Analysis for Mean Germination Percentages for the Clay Pit.

Source	D.F.	S.S.	M.S.	F
Blocks	2	.05890	.02945	6.67*
Species	2	.17740	.08870	20.10*
Error	22	.09708	.004413	
Total	26			

Blocks	MGP
1	1.73 a**
3	11.56 b
2	11.71 b

Species	MGP
Agropyron smithii	0.70 a**
Agropyron dasystachyum	4.73 a
Agropyron riparium	19.56 b

*Significant at the 0.05 level.

**MGP values followed by the same letter are not significantly different at the 0.05 level.

APPENDIX D

PHYSICAL AND CHEMICAL PROPERTIES OF WASTE ROCK, TAILINGS, AND CLAY

Table 17. Physical and Chemical Properties of the Waste Rock.

Depth (cm)	pH	Ec (mmhos/cm)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	SAR	NO_3-N (ppm)	P (ppm)	K (ppm)	% Sand	% Silt	% Clay	Sat. %
0-5	7.9	0.65	100.4	19.4	15.6	0.37	3.0	11.5	44.8	77	10	13	21.5
15-30	7.7	0.16	8.4	2.6	6.8	0.53	2.9	13.4	40.4	70	13	17	22.3
0-5	7.4	0.21	16.8	4.4	9.0	0.51	2.8	12.4	32.0	70	16	14	20.3
15-30	7.2	0.15	10.4	3.0	6.7	0.47	3.0	11.5	30.4	76	12	12	24.7
0-5	7.4	0.21	19.3	9.8	10.2	0.47	3.1	13.7	43.6	59	23	18	18.5
15-30	7.4	0.13	11.5	7.6	10.3	0.58	2.3	10.6	48.4	61	22	17	24.4

Table 18. Physical and Chemical Properties of the Tailings.

Depth (cm)	pH	Ec (mmhos/cm)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	SAR	NO_3-N (ppm)	P (ppm)	K (ppm)	% Sand	% Silt	% Clay	% CF	Sat. %
0-5	7.5	1.73	552.0	8.4	6.8	0.08	3.6	4.9	84.2	80	12	8	29	18.6
15-30	7.6	2.12	632.4	26.3	9.2	0.10	3.8	4.9	86.7	86	7	7	24	16.5
0-5	7.4	2.06	600.0	16.5	11.8	0.13	3.7	5.1	121.6	83	9	8	26	15.4
15-30	7.6	1.93	608.4	15.8	12.3	0.13	4.3	7.1	90.3	80	9	11	29	15.6

Table 19. Physical and Chemical Properties of the Clay.

Block	Depth (cm)	pH	Ec (mmhos/cm)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	SAR	NO_3-N (ppm)	P (ppm)	K (ppm)	% Sand	% Silt	% Clay	% CF	Sat. %
1	0-5	7.9	1.85	218.3	150.0	64.0	0.82	8.3	7.8	144.0	11	51	38	0.7	57
	15-30	7.9	2.72	188.5	212.7	302.7	3.59	6.8	8.7	170.8	3	35	62	0.9	66
	0-5	8.1	0.46	18.2	39.6	15.7	0.47	4.4	7.5	125.6	18	39	43	1.1	49
	15-30	8.1	1.20	28.2	41.2	52.8	1.48	4.4	6.0	134.0	14	52	34	0.8	78
2	0-5	8.0	2.45	440.0	210.5	95.4	0.94	5.4	3.5	235.9	8	41	51	0.6	69
	15-30	7.9	4.16	444.6	481.3	354.0	2.77	10.8	1.8	237.0	8	39	53	1.1	76
	0-5	8.1	2.40	430.8	207.4	57.5	0.57	5.8	19.6	243.5	5	42	53	0.7	61
	15-30	7.9	4.84	390.4	513.0	526.7	4.13	3.8	7.9	166.9	10	37	53	0.8	75
3	0-5	8.2	1.42	199.5	127.0	10.2	0.14	3.3	1.5	174.6	24	40	36	0.9	52
	15-30	8.0	2.53	351.3	309.0	80.4	0.75	3.1	—	178.2	24	46	30	0.8	51
	0-5	8.3	0.46	30.9	26.3	26.2	0.84	4.9	—	213.4	12	52	36	1.0	64
	15-30	8.3	0.61	13.3	51.4	58.7	1.63	3.3	—	190.5	10	61	29	0.9	75

Table 20. Clay Minerals in Clay Pit Samples.

Block	Illite %	Kaolinite %	Smectite %	Vermiculite %
1	40	30	–	20*
	50	30	trace	20
2	50	20	20	–*
	50	20	20	–*
3	50	30	–	20
	50	30	trace	20

*Remaining volume was 10% quartz.

APPENDIX E

PRECIPITATION DATA FOR ZORTMAN, MONTANA

Table 21. Average Long Term Monthly Precipitation, 1984 Monthly Precipitation, and Deviation from Monthly Average for Zortman, MT.

Month	Average Precipitation (cm)*	1984 Precipitation (cm)	Deviation (cm)
January	2.2	no data	—
February	1.4	no data	—
March	2.4	no data	—
April	4.7	no data	—
May	7.2	2.6	-4.6
June	9.4	7.4	-2.0
July	5.3	1.1	-4.2
August	4.3	2.7	-1.6
September	4.7	5.2	+0.5
October	1.9	1.7	-0.2
November	1.2	2.0	+0.8
December	1.6	no data	—

*Data from 1966-1983.

APPENDIX F

SOIL WATER DATA

Table 22. Results of Retention Analysis for Waste Rock (n = 5).

	Suction (bar)					
	0	−0.1	−0.33	−1	−3	−15
mean	22.82	16.96	13.61	12.26	9.59	5.60
s.d.	0.90	1.13	0.59	0.53	0.75	0.51

All values are % soil water by wt.

Table 23. Results of 1984 Soil Water Monitoring at the Waste Rock Dump.

Sample Depth (cm)	Sample Date			
	5/5/84	6/13/84	7/5/84	8/26/84
10 - 20	11.5	7.8	4.1	5.0
21 - 30	—	8.5	4.9	5.9

All values are % soil water by wt.

Table 24. Results of Retention Analysis for Tailings (n = 5).

	Suction (bar)					
	0	−0.1	−0.33	−1	−3	−15
mean	18.89	10.88	8.30	7.39	5.72	3.86
s.d.	0.80	0.98	0.87	1.10	0.72	0.52

All values are % soil water by wt.

Table 25. Results of 1984 Soil Water Monitoring at the Tailings Site.

Sample Depth (cm)	Sample Date 5/5/84	6/14/84	7/6/84	8/26/84
10 - 20	9.0	11.1	4.8	4.7
21 - 30	7.8	9.6	9.3	8.4

All values are % soil water by wt.

Table 26. Results of Retention Analysis for Clay (n = 3).

Block		Suction (bar) 0	−0.1	−0.33	−1	−3	−15
1	mean	67.80	41.91	35.52	29.98	24.10	21.78
	s.d.	8.66	4.63	3.30	3.24	1.43	5.75
2	mean	80.75	52.53	42.56	38.12	27.29	23.44
	s.d.	3.32	1.26	1.57	0.48	4.37	0.27
3	mean	58.01	40.59	33.06	28.75	24.18	19.47
	s.d.	6.46	6.49	5.76	5.11	3.73	2.90

All values are % soil water by wt.

Table 27. Results of 1984 Soil Water Monitoring at the Clay Pit.

Block	Sample Depth (cm)	Sample Date 5/5/84	6/14/84	7/7/84	8/27/84
1	10 - 20	15.0	16.6	14.3	9.9
	21 - 30	25.5	14.4	14.8	11.8
2	10 - 20	22.6	13.6	10.2	10.0
	21 - 30	21.5	15.2	11.9	11.1
3	10 - 20	18.2	15.2	13.0	9.8
	21 - 30	15.2	15.9	13.7	13.4

All values are % soil water by wt.

Table 28. Mean Infiltration Rate Over Time on Two Slopes at the Clay Pit.

	Infiltration Rate (mm/hr)	
Time (min.)	5 to 10% Slope	40 to 45% Slope
0	12.5	12.5
3	12.5	11.7
6	12.4	10.8
9	12.4	10.1
12	12.5	9.4
15	12.4	9.1
18	12.5	7.9
21	12.5	7.7
24	12.4	5.8
27	12.4	4.7
30	12.3	5.1

APPENDIX G

DSL AND SCS GUIDELINES

Table 29. Selected Montana Department of State Lands Guidelines Used to Evaluate Physical and Chemical Properties of the Waste Rock, Tailings, and Clay.

Parameter	Suspect Level
pH	<5.5, >8.5
EC (mmhos/cm)	>4.0
Sodium adsorption ratio	>11
Saturation %	<25%, >85%
Coarse fragments (% by wt.)	>35%
Textual class	c, sc, sic, cl*, sicl**, sil***, si, ls, s

*>35% clay.
**>35% clay, <15% sand.
***<15% sand.

Table 30. Selected Soil Conservation Service Guidelines Used to Evaluate Physical and Chemical Properties of the Waste Rock, Tailings, and Clay.

Parameter	Good	Fair	Poor
pH	5.6 – 7.8	4.5 – 5.5	4.5
EC (mmhos/cm)	<8	8 – 16	>16
Sodium adsorption ratio	<5	5 – 12	>12
Available water (cm/cm)	>.10	.05 – .10	<.05
Textural class	—	scl, cl, ls, sicl	c, sic, sc, s

DATE	ISSUED TO
[illegible]	[redacted]