Volume 2-Chapter 2, Section 2.9

MINERAL EXTRACTION (Mining) RECLAMATION

(NOTE: For final publication, this section will appear as part of Volume 2-Chapter 2.)

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Regional Copper-Nickel Study
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REGIONAL COPPER-NICKEL STUDY REPORT OUTLINE

A NOTE ABOUT UNITS

This report, which in total covers some 36 chapters in 5 volumes, is both international and interdisciplinary in scope. As a result, the problem of an appropriate and consistent choice of units of measure for use throughout the entire report proved insurmountable. Instead, most sections use the system of units judged most common in the science or profession under discussion. However, interdisciplinary tie-ins complicated this simple objective, and resulted in the use of a mix of units in many sections. A few specific comments will hopefully aid the reader in coping with the resulting melange (which is a reflection of the international multiplicity of measurement systems):

1) Where reasonable, an effort has been made to use the metric system (meters, kilograms, kilowatt-hours, etc.) of units which is widely used in the physical and biological sciences, and is slowly becoming accepted in the United States.

2) In several areas, notably engineering discussions, the use of many English units (feet, pounds, BTU's, etc.) is retained in the belief that this will better serve most readers.

3) Notable among the units used to promote the metric system is the metric ton, which consists of 2205 pounds and is abbreviated as mt. The metric ton (1000 kilograms) is roughly 10% larger (10.25%) than the common or short ton (st) of 2000 pounds. The metric ton is quite comparable to the long ton (2240 pounds) commonly used in the iron ore industry. (Strictly speaking, pounds and kilograms are totally different animals, but since this report is not concerned with mining in outer space away from the earth's surface, the distinction is purely academic and of no practical importance here).

4) The hectare is a unit of area in the metric system which will be encountered throughout this report. It represents the area of a square, 100 meters on a side (10,000 m^2), and is roughly equivalent to 2½ acres (actually 2.4710 acres). Thus, one square mile, which consists of 640 acres, contains some 259 hectares.

The attached table includes conversion factors for some common units used in this report. Hopefully, with these aids and a bit of patience, the reader will succeed in mastering the transitions between measurement systems that a full reading of this report requires. Be comforted by the fact that measurements of time are the same in all systems, and that all economic units are expressed in terms of United States dollars, eliminating the need to convert from British Pounds, Rands, Yen, Kawachas, Rubles, and so forth!

<u>Conversions for Common Metric Units Used in the Copper-Nickel Reports</u>

1 meter (m)	=	3.28 feet = 1.094 yards
1 centimeter (cm)	=	0.3937 inches
1 kilometer (km)	=	0.621 miles
1 hectare (ha)	=	10,000 sq. meters = 2.471 acres
1 square meter (m^2)	=	10.764 sq. feet = 1.196 sq. yards
1 square kilometer (km^2)	=	100 hectares = 0.386 sq. miles
1 gram (g)	=	0.037 oz. (avoir.) = 0.0322 Troy oz.
1 kilogram (kg)	=	2.205 pounds
1 metric ton (mt)	=	1,000 kilograms = 0.984 long tons = 1.1025 short tons
1 cubic meter (m^3)	=	1.308 yd^3 = 35.315 ft^3
1 liter (l)	=	0.264 U.S. gallons
1 liter/minute (l/min)	=	0.264 U.S. gallons/minute = 0.00117 acre-feet/day
1 kilometer/hour (km/hr)	=	0.621 miles/hour
degrees Celsius (°C)	=	(5/9)(degrees Fahrenheit -32)

2.9 RECLAMATION

An important operational and post-operational activity of any mining operation is the reclamation of mined lands and industrial sites to some productive use. Lands that have been mined and abandoned are termed "derelict" or "orphaned" lands. Such lands not only are more difficult to reclaim at a later date, but cause more erosion and air and water pollution than lands that are returned to some planned use as soon as active mining is completed. In the United States in 1971, metal mining reclaimed fewer acres than the coal industry, but the difference arose partly from efforts by the coal industry and government to reclaim a backlog of orphaned coal lands (Down and Stocks 1977). Metalliferous mines in the United States have generally been located in areas that are sparsely populated, thus reducing the psychological impact of unreclaimed lands. As mines are developed in areas with higher populations or with a large tourist industry, the aesthetic and psychological aspects of reclamation take higher priority than in largely unpopulated areas.

Reclamation includes all potential post-production uses of minelands, as well as those measures not inherent in the mining process that are used to mitigate adverse environmental impacts created during the course of mining. Because afteruses are not restricted to the establishment of natural plant and animal communities, reclamation should be distinguished from restoration, which attempts to return the land to its previous ecological condition (including agriculture or other previous uses) and revegetation, which may be restricted to mere provision of plant cover, and is only one of three aspects of reclamation recognized by the Bureau of Land Management in its definition of reclamation for potential wilderness areas (BLM 1979). According to this definition "Reclamation" in wilderness areas means:

1) Reshaping of the land disturbed or affected by mining operations, to its appropriate original contour or to an appropriate contour considering the surrounding topography.

2) Restoring such reshaped lands to a stable soil condition consistent with its pre-mining productivity and capable of supporting all practicable uses it was capable of supporting at the time of initiation of mining operations.

3) Revegetating the land, to provide a vegetative cover capable of self-regeneration and equal in its permanence to its vegetative state at initiation of mining operations.

Four levels of revegetation can be distinguished as part of reclamation goals directed toward agricultural production or forested lands. The first level, revegetation with annual cover, may be an intermediate goal in reforestation or a final goal in agricultural cropland. The second level is the establishment of self-sustaining herbaceous cover or non-woody perennial cover. This step is usually intermediate in the process of reforestation. A third level of revegetation, which may well be the final step in most mining areas, involves reforestation with exotic species, monocultural plantations, or invasion by native pioneer species into areas where succession is unlikely to proceed to more mature forests. This level of revegetation results in a forested landscape that can be perpetuated by management. The fourth level of revegetation, ecosystem restoration, involves the reconstruction of a self-perpetuating natural ecosystem whose structural and functional characteristics are analogous to the previous vegetation at the site or to mature communities in the area.

Restoration and possibly reclamation (depending upon desired reclamation goals) includes regeneration of soils comparable to those formerly in the area, reconstitution of hydrologic characteristics, and return of former or comparable species diversity, structural attributes, nutrient pathways, and productivity of the ecosystem. Such complete restoration is an unlikely goal for many mineland areas and an impossible goal for areas whose physical conditions have been altered beyond the normal range of variability of the natural landscape (such as steep slopes of poorly designed waste rock piles or walls of open pit mines). Because restoration seeks a return to former levels of ecosystem function associated with mature communities, its success cannot be measured until adequate time has elapsed for the revegetated area to undergo succession to the former state, probably 40 to 70 yr to become comparable with "mature" forests of the Study Area as they are today.

2.9.1 Reclamation Goals

Reclamation of some mine lands may not involve revegetation but rather may consist mainly of site conversion and perhaps construction of new facilities. Plant sites, office buildings, and large flat areas may best be converted to other industrial uses, if a demand for such facilities exists.

During the course of an operation, minelands are expected to be used in a variety of ways. Final reclamation goals will vary with mineland use, because each area will differ slightly in topographical, chemical, and biological characteristics and the costs of reclamation procedures will vary accordingly. Twelve land uses are differentiated in this discussion of reclamation, including: plant site, open pit mine, underground mine, overburden pile, lean ore pile, waste rock pile, tailing basin, smelter/refinery site, slag pile, undisturbed watershed, reservoir, and haul roads. Table 14 presents estimates of the amounts of materials expected to be generated from mines of various sizes, as well as the areas of land to be reclaimed.

Table 14

Table 14. Materials likely to be generated by the five alternate mine models generated by the Study.

PARAMETER	UNDERGROUND[a]	OPEN PIT[a]	UNDERGROUND	COMBINATION UNDERGROUND AND OPEN PIT	OPEN PIT
Mine size, 10^6 mtpy	5.35	11.33	12.35	16.68	20.00
Mine life, yr	30	30	30	30	30
Effective mine life, yr	23	25	23	24.4	25
Waste Disposal Quantities					
Overburden,[b] 10^6 yd^3	0	19	0	19	25
Waste rock,[b] 10^6 mt	12	184	28	196	325
Lean ore, 10^6 mt	0	184	0	184	325
Tailing, 10^6 mt	117	274	269	391	484
Slag, 10^6 mt	0	0	14	15	15
Total,[d] 10^6 mt	129	671	311	815	1,187
Area to be Revegetated (acres)					
Overburden	0	137	0	137	173
Waste rock	51	560	96	611	994
Lean ore	0	559	0	559	994
Tailing	1,067	2,348	2,309	3,279	4,016
Slag	0	0	25	25	25
Total	1,118	3,604	2,430	4,611	6,202
Number of Waste Piles, 200 ft height and up to 50 X 10^6 mt per pile					
Waste Rock	1	4	1	4	7
Lean Ore	0	4	0	4	6
Overburden	0	1	0	1	1
Total	1	9	1	9	14

[a]These smaller models consist of mining and processing only.

[b]Overburden shown as cubic yards and included in total below as metric tons.

[c]In this discussion, it is assumed that all non-ore material removed from the underground mine is waste rock which is adequate for the purposes of this section. However, Chapter 5 arbitrarily splits the non-ore material evenly between waste rock and lean ore to best serve the purposes of that chapter.

[d]Including overburden at a bulk density of 2 mt/m^3.

Both the amount of waste material generated and extent of surface disturbance are less for underground than for open pit mines. The higher grade ore extracted from an underground mine results in a smaller volume of tailing. Large quantities of waste rock are avoided in underground ore extraction, and no overburden is generated as no surface excavation is necessary to expose the mineralized rock. In addition to overburden and lean ore, which are unique to open pit operations, greater volumes of waste rock and tailing are generated by open pit mining. The discussions that follow are based on the model of the 20 X 10^6 mtpy open pit mine, which creates the largest reclamation task per unit of production as compared to the other models presented.

In order to adequately plan for future reclamation activities and to minimize the need for such work, the planned post-operational use of minelands should be determined during the pre-construction planning phase. As can be seen from Table 15, possible uses of reclaimed lands fall into 2 broad categories: natural ecosystems and human-use areas. Agricultural areas such as pasture, lakes, recreational facilities, and residential sites overlap these 2 categories. Table 15 shows major types of uses that can be expected for each of 12 types of mining areas. For example, abandoned haul roads and large, flat areas have the potential of providing transportation facilities, including roads, trails, airstrips, wildlife habitat, and forests.

Table 15

Not all lands and facilities are likely to become available for permanent reclamation at the same time. For tailing basins and waste rock piles, reclamation can be an ongoing process beginning whenever a portion of a given basin or pile is completed. Other areas, such as the plant site, will become available only

Table 15. Uses for reclaimed lands.

	OPEN PIT	UNDERGROUND MINE SITE	TAILING BASIN	LEAN ORE PILE	WASTE ROCK PILE	SLAG PILE	OVERBURDEN PILE	MILL SITE	SMELTER SITE	HAUL ROAD	RESERVOIR	UNDISTURBED WATERSHED	
Agricultural		X	X					X			O	X	Pasture, haylands, nurseries, sod farms
Wildlife Openings		X	X		X	X	X	X	X	X	O	X	Forage, brose, cover, travel corridors
Forested Lands		X	X		X	X	X	X	X	X	O	X	Multiple use but not commercial forest products
Intensive Forestry		X	X				X	X	X		O	X	Commercial forestry
Lakes and Ponds	X		X								X		May or may not be open to fisheries/recreation
Recreational Facilities		X	X		X	X	X	X	X	X	X	X	Rifle ranges, historic sites, hiking areas, playgrounds, race tracks, golf courses, ski slopes, campgrounds, snowmobile trails
Residential Sites		X					X	X	X		O	X	Housing near population centers and natural amenities
Transportation Facilities										X			Roads, trails, airstrips
Industrial Sites		X						X	X				
Waste Disposal	X	X					X	X	X				Sanitary landfills, sewage disposal
Other		X	X		X	X	X	X	X	X			Underground storage, bombing ranges, sites for communication towers

X Possible uses, based on the judgement of Copper-Nickel Study staff, taking into account suggestions and reports in the literature and assuming that the most economically feasible methods of reclamation are used.

O If filled in.

when the entire operation is completed. Table 16 shows the point in the typical life of the operation at which each of the 12 major mining land use areas is likely to become available for reclamation.

Table 16

As has been suggested earlier, reclamation goals, availability of lands for reclamation, and necessary treatments can be expected to vary depending on mineland use. Table 17 suggests the levels of revegetation that may be achieved on lands that have supported each of the 12 mineland uses, assuming that all necessary ameliorative steps are economically feasible and that reclaimed lands are maintained long enough to assure success. Table 18 suggests steps that are appropriate to treat each of 10 environmental conditions that adversely affect revegetation. Table 19 is a matrix showing which of these conditions occur in each type of mineland. Tables 20 through 23 illustrate the steps necessary to revegetate each use area to each level of revegetation. Potential costs of ameliorative practices are summarized in Table 24. Together, Tables 17 through 23 can be used to identify the relationships between mining land uses, environmental conditions, mitigating procedures, and costs. However, a fuller explanation of these relationships is presented in sections 2.9.1.1 to 2.9.1.11 (immediately following the tables), discussing reclamation of each mineland type. All these factors are likely to figure in the choice of reclamation goals and methods at the site-specific level. If the area of concern is a waste rock pile, the associated environmental conditions can be identified from Table 19. Procedures useful in reclaiming steep slopes can be ascertained from Table 18 and their relative costs from Table 24. Although Table 17 suggests that waste rock piles can be converted to forested lands, this goal might be modified on the basis of

Table 16. Stage at which mine areas would be available for reclamation.

TYPE OF MINING USE	WHEN AVAILABLE	TYPE OF RECLAMATION[a]	
		Temporary	Permanent
Open pit	Cessation of mining		X
Smelter site	Cessation of smelting		X
Lean ore pile	Completion of pile (will depend on design)	X	
Waste rock pile	Completion of pile (will depend on design)		X
Tailing basin	Dormant periods in single basin	X	
	Completion of basin or cells		X
Underground mine site	Closing of shaft		X
Overburden pile	Storage periods	X	
	Completion of pile		X
Mill site	Cessation of beneficiation		X
Undisturbed watershed	Continuous maintenance	X	X
Slag pile	Completion of pile		X
Reservoir	Continued maintenance	X	X
	Conversion to terrestrial		X
Haul roads	When roads become inactive		X
	During operation	X	

[a]This assumes, in the case of permanent reclamation, that the mine is exhausted and no change in technology or market conditions could cause it to reopen. Otherwise, many permanent types of reclamation would become temporary.

cost or of the number of preparatory steps, shown in Table 22. In the discussion that follows, each type of mineland is treated separately.

Tables 17-24

2.9.1.1 Open Pit Mines--Open pit mines which may be 1.6 to 4.8 km (1 to 3 mi) long, 0.8 to 1.6 km (0.5 to 1 mi) wide, and 240 to 460 m (800 to 1,500 ft) deep are unlikely to be reclaimed except by conversion to lakes. Because precipitation exceeds evaporation in the Study Area, any other use would require continual pumping or filling with solid material. Models developed by the Regional Study suggest that a 20 X 10^6 mtpy open pit mine would require a 1,287 ha (523 acre) pit with dimensions of 1,994 by 1,048 m and a depth of 273 m. Assuming an average groundwater seepage of 300 acre-ft/yr with regional precipitation of 2.4 ft/yr (73 cm/yr) and an annual evaporation of 1.3 ft (40 cm), an annual input of 919 acre-ft (50 cm/yr) is anticipated from an area of 563 acres including actual pit area of 523 acres plus 40 acres surrounding the pit to accommodate mine facilities. At this rate of input, the pit would fill in approximately 340 yr.

The rate of open pit filling will vary with groundwater discharge into the pit which is dependent on the thickness and textural properties of surficial materials, the saturated thickness, hydraulic gradient, and hydraulic conductivity of the overburden (see Volume 3-Chapter 1). The highest rates of discharge can be expected in areas where thick sands or gravels are in communication with both a body of water and the open pit. Lowest inputs from groundwater can be expected in the areas where surficial materials are shallowest.

In order to assess the probable water quality in an open pit lake, the Regional Study's model took into account the leaching of metals from the walls of a

Table 17. Levels of natural reclamation achievable in areas with various mining histories.

	OPEN PIT[a]	SMELTER SITE	LEAN ORE PILE	MILL SITE	WASTE ROCK PILE	TAILING BASIN	UNDERGROUND MINE SITE	UNDISTURBED WATERSHED	OVERBURDEN PILE[b]	SLAG PILE[c]	RESERVOIR	HAUL ROADS
Annual Cover Revegetation	X	X	X	X	X	X	X	X	X			X
Self-Sustaining Herbaceous Vegetation (Revegetation)	X	X	X	X	X	X	X	X	X			X
Planted Forest Revegetation	X	X	X	X	X	X	X	X	X			X
Self-Sustaining Forest Similar to Original Vegetation	d	X	d	X	X	X	X	X				X
Pond or Lake	X					X	d	X			X	
Other	X	X	X	X	X	X	X					

[a]Reclamation of overburden bank slopes above ore zone only.
[b]Can be expected to be redistributed as topdressing.
[c]Most likely to be used as construction material.
[d]Economics may change conditions before lifetime of mine is over.

Table 18. Ameliorative treatments for various environmental conditions commonly found in mine lands.

CONDITION	DRAINING	MECHANICAL LOOSENING	TOPDRESSING	CONTOURING	APPLICATION OF INORGANIC STABILIZER	LIMING	FERTILIZATION	APPLICATION OF ORGANIC MATTER	ADDITION OF MICROBIAL INOCULUM	SEEDING	PLANTING	IRRIGATION	INVASION BY NATIVE SPECIES	MULCHING	APPLICATION OF SEWAGE SLUDGE
Droughtiness			X					X				X		X	
Poor Drainage	X	X		X				X		X	X				
Lack of Nutrients			X			X	X	X	X						X
Acidity			X			X		X							X
Heavy Metals			X			X		X							
Physically Unreceptive Surfaces		X	X	X		X	X	X	X					X	X
Excess Slope				X	X								X	X	X
Heat Stress			X					X						X	X
Wind Erosion			X		X			X		X	X			X	X
Compaction		X	X					X						X	
Eye Pollution			X	X				X		X	X		X	X	

Table 19. Occurrence of adverse environmental conditions in areas subjected to eleven mine land uses.

ENVIRONMENTAL CONDITION	OPEN PIT	SMELTER SITE	LEAN ORE PILE	MILL SITE	WASTE ROCK PILE	TAILING BASIN	UNDERGROUND MINE SITE	UNDISTURBED WATERSHED	OVERBURDEN PILE	RESERVOIR	SLAG PILE	HAUL ROADS
Droughtiness	X[a]		X		X	X					X	
Poor Drainage	X					X						
Lack of Nutrients	X	X	X		X	X					X	
Acidity			X									
Heavy Metals	X	X	X			X						
Physically Unreceptive Surfaces	X[a]		X		X	X					X	X
Excess Slope	X[a]		X		X				X		X	
Heat Stress[b]	X		X		X	X			X			
Wind Erosion of Particulates	X		X		X	X			X			X
Compaction		X	X	X	X		X		X		X	X
Eye Pollution	X	X	X		X				X		X	X

[a]Walls.
[b]On south-facing slopes.

Table 20. Amelioration practices which may be needed to attain revegetation with annual cover on areas with different mining history.[a,b]

	OPEN PIT[c]	SMELTER SITE	LEAN ORE PILE	MILL SITE	WASTE ROCK PILE	TAILING BASIN	UNDERGROUND MINE SITE	UNDISTURBED WATERSHED	OVERBURDEN PILE	RESERVOIR[d]	SLAG PILE	HAUL ROADS
Draining						X						
Mechanical Loosening of Soil				X			X		X			X
Topdressing		X	X	X	X	X	X				X	
Contouring	X		X		X	X			X		X	
Application of Organic Stabilizers						X						
Liming[e]			X		X	X						
Fertilization			X		X	X			X			
Application of Organic Matter			X		X	X						
Addition of Microbial Inoculum					X	X						
Seeding	X	X	X	X	X	X	X		X		X	
Planting												
Irrigation												
Natural Invasion by Native Species	X		X	X	X	X	X	X	X		X	X
Mulching					X	X						
Application of Sewage Sludge						X						

[a]Descriptions of ameliorative practices are discussed in the text, sections 2.9.1.1 to 2.9.1.11.

[b]Revegetation with annual cover may be the final goal where it is being used to stabilize temporary surfaces; or it may be an intermediate step in establishing more permanent vegetation on completed surfaces.

[c]Assume that open pit is converted to a lake with revegetation efforts restricted to upper slopes.

[d]Assume that reservoirs are not contaminated with recycle water and may be maintained as lakes, rather than being converted to terrestrial ecosystems.

[e]If highly acid materials are generated (unlikely in the case of a Minnesota copper-nickel industry).

Table 21. Amelioration practices which may be needed to attain self-sustaining herbaceous vegetation on areas with different mining history.[a,b]

	OPEN PIT[c]	SMELTER SITE	LEAN ORE PILE	MILL SITE	WASTE ROCK PILE	TAILING BASIN	UNDERGROUND MINE SITE	UNDISTURBED WATERSHED	OVERBURDEN PILE	RESERVOIR[d]	SLAG PILE	HAUL ROADS
Draining	X					X						
Mechanical Loosening of Soil		X	X	X			X		X			X
Topdressing		X	X	X	X	X	X				X	
Contouring	X		X		X	X			X		X	
Application of Organic Stabilizers						X						
Liming[e]		X	X		X	X					X	
Fertilization	X	X	X	X	X	X			X		X	
Application of Organic Matter		X			X	X					X	
Addition of Microbial Inoculum	X	X	X	X	X	X			X		X	
Seeding	X	X	X	X	X	X	X		X		X	
Planting												
Irrigation												
Natural Invasion by Native Species	X	X	X	X	X	X	X	X	X		X	X
Mulching			X		X	X					X	
Application of Sewage Sludge						X						

[a]Descriptions of ameliorative practices are discussed in the text, sections 2.9.1.1 to 2.9.1.11.

[b]Achievement of self-sustaining annual or perennial non-woody vegetation may be the final goal in stabilizing temporary surfaces for periods of more than a year, or it may be an intermediate step in the achievement of forest cover.

[c]Assume that open pit is converted to a lake with revegetation efforts restricted to upper slopes.

[d]Assume that reservoirs are not contaminated with recycle water and may be maintained as lakes, rather than being converted to terrestrial ecosystems.

[e]If highly acid materials are generated (unlikely in the case of a Minnesota copper-nickel industry).

Table 22. Ameliorative practices which may be needed to attain planted forest cover on areas with different mining history.[a,b]

	OPEN PIT[c]	SMELTER SITE	LEAN ORE PILE	MILL SITE	WASTE ROCK PILE	TAILING BASIN	UNDERGROUND MINE SITE	UNDISTURBED WATERSHED	OVERBURDEN PILE	RESERVOIR[d]	SLAG PILE	HAUL ROADS
Draining	X											
Mechanical Loosening of Soil		X	X	X			X		X			X
Topdressing		X	X	X	X	X	X				X	
Contouring	X		X		X	X			X		X	
Application of Organic Stabilizers						X						
Liming[e]		X	X		X	X					X	
Fertilization	X	X	X	X	X	X			X		X	
Application of Organic Matter		X	X		X	X			X		X	
Addition of Microbial Inoculum	X	X	X	X	X	X			X		X	
Seeding	X	X	X	X	X	X	X		X		X	
Planting	X	X	X	X	X	X	X		X		X	
Irrigation												
Natural Invasion by Native Species	X	X	X	X	X	X	X	X	X		X	X
Mulching			X		X	X						
Application of Sewage Sludge						X						

[a] Descriptions of ameliorative practices are discussed in the text, sections 2.9.1.1 to 2.9.1.11.

[b] Achievement of forested cover by pioneer or exotic species may be the long-range goal in areas that are too steep to be restored to an ecosystem similar to that previously in the area or may be an intermediate step in ecosystem restoration.

[c] Assume that open pit is converted to a lake with revegetation efforts restricted to upper slopes.

[d] Assume that reservoirs are not contaminated with recycle water and may be maintained as lakes, rather than being converted to terrestrial ecosystems.

[e] If highly acid materials are generated (unlikely in the case of a Minnesota copper-nickel industry).

Table 23. Ameliorative practices which may be needed to attain ecosystem restoration on areas with different mining history.[a,b]

	OPEN PIT[c]	SMELTER SITE	LEAN ORE PILE[d]	MILL SITE	WASTE ROCK PILE[d]	TAILING BASIN	UNDERGROUND MINE SITE	UNDISTURBED WATERSHED	OVERBURDEN PILE	RESERVOIR[d,e]	SLAG PILE[c]	HAUL ROADS
Draining						X						
Mechanical Loosening of Soil		X	X	X			X		X			X
Topdressing						X						
Contouring						X			X			
Application of Organic Stabilizers						X						
Liming[f]		X		X		X						
Fertilization		X		X		X						
Application of Organic Matter		X		X		X						
Addition of Microbial Inoculum		X		X		X						
Seeding		X		X		X	X		X			
Planting		X		X		X	X		X			
Irrigation												
Natural Invasion by Native Species		X		X		X	X	X	X			X
Mulching						X						
Application of Sewage Sludge						X						

[a]Descriptions of ameliorative practices are discussed in the text, sections 2.9.1.1 to 2.9.1.11.

[b]Restoration of the natural ecosystem is a feasible goal in areas where physical conditions such as topography, heat, and hydrologic features are similar to those that occur naturally in the area.

[c]Assume that open pit is converted to a lake with revegetation efforts restricted to upper slopes. Ecosystem restoration is therefore not considered an achievable goal for this mineland use.

[d]Ecosystem restoration is an unfeasible goal for areas with this mining history.

[e]Assume that reservoirs are not contaminated with recycle water and may be maintained as lakes, rather than being converted to terrestrial ecosystems.

[f]If highly acid materials are generated (unlikely in the case of a Minnesota copper-nickel industry).

Table 24. Cost of stabilization methods.

TYPE OF STABILIZATION	EFFECTIVENESS	MAINTENANCE	APPROXIMATE COST PER ACRE (dollars[a])	APPROXIMATE COST PER HECTARE (dollars[a])
Physical				
Water sprinkling	Fair	Continual	---	---
Slag 9-in.(229 mm) depth				
By pumping............	Good	Moderate	350-450	864-1,112
By trucking...........	Good	Moderate	950-1,050	2,347-2,594
Straw harrowing.........	Fair	Moderate	40-75	99-185
Bark covering...........	Good	Moderate	900-1,000	2,224-2,571
Country gravel & soil				
4-in. (102 mm) depth	Excellent	Minimal	250-600	618-1,482
12-in. (305 mm) depth	Excellent	Minimal	700-1,700	1,730-4,201
Chemical				
Elastomeric Polymer.....	Good	Moderate	300-750	741-1,853
Lignosulfonate..........	Good	Moderate	250-600	618-1,482
Vegetative				
4-in soil cover and vegetation........	Excellent	Minimal	300-650	741-1,606
12-in cover and vegetation[b]...........	Excellent	Minimal	750-1,750	1,853-4,324
Hydroseeding............	Excellent	Minimal	200-450	494-1,112
Matting[c]................	Excellent	Minimal	600-750	1,482-1,853
Chemical-Vegetative	Excellent	Minimal	100-250	247-618

SOURCE: Morrison and Simmons 1977.

[a]Based on average tailing (1977 dollars). Costs should be revised upwards for acid tailing requiring limestone or other neutralizing activities.

[b]Generally used on pond area rather than on dams. Not as effective as 12 in. soil cover when tailing are excessively acidic or saline.

[c]Based on placing 3 ft (0.91 m) wide matting at 3 ft intervals over the seeded area.

hypothetical open pit mine lake (Volume 3-Chapter 4). Despite decreasing concentrations of heavy metals caused by the increasing volume of water as the pit fills, levels of copper, nickel, zinc, and cobalt are expected to exceed chronic toxicity levels for aquatic organisms (Volume 4-Chapter 1). Levels of copper are likely to remain higher than state standards for fisheries and recreation (swimming), unless leachable pit walls are sealed. No method is presently known that would accomplish this goal.

Contamination of groundwater is a concern where open pit mines are converted into lakes which may exhibit elevated levels of heavy metals. Only one bedrock unit in the area, the Biwabik formation, shows any significant permeability. The discontinuous permeability of this unit is known because water levels of abandoned iron ore mines used as water supplies for the municipalities of Hibbing and Aurora could not have been attained by precipitation alone. The input of water from the Biwabik formation into these pits is of unknown magnitude.

It is likely that the Biwabik formation in the area where it underlies the Duluth Gabbro Complex is more highly metamorphosed than in the iron mining areas and therefore less permeable than near Hibbing. The Biwabik formation is likely to intersect the open pit mine walls in the central Copper-Nickel Development Zones (3, 4, and 5). However, the potential copper-nickel open pit mines lie down-dip of the abandoned iron ore pits, so that current municipal water supplies should not be contaminated with heavy metals leached from sulfide mining operations.

Contamination of surficial groundwater can be expected at the time that abandoned open pit mines are filled to such a depth that the water is in direct contact with surficial materials. The ability of surficial materials to absorb heavy metals can be expected to vary with their particle size and cation exchange capacities. Areas with thick organic or clayey deposits will generally absorb heavy metals better than those with thin or coarse surficial materials. Before lake development is accepted as a method of reclamation for open pit mines, the metal absorbing capacities of the surficial materials need to be better understood.

Management of abandoned pits as meromictic (non-mixing) bodies of water has been proposed as a technique for isolating contaminated waters in the deepest layer (Flambeau 1976). Although this proposal may have some merit in deep, sheltered basins whose waters are enriched with heavy metals, its success has not been demonstrated.

Although it is foreseen that abandoned pits will eventually fill with water, there is a long lag-time between abandonment and complete filling. Pit walls present inhospitable surfaces for revegetation and are too steep to be contoured. An abandoned open pit mine with its steep slopes, extreme depth, and unstable walls could be a public hazard unless it is adequately fenced and posted. The more isolated geographical setting of the copper-nickel resource zone as compared to the populated iron range may reduce the frequency of accidents, but it does not reduce the severity of the hazard.

2.9.1.2 Tailing Basins--Reclamation of tailing basins is better understood than that of most mineland areas. Construction methods for tailing basins are detailed in Chapter 3. Regardless of the method used, the difference in settling rates of coarse and fine particles will result in deposition of coarser materials near the point of discharge of tailing into the basin and finer materials farther away. These differences may affect the kinds of treatment required to reclaim various parts of the basin.

Slimes are composed of the fine particulates that settle in the bottom of the basin. During the operation, these materials may not require stabilization or revegetation because they are likely to be underwater. In contrast, coarser tailing material around the perimeter of the basin is exposed. Particulate materials in the size range less than 30 to 50 um may become airborne as dusts at wind velocities of around 6 to 10 mph, comparable to average velocities in the Study Area (Golder 1978). In addition to the health hazards of dust, natural characteristics of ecosystems may be modified by dust blown off a dry tailing basin.

Based on modeling studies conducted by the Regional Study (Volume 3-Chapter 3, section 3.6.2.2), it appears that about 4% of all airborne particulates can be expected to come from tailing basins if 80% of the basin is maintained underwater. According to the Study's model (Volume 3-Chapter 3), increases in airborne particulates of 1-2 ug/m^3 above annual average ambient levels are expected at the edge of tailing basins. Certain areas of the basin may become dormant for varying periods of time before reactivation if rotation of tailing discharge points around the basin is used to facilitate even filling. Such areas may require temporary stabilization by spraying with water, application of slag, chemical stabilization, or seeding for annual cover. Comparative costs and effectiveness of stabilization methods are presented in Table 24. Costs are based on 1973 data and will undoubtedly continue to increase.

The large size of tailing basins usually precludes the erection or planting of wind barriers. Generally, the sheltered area downwind from a barrier is only 5 to 10 times the height of the barrier (Golder 1978). Mature native deciduous and coniferous species in the Study Area would thus provide shelter no farther than 200 m.

An alternative to a single large basin is a series of cells, each of which is limited to the size required for the clarification of the tailing water and collection of make-up water, to be operated individually and sequentially and revegetated immediately upon completion. The major advantage of a multi-cell basin is the opportunity to revegetate part of the disposal tailing without waiting for the completion of the entire operation. The major disadvantage of the multi-cell approach is economic. The greater length of dam per unit volume of stored tailing requires a larger borrow material source, more excavation, hauling, compaction, and more labor.

At the termination of the operation, the pond may be drained for revegetation. The fine particle size of slimes may then present dewatering problems and several years may elapse before drying is complete (Chosa and Shetron 1976). During wet periods, puddling may develop and during dry periods crusts may form. Poor soil aeration may result in high carbon dioxide levels that hinder root development (Blake 1975).

In contrast to the slimes, coarse particulates in abandoned tailing basins are likely to develop water deficiencies. Because of their lack of organic matter, tailing materials in general may develop high thermal conductivities, but heat stresses are likely to be greater in coarse materials where less moisture is available. The dark-surfaced tailing may absorb heat and result in excessive ground temperatures that cause mortality in germinating seeds and heat girdling of stems at the ground/stem interface (Deeley and Borden 1973; Shirts and Bilbrey 1976). Mulching can be used to shade the ground and decrease radiant heat problems (Dickinson 1975).

Tailing materials generally exhibit deficiencies of nitrogen, phosphorous, and potassium. In areas where percolation is rapid, as in coarse tailing, leaching of N and K is also rapid. The more acid the tailing, the less soluble the nutrients become, making them unavailable for plant use. Nitrogen deficiencies are common but can be alleviated, in part, by the planting of nitrogen-fixing legumes such as crown vetch, birdsfoot trefoil, and various clovers. The same conditions that make nutrients unavailable to plants enhance the availability of heavy metals, if they are present. Toxic metal elements such as Cu, Ni, Pb, As, Al, Zn, Co, and Cd are suspected to cause injury to plants, but few data are available on their levels of toxicity. Practically no information is available on synergistic effects. Table 25 summarizes tests of toxicities and levels at which toxicity has been reported.

Table 25

The primary factors affecting both the toxicity and leachability of metals are their initial concentrations and their availability. Concentrations of metals in tailing will depend on the nature of the original mineralized material (semi-massive or disseminated ore) and on the milling process. Availability is largely dependent on the grind of the material and the pH of the water in the tailing basin, with pH having the greater influence. Figure 16 shows the relationship between metal ion solubility and pH. In general, the lower the pH, the more soluble the metal ions. The pH of tailing generated from materials in the Study Area is expected to be near neutrality during operation. In the event that processing techniques change or if smelter effluents are added to the basin, the pH could range either direction from neutrality, depending on the nature of these effluents. The potential influence of acid precipitation after the operation ceases remains unknown, but precipitation pH values as low as 3.2 have been recorded in the region (see Volume 3-Chapter 4).

Table 25. Summary of results of copper and nickel toxicity studies.

SOURCE	METAL	CONCENTRATION (ppm)	METHOD OF CONCENTRATION DETERMINATION	MEDIA	EFFECTS
Whitby and Hutchinson (1974)	Ni	2	Known quantity of metal salts added	soil-H_2O extract on filter paper	-reduced root elongation by nearly 70%
	Ni	10			-almost complete inhibition
	Cu	2			-reduced root elongation by 30%
	Cu	15			-nearly 100% reduction in root elongation
Goodman et al. (1973)	Cu	0.5	H_2O soluble	water culture	-toxic (undefined)
	Ni	2	H_2O soluble		-toxic (undefined)
Dean et al. (1974)	Cu	1,000	Known quantity of metal salts added	tailing	-little effect
	Ni	100			-toxic (undefined)
	Cu-Ni-Zn	10			-toxic effect "evident"
	Cu-Ni-Zn	100			-toxic effect "pronounced"
Olson (1978)	Cu	75-200	Known quantity of metal salts added		- 75% reduction in mean radical length
	Ni	50-100			

Figure 16

Salinity and alkalinity are problems generally associated with tailing in the southwest, where evaporation exceeds precipitation and high salt concentrations occur in the ore. Although salinity is an unlikely problem in the Study Area, high conductivities in some waters at the AMAX shaft site and at certain drill hole sites appear to be associated with high levels of Na and Cl. These levels appear to be in excess of concentrations that could result from the application of calcium chloride and sodium silicate to stabilize ground around the shaft. The origin of the salinity at these sites is believed to be trapped saline water in bedrock fracture zones, the extent of which is unknown.

The 20 X 10^6 mtpy mine model used by the Regional Study postulates a total of 484 X 10^6 mt of tailing to be deposited in a basin covering 1,625 ha. Particle size distribution is expected to be more homogeneous than some of the tailing products discussed in the literature. The proportion of coarse and fine particles in copper-nickel tailing, as compared to taconite tailing, is illustrated in Figure 17.

Figure 17

Analysis of tailing processed from ore taken at the INCO test site near Ely, Minnesota, suggests that the possibility of phytotoxicity caused by heavy metals is minimal. Concentrations of total Cu and Ni were found to be as low or lower than those of soil samples taken near the Duluth Gabbro contact. However, seed germination studies conducted by researchers at the University of Minnesota's College of Forestry (Olson 1978) emphasize the potential for heavy metal toxi-

FIGURE 16

RELATIONSHIP OF SELECTED METAL ION SOLUBILITY AND SOLUTION PH

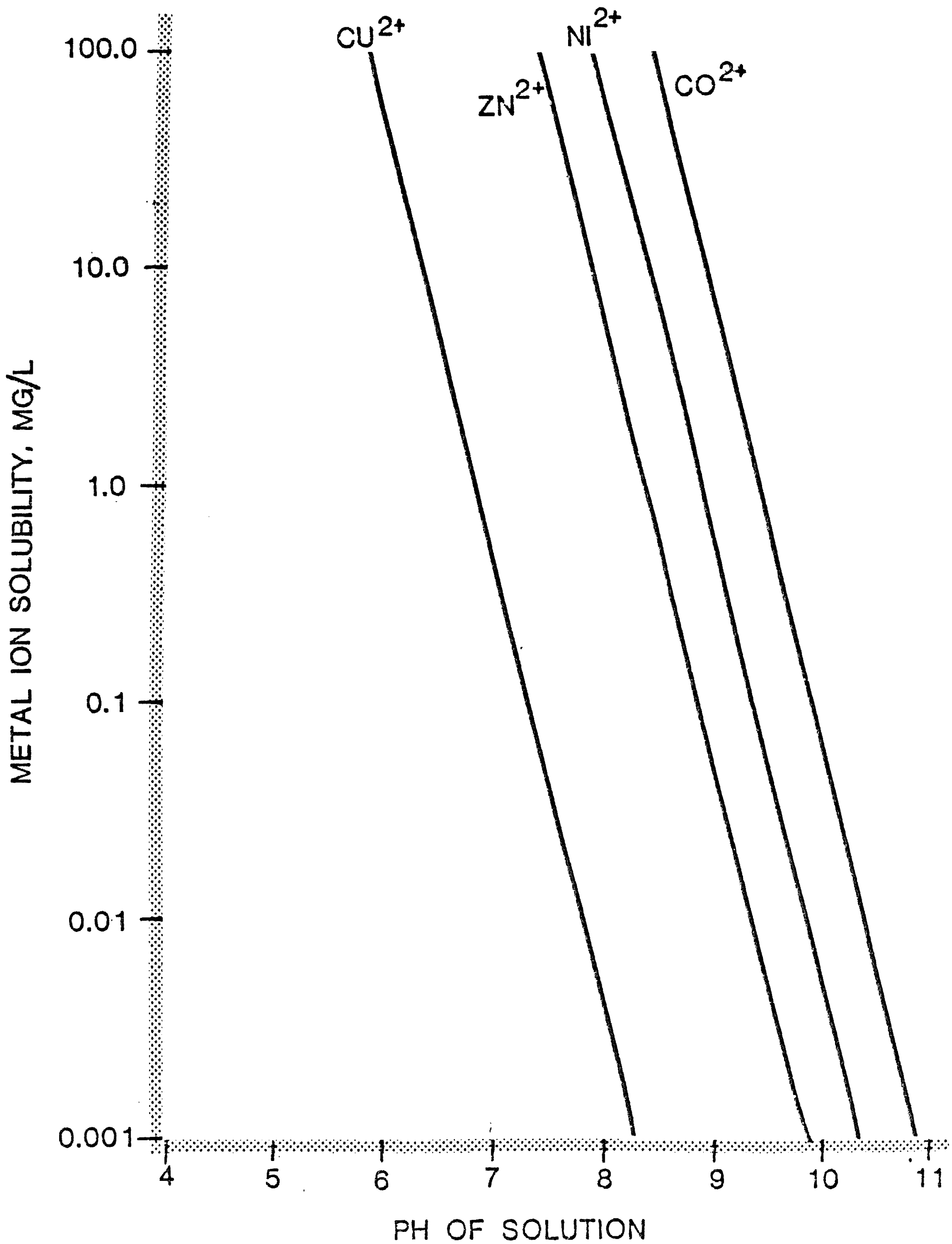
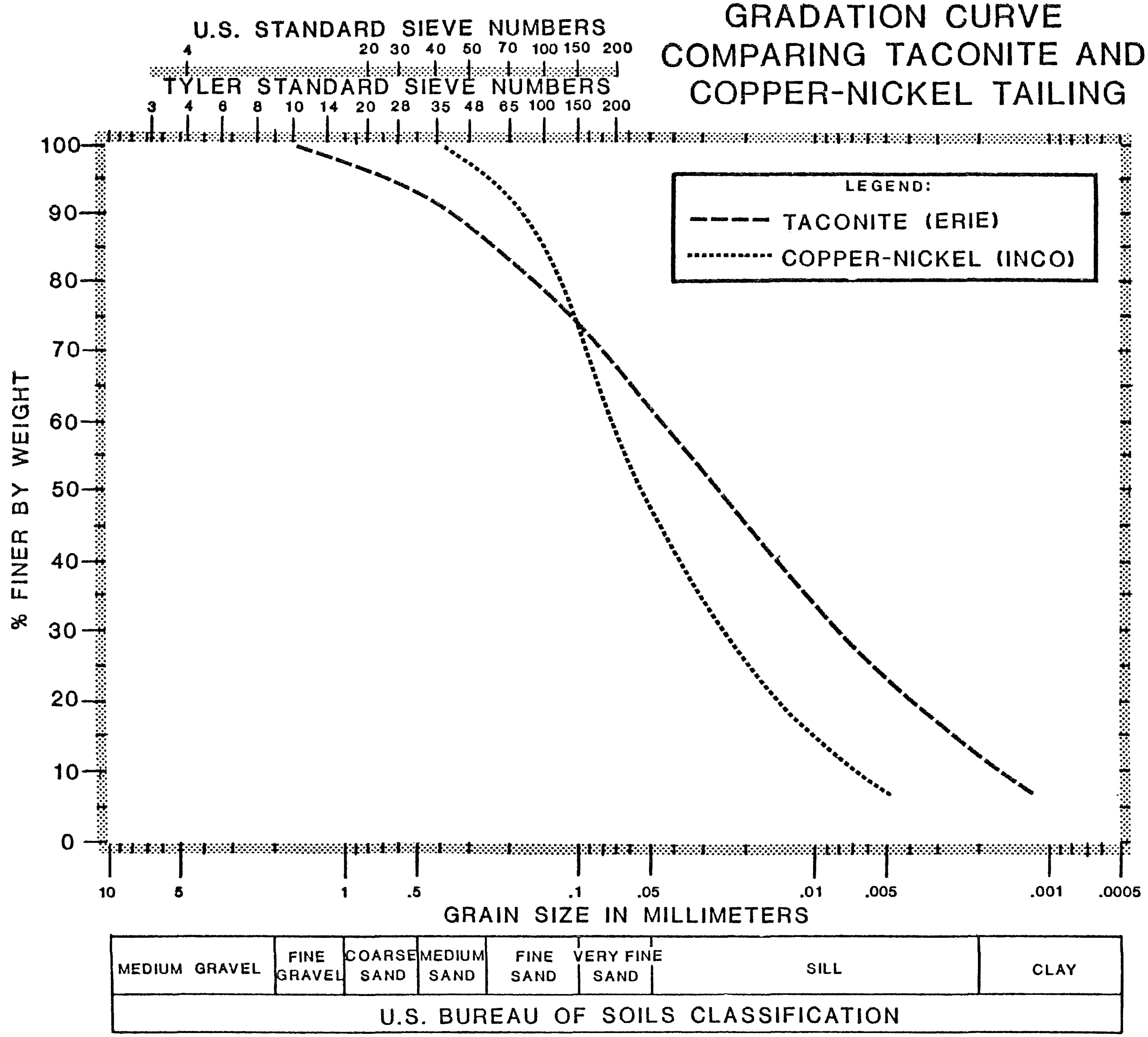


FIGURE 17

GRADATION CURVE COMPARING TACONITE AND COPPER-NICKEL TAILING



city. Root elongation in seedlings of 7 native woody species grown on filter paper was significantly reduced by elevated levels of Cu, Ni, and Co. Available metal concentrations as low as 5 ppm in wet filter paper adversely affected elongation and concentrations of 50 to 100 ppm killed the seedlings. Generally, species with small seeds were affected to a greater extent than species with large seeds, and deciduous species were affected at lower concentrations than were coniferous species. Seed germination tests in mineral soils showed results similar to those on filter paper, but the metal concentrations at which growth reductions were observed were a factor of 10 higher. Similarly, seedlings grown on organic soils were affected by metal concentrations that were a factor of 100 higher than on filter paper. These results demonstrate the binding potential of mineral and organic soil and suggest that organic matter additions might be a useful means of ameliorating metal toxicity problems. Seed germination tests in Cu-Ni tailing from several Minnesota sites indicate that root elongation is reduced, but heavy-metal toxicity symptoms were not observed. Further studies of the suitability of tailing materials for plant growth are needed.

Concentrations of Cu and Ni in tailing from disseminated and semi-massive ore sources are projected to be similar, but tailing from semi-massive sources is expected to be richer in sulfides, with the possibility of creating leachate with a lower pH (Volume 3-Chapter 2).

Methods for the amelioration of tailing are well understood and generally make use of standard agricultural practices that modify tailing to resemble normal soils (see Aaseng 1978 for detailed discussion). Before soil alteration can begin, the basin must be dewatered, dried, contoured, and stabilized against erosion. Physical stabilizers such as crushed rock or slag alone are only suitable for temporary stabilization of areas that will be reactivated, as they provide adverse conditions for root establishment. Chemical stabilizers, however, can be used in conjunction with planting or in combination with mulches. Chemical binders, sewage sludge, and tailing have been combined to form pellets of 0.3 to 1.0 cm in diameter which have been used successfully as a topdressing in revegetation (Dean and Shirts 1977). One of the most effective stabilizers is a topdressing of overburden or soil. Michelluti (1974) used soil coverings in Canada, and reported best results when 15 cm of covering material was added, although even 5 cm were beneficial. Although Michelluti reports that pH of the topdressing fell to 3.5 within a few months after emplacement on acid tailing, he observed no detrimental effects on the vegetation. Such a pH change is unlikely on Minnesota Cu-Ni tailing because of its alkaline nature, high buffering capacity, and low sulfide level. In areas where overburden is thick, segregation of the soil layer for use as a final covering of waste materials may be especially beneficial because soils have a higher organic content and contain seeds and micro-organisms not present in the parent material (till).

As was discussed previously, overburden is not a significant byproduct of underground mining, but solid waste materials are still generated. Table 26 suggests the relationship between overburden supply and demand for each model size by development zone. Volume 3-Chapter 2 details this relationship in comparing the overburden availability and probable needs for topdressing.

Table 26

If soil is not used as the final topdressing, addition of other organic material may be advisable. Mulches of straw or wood chips, sewage sludge, and peat are all organic materials that may be used. Organic matter ameliorates the surface by: moderating temperature extremes, increasing water holding capacity,

TABLE 26

THE RELATIONSHIP BETWEEN OVERBURDEN SUPPLY AND DEMAND IN THE SEVEN DEVELOPMENT ZONES

- [cross-hatched] DEMAND GREATER THAN SUPPLY AVAILABLE FROM OPEN PIT EXCAVATION
- [blank] DEMAND APPROXIMATELY EQUAL TO SUPPLY AVAILABLE FROM OPEN PIT EXCAVATION
- [stippled] SUPPLY FROM OPEN PIT EXCAVATION IN EXCESS OF DEMAND FOR RECLAMATION OR, IN THE CASE OF SAND AND GRAVEL, FOR CONSTRUCTION
- [solid] SUPPLY FROM OPEN PIT EXCAVATION GREATLY IN EXCESS OF DEMAND SO THAT OVERBURDEN MAY BE CONSIDERED A WASTE MATERIAL

TYPE OF OVERBURDEN AND MINE MODEL	DEVELOPMENT ZONES 1	2	3	4	5	6	7
12.35 X 10^6 MTPY UNDERGROUND							
SOIL	DOES NOT APPLY*						
SAND / GRAVEL	DOES NOT APPLY*						
TILL	DOES NOT APPLY*						
PEAT	DOES NOT APPLY*						
16.68 X 10^6 MTPY COMBINED							
SOIL	[cross-hatched]	[cross-hatched]	[cross-hatched]	[cross-hatched]	[cross-hatched]	[cross-hatched]	[cross-hatched]
SAND / GRAVEL	[cross-hatched]	[stippled]	[solid]	[solid]	[cross-hatched]	[solid]	[cross-hatched]
TILL	[cross-hatched]	[cross-hatched]	[cross-hatched]	[cross-hatched]	[solid]	[stippled]	[solid]
PEAT	[stippled]	[stippled]	[solid]	[solid]	[solid]	[solid]	[solid]
20.00 X 10^6 MTPY OPEN PIT							
SOIL	[cross-hatched]	[cross-hatched]	[cross-hatched]	[cross-hatched]	[cross-hatched]	[cross-hatched]	[cross-hatched]
SAND / GRAVEL	[cross-hatched]	[stippled]	[blank]	[blank]	[cross-hatched]	[blank]	[blank]
TILL	[stippled]	[cross-hatched]	[cross-hatched]	[cross-hatched]	[solid]	[cross-hatched]	[solid]
PEAT	[stippled]	[stippled]	[solid]	[solid]	[solid]	[solid]	[solid]

* NO OVERBURDEN IS GENERATED WHEN MINNING IS EXCLUSIVELY BY UNDERGROUND METHODS.

decreasing evaporation, increasing cation exchange capacity (thereby reducing loss of nutrients and availability of heavy metals), lowering the bulk density so that plant roots are exposed to more favorable water and air relationships, and introducing chelates that bind heavy metals and make them less available to plants. As organic matter decomposes, it releases nutrients for uptake by plants. Some organic materials rich in cellulose require addition of N_2 to counterbalance their high C/N_2 ratio because the N_2 supply available to higher plants may otherwise be depleted by decomposer organisms.

Liming has been used in the case of acid tailing where neutralization is needed to prevent leaching of heavy metals and nutrients. Although Minnesota Cu-Ni tailing is not expected to be acidic, the acid nature of regional precipitation could result in long-term soil acidification in the post-operational phase. The possibility of liming with large fragments of limestone or with dolomite to attain slow release of carbonate over a period of years may merit investigation as a preventive measure.

Not all species will survive equally well on tailing. Establishment of a stabilizing ground cover that includes nitrogen-fixing legumes is generally the first step. A large number of native and exotic species have been tried. Species that have been used on Cu ore tailing in Ontario and Michigan and on taconite tailing in Minnesota are listed in Table 27. Although trees have been successfully established on taconite tailing in the Study Area (Dickinson 1972), of 32 tree and shrub species tested in early stages of revegetation in Michigan, only 5 were successful (Jones 1972). Willow cuttings have been successfully planted on slimes (Chosa and Shetron 1976) where they are well-adapted because of their tolerance of wet soil. Dickinson has tested plant species on iron ore tailing in Minnesota (see Table 27) and has found that an initial plant cover of grasses and legumes helps stabilize slopes, reducing both water loss and land erosion. Because reduction of erosion hazard is the most important initial concern in reclamation, Dickinson recommends that trees not be planted until extensive binding of surface materials by the roots of herb species is accomplished. Dickinson (personal communication 1978) argues strongly against the practice of using only native species in initial revegetation efforts, for he feels that the exclusive use of native species results in unnecessary delays in the attainment of complete vegetative cover. Several grasses and legumes are available commercially and have been successfully employed on both tailing and other mine wastes (see Aaseng 1978 for a complete list of species). Initial use of exotics to stabilize soil, followed by gradual introduction of natives may be a reasonable management approach, assuming natives could successfully compete with the exotics.

Table 27

The use of non-native species may seem questionable from an aesthetic and ecological point of view, but many of these species are better adapted to the conditions of tailing basins than are natives. Many of the native ruderals (weeds) are naturalized exotics that compete well in disturbed areas and are likely to invade tailing basins soon after artificial soil is established. Sunloving native species such as aspen and balsam poplar can be expected to be the first native trees to invade the area.

The use of ponded areas in tailing basins for wildlife has been successful on taconite tailing, but may be questioned on copper-nickel tailing rich in heavy metals because of the possible contamination of migratory waterfowl. Emergent aquatic plants are known to concentrate both copper and nickel. The mechanism of

Table 27. Species that have been used in tailing revegetation in Minnesota, Michigan, and Sudbury, Ontario.

		SOURCE				
		1	2	3	4	5
Grasses						
Agropyron sp.	wheatgrass					x
Agropyron cristatum	crested wheatgrass	x				x
Agropyron elongatum	tall wheatgrass					x
Agropyron intermedium	intermediate wheatgrass	x				x
Agropyron smithii	western wheatgrass	x				x
Agrostis alba	red top	x				x
Agrostis tenuis	colonial bentgrass		x	x		
Andropogon gerardii	big bluestem	x				
Avena sp.	oats			x		x
Bromus sp.	brome grass	x	x	x		
Bulbilis dactyloides	buffalo grass					x
Dactylis glomerata	orchardgress				x	x
Echinochloa crus-galli	Japaneese millet	x				x
Festuca sp.	fescue	x				
Festuca arundinacea	alta tall fescue					x
Festuca elatior	tall fescue					
Festuca rubra	red fescue	x	x	x		x
Festuca ovina	sheep fescue		x			
Hordeum sp.	barley	x				x
Lolium sp.	cougar ryegrass					x
Lolium multiflorum	rye grass	x			x	x
Panicum virgatum	switch grass	x				x
Phlaris arundinacea	read canary grass	x				x
Phleum pratense	timothy	x		x	x	x
Poa compressa	Canada bluegrass			x		
Poa pratensis	Kentucky bluegrass			x		x
Secale cereale	annual rye	x		x		
Setaria italica	millet	x				
Stipa virdula	green needle grass	x				x
Legumes Forbs						
Astragalus sp.	milk vetch	x				
Coronilla varia	crown vetch	x				x
Lathyrus japonicus	beach pea					x
Lotus corniculatus	birdsfoot trefoil	x				x
Medicago sativa	alfalfa	x	x	x	x	x
Melilotus sp.	sweet clover	x	x	x		
Trifolium hybridium	alsike clover	x				x
Trifolium pratense	red clover	x				
Trifolium repens	white clover		x		x	
Vicia americana	purple vetch					x

Table 27 continued.

		Source 1	2	3	4	5
Shrub and Trees						
Caragana arborescens	Siberian pea	x				x
Robinia pseudoacacia	black locust	x[a]			x	x
Other						
Linaria dalmatica	dalmatian toadflax					x
Verbascum thapsus	mullein					x
Shrubs						
Alnus glutinosa	European black alder	x				
Alnus rugosa	tag alder					x
Amelanchier sp.	service berry	x				
Comptonia peregrina	sweet fern					x
Prunus pensylvanica	pin cherry					x
Prunus virginiana	choke-cherry					x
Rosa sp.	rose					x
Salix sp.	willow	x				
Shepherdia sp.	silverberry	x				
Vaccinium sp.	blueberry					x
Trees						
Betula papyrifera	paper birch	x				x
Elaegnus angustifolia	autumn olive	x[a]				
Elaegnus umbellata	Russian olive					x
Larix decidua	European larch					x
Pinus banksiana	jack pine	x			x	
Pinus resinosa	red pine	x			x	
Populus sp.	hybrid poplars	x				x
Populus alba	white poplar					x
Populus balsamifera	balsam poplar					x
Populus grandidentata	large-toothed aspen					x
Populus tremuloides	trembling aspen					x
Sorbus sp.	mountain ash					x
Thuja occidentalis	eastern white cedar	x				x

SOURCES: [1]Dickinson (1971, 1972) Minn.--taconite tailing
[2]Michelluti (1974) Sudbury, Canada--Cu-Ni tailing
[3]Young (1969) Sudbury, Canada--Cu-Ni tailing
[4]Shetron and Dufeck (1970) Michigan--iron ore tailing
[5]Prather (1973) Michigan--Cu tailing

[a]Poor results.

differential uptake is unknown, but the possibility of contamination of higher members of the food chain, is of concern.

2.9.1.3 Lean Ore and Waste Rock Piles--Lean ore and waste rock piles share with each other several characteristics that inhibit the growth of vegetation, including nutrient deficiencies, water deficiencies, heat stress, and adverse physical conditions for rooting. The steepness and aspect of the slope are important factors in establishment of vegetation because south-facing slopes have a tendency to be droughtier and warmer, whereas on north-facing slopes continuous shade may influence species selection. The high thermal conductivity of the rock can result in high surface temperatures and great temperature variations over short periods of time. Boulder to rock-size fragments and highly compacted particulates all present surfaces adverse to seedling germination. The design of piles can be modified to aid revegetation, reduce environmental impacts, and lower costs in accordance with final reclamation goals. Possible influences of design parameters on impacts are presented in Table 28.

Table 28

Lean ore piles differ from waste rock piles in 2 major respects, they contain a higher concentration of heavy metals and sulfides than waste rock piles and they are considered to be temporary features. The available information does not permit development of an accurate estimate of the amount of lean ore likely to be generated. For this reason, the Study's mine models arbitrarily allocate 50% of the waste rock to lean ore. As was the case with taconite, changing technological and economic factors may affect the grade of material that can be beneficiated in the future. Lean ore is a material which may be beneficiated at some time during the life of the operation. For this reason, it may be economi-

Table 28. Effects of design parameters on reclamation of waste rock piles.

1. Effect of Pile Slope Angle--Steep slopes are unstable and subject to slides, and are thus more difficult to revegetate than are gentle, stable slopes.

2. Effect of Pile Location--Piles exposed to wind result in greater stabilization difficulty due to wind erosion.

3. Effect of Pile Height--Although higher piles occupy less area to store a given amount of material than equivalent lower piles, high piles expose more surface area to wind erosion above the level of surrounding vegetation.

4. Effect of Pile Slope Aspect--South-facing slopes receive the most sunlight which is beneficial for revegetation, but the soil tends to dry more than north-facing slopes due to the greater heat exposure

5. Effect of Number of Piles--Multiple pile disposal allows revegetation to be practiced as the operation progresses; however, more surface area is consumed than with a single equivalent large pile.

6. Effect of Pile Construction Method--Visual impact and wind erosion can be reduced by constructing the perimeter of waste rock piles first, then stabilizing and revegetating these permanent structures. Subsequent disposal takes place on the inside of revegetated perimeters and is much less exposed to visual and wind impact.

cally unfeasible to reclaim lean ore piles in the same ways as permanent waste rock piles. Although water quality considerations suggest a need for reduction of water retention, often facilitated by evapotranspiration, the expensive preparation procedures required for revegetation may be unfeasible for these short-lived piles. Because such piles are likely to be temporary, the simplest solution to fugitive dust problems is to stabilize them with chemical binders that do not later interfere with the beneficiation process. Several of such products are commercially available. Water quality problems are best solved by siting the piles so that all leachates are collected and channeled into the tailing basin water system. If lean ore piles are not processed prior to mill closure, reclamation procedures are likely to be similar to those used for waste rock piles, although special efforts to mitigate leaching may be required.

Final reclamation goals for waste rock piles are likely to be heavily influenced by water quality considerations. Leaching from these piles is one of the most serious potential environmental impacts of the prospective Cu-Ni mining industry. Visible damage to vegetation observed as far as 60 m from a seep receiving waters from stockpiles at Erie Mining Company's Dunka Pit may provide an analog for potential effects of leachate from lean ore piles. During the 1976 and 1977 seasons, several species within the bog exhibited chlorosis and death. The cause of the pathological symptoms is not known, but elevated levels of Ni were observed in the leaves of alder plants in this same bog. Elevated levels of Ni were not found in alder from other sites in the Study Area.

The ability of water to move through waste materials is important to the kinetics of metal release. Where movement is rapid, well oxygenated water is continuously in contact with oxidizable material and metals are released into solution. Minnesota (unlike the arid southwest) is in a region where precipitation normally exceeds evapotranspiration on an annual basis and pollutants released into soil solution are likely to be carried into the substratum and ultimately may contaminate ground water. Revegetation is generally accepted as an important means of reducing the magnitude of this problem. The establishment of an actively transpiring ground cover greatly reduces the net downward movement of soil moisture. Through the action of root respiration and the decomposition of organic matter deposited in the form of litter on the soil surface, soil oxygen levels decline and the oxidization of waste materials is reduced.

There is some evidence to suggest that revegetation of piles may not always have the expected positive effect of diminishing leaching. Seasonal cycles of wetting and drying caused by seasonal photosynthetic activity have been suggested as the cause of increased leaching in sanitary landfills (Molz and Browning 1977) and could cause similar effects on waste rock. Organic acid production and physical exposure of deeper surfaces by root penetration are additional mechanisms by which plants could enhance leaching.

Projected heavy metal concentrations (in mg/l) in runoff waters at the base of waste rock piles may reach values around 1.40 Cu, 37.2 Ni, 8.18 Zn, and 1.78 Co (see Volume 3-Chapter 4). Concentrations in water from lean ore piles are likely to exceed these values, but runoff from these piles is likely to be recycled through the tailing basin. If lean ore is stockpiled only during the life of the operation, no post-operational maintenance problems should be generated by waters from such piles.

The model postulated by the Regional Study anticipates that leachate from waste rock piles will be pumped into the tailing basins during the operational phase, but this option is no longer available after the basin has been reclaimed and methods must be sought to control water quality at the source, especially during the post-operational period. Topdressing, application of inert materials, application of organic materials with high cation exchange capacities, emplacement on clay or peat pads, and liming are all measures that could alleviate the effect of heavy metals.

Contouring of piles may be the first step in revegetation. Orientation of piles so as to reduce the surface area of south facing slopes, slope reduction on north facing slopes, and construction of ramps for wildlife access may be desired. The heavy equipment used in contouring is likely to compact the surface layer so that loosening is necessary. Several methods of surface manipulation have been tried on coal wastes with the goals of encouraging seedling growth, reducing erosion, and alleviating soil compaction. Methods such as furrow grading would appear unsuited to steep slopes. Most methods which encourage seedlings result in the creation of depressions that collect moisture, fine-sized soil particles, and wind-blown seeds. Although such methods encourage revegetation, collection of moisture on metalliferous waste materials might be counter-productive because it may increase the leaching potential. Insufficient experience with this problem makes specific conclusions impossible at this time.

In order to reduce their visual impact, waste piles could be contoured to reflect the mass and form of existing man-made and topographic features. Because of the high cost of earthmoving ($0.85/m^3)(Golder 1978), procedures which require the redistribution of waste materials after initial dumping are more costly than those which initially dispose of materials at their desired location. If final reclamation goals are taken into account during waste pile design, excessive earthmoving costs may be avoided.

An alternative to contouring is the bench and lift method illustrated in Figure 18. If such a method is used, the piles should be designed to control surface erosion, facilitate early reclamation, and minimize infiltration of water beyond what is needed for plant growth. The design of the piles is also based on rock competence and angle of repose of the material being stored. If such piles are contoured for the purposes of reducing visual impacts after construction of the benches and lifts, costs can be expected to be greater than for piles that are contoured during their construction.

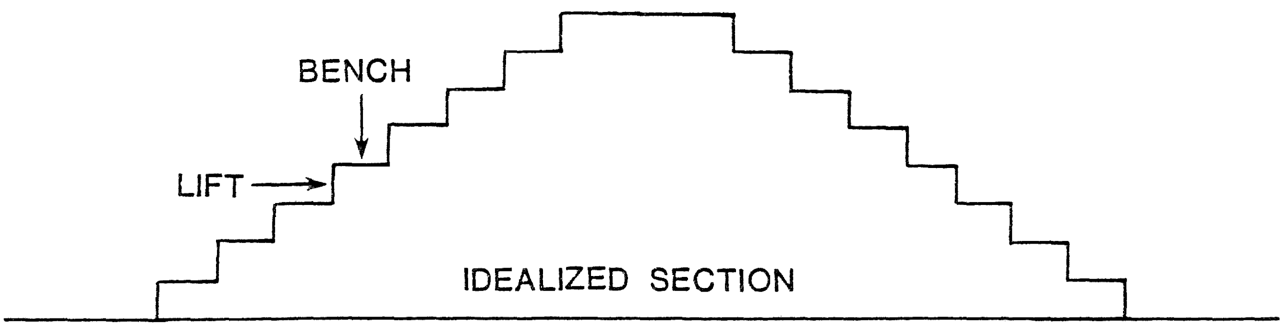
Figure 18

Almost all effective methods for revegetation of metalliferous wastes involve top dressing with a layer of overburden or soil. The choice of material and depth of top dressing are dependent on the physical and chemical characteristics of the waste rock, the reclamation goal, the availability of borrow material, and relative costs. Top dressings of 20 cm have been highly beneficial in the very arid and infertile copper-cobalt wastes in Idaho (Farmer et al. 1976). Vogel (1977) suggests that 61 to 122 cm may be required for piles composed primarily of boulders. A single large pile or 13 smaller piles postulated in the Regional Study's 20 X 10^6 mtpy mine model would require 1.7 X 10^6 m^3 of overburden for a 20 cm topdressing and 10.1 X 10^6 m^3 for 120 cm topdressing.

Chemical conditions of the waste rock and the final reclamation goals may influence the choice of one type of overburden over another for top dressing. If control of leaching is an important reclamation goal, loamy topsoil may be favored as topdressing where waste materials are easily leached (Michelluti 1974). On the other hand, preliminary evidence from leaching and revegetation experiments on 6 waste rock piles at the AMAX exploration site contradicts the

FIGURE 18

BENCH AND LIFT METHOD
OF WASTE PILE CONSTRUCTION



literature and suggests that during 1978, concentration of leachates was greater on the pile topdressed with soil than on the 2 piles topdressed with till (Eger et al. 1979). Analyses presented in Volume 3-Chapter 1 suggest that supplies of topsoil available from the excavation of the open pit in all development zones may be inadequate to meet reclamation needs for all mine models. If topsoil is preferred for topdressing, use of the tailing basin site as a borrow source could supplement the available soil supplies if soil were stripped from the area and stockpiled before tailing was introduced into the basin.

If soil were used to fill all model needs for topdressing, an additional volume ranging from 0.5 to 1.8 $X\ 10^6\ m^3$ would need to be excavated from an additional area ranging from 117 to 469 ha, depending on the size of the mine (see Table 29). Conservation of topsoil from tailing basin sites is not typically practiced by the industry and would incur additional costs. Estimated additional costs for excavation, stockpiling, and redistribution of tailing basin topsoils have already been presented in Table 20. These estimates are based on figures of $\$1.70/m^3$ for excavation and loading, $\$0.65/m^3$ for placement in stockpiles or as topdressing, and $\$0.65/m^3$ for one mile of transport to and from the stockpiles (Golder 1978). The total estimate of $\$4.30/m^3$ may be low because most potential tailing basin sites are likely to be forested and costs of tree removal and grubbing are not included. The total additional costs of \$2.5 to $\$7.7\ X\ 10^6$ for stockpiling soil from the tailing basin in the 20 $X\ 10^6$ mtpy open pit mine model can be compared with estimates of $\$9.8\ X\ 10^6$ for dam construction and $\$8.5\ X\ 10^6$ for tailing transportation and water reclamation, with a 5 mi tailing line (Volume 2-Chapter 3).

If topdressing is required and the mine is located near the tailing basin, the use of till from mine excavation may be less expensive than stockpiling topsoil, but if the distance between the mine and basin exceeds 6.5 mi the additional cost of stockpiling topsoil would be offset by the cost of hauling till to topdress tailing. In general, costs can be reduced by any procedure that reduces the number of times the material must be loaded, transported, and dumped.

Table 29

Although depths of overburden are thinner in zones 1 through 4 than in the remaining 5 zones, calculations presented in Volume 3-Chapter 2 demonstrate that sufficient till should be available from pit excavation to meet the reclamation needs of both the combined mine and open pit mine models in all zones. In the case of an underground mine, sufficient topdressing could be made available for all waste materials by stripping and stockpiling the top 20 cm of soil from the tailing basin site prior to filling.

Addition of organic matter would probably increase soil water retention capacity, decrease surface evaporation, moderate temperature extremes, stabilize surface erosion and make heavy metals less available to plant roots and surface runoff. Organic matter in the form of sewage sludge and domestic refuse has been effective in ameliorating heavy-metal contamination in mining wastes near Swansea, Wales (Goodman et al., 1973). A more available form of organic matter in the Study Area may be peat. Although organic matter may provide one of the best materials for controlling leaching on waste rock piles, its use on lean ore piles is restricted because it may disrupt the flotation process during beneficiation.

Fertilizers have been used to correct soil deficiences on waste rock piles (Farmer et al., 1976, Brown and Johnston, 1976). Optimum results are obtained

Table 29. Topsoil deficit and additional surface area and cost required to provide topsoil to meet all topdressing needs in each development zone.

MINE MODEL	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
	TOPSOIL DEFICIT[a], $10^6 m^3$						
12.35×10^6 mtpy underground	1.5	1.5	1.5	1.5	1.5	1.5	1.5
16.68×10^6 mtpy combined	1.4	1.4	1.4	1.4	0.5	0.5	0.5
20.00×10^6 mtpy open pit	1.8	1.8	1.8	1.8	0.6	0.6	0.6
	ADDITIONAL EXCAVATION AREA REQUIRED, ha						
12.35×10^6 mtpy underground	214	214	214	214	117	117	117
16.68×10^6 mtpy combined	357	357	357	357	195	195	195
20.00×10^6 mtpy open pit	469	469	469	469	256	256	256
	TOTAL ADDITIONAL COST OF EXCAVATING AND STOCKPILING SOILS FROM TAILING BASINS FOR TOPDRESSING IF STOCKPILE IS ONE MILE FROM BASIN, $\$10^6$						
12.35×10^6 mtpy underground	6.45	6.45	6.45	6.45	6.45	6.45	6.45
16.68×10^6 mtpy combined	6.02	6.02	6.02	6.02	2.15	2.15	2.15
20.00×10^6 mtpy open pit	7.74	7.74	7.74	7.74	2.58	2.58	2.58

[a]Topsoil depths for each zone (see Volume 3-Chapter 2, Table 10) are assumed to be 0.70 m for zones 1 through 4, and 1.28 m for zones 5 through 7.

when fertilizer is used in conjunction with topsoiling. Lower levels of N_2 in fertilizer are used when nitrogen-fixing legumes are being established because natural nitrogen fixation is inhibited in soils with high nitrogen values.

Liming is generally applied only to acid wastes and should not be necessary for wastes in the Study Area. However, the possible effects of decreasing pH of regional precipitation may need to be tested in an experimental setting to determine whether liming may be advisable to deter release of heavy metals with increasing soil acidification.

Pilot studies of waste rock revegetation and leaching were initiated in June, 1978, by AMAX in cooperation with the MDNR. Six waste rock piles at the company's exploration site southeast of Babbitt were monitored for leachate quality and quantity. Three of the 6 piles were covered with 20 to 30 cm of overburden and seeded according to a random block design with 2 rates of application of 3 seed mixes (listed in Table 30) and control plots. Sixteen 10 by 25 ft square plots were established on each of the 3 piles. At the time of planting, each plot received a single application of 10-20-20 fertilizer at the rate of 300 lb/acre. Piles were stabilized with nylon mesh and mulched with one ton of oat straw per acre. At the end of the growing season, biomass measurements and estimates of ground cover were made on each plot. During the first season, a successful nurse-crop of oats (not part of the seed mixes listed in Table 30) was established as a result of the mulching. Plans for the second season include the planting of several perennial species, including aspen, red pine, jack pine, and willow. No replanting of annual species is planned. Such experiments provide useful information regarding the relative ability of different seed mixes to germinate and provide rapid groundcover in the first year, as well as their ability to compete in subsequent years. A preliminary report on the first season's findings is available from the MDNR (Eger et al. 1979).

Table 30

One suggestion has recommended that Minnesota minelands be reclaimed to a high proportion of vegetative cover within the first 5 yr of revegetation activity. Specifically, and regardless of the type of site, this suggestion calls for 75% cover at the end of the first year, 85% after 3 yr, and 95% after 5 yr. These percentages of ground cover are higher than those often attained by natural processes in clearcuts which have been rock raked. The same suggestion calls for the establishment of a self-regenerating and self-sustaining plant community "similar in density to comparable naturally occurring communities" no later than 10 yr after revegetation begins.

The use of naturally-occurring metal-tolerant varieties for revegetation of metalliferous wastes has been pioneered in the British Isles (Gadgil 1969; Smith and Bradshaw 1970). Such tolerant species not only can withstand higher concentrations of heavy metals in the soil but also exhibit higher concentrations of metals in plant tissue (Antonovics et al. 1971). Several forage species such as grasses, alfalfa, and clover have evolved metal-tolerant varieties. The usefulness of these varieties for rapid revegetation of mine wastes in the Study Area may be counteracted by the risk of exposing foraging animals such as deer to food sources high in heavy metals.

Natural plant invasion has been reported on iron ore wastes in northern Minnesota (Leisman 1957). Rock piles up to 45 m high with particle sizes of 7.5 to 15 cm were invaded by balsam poplar and trembling aspen with very little herbaceous cover. Similar vegetation has invaded a gravel slope at the north end of Bass

Table 30. Seed mixes used by AMAX in waste rock revegetation studies.

<u>Minnesota Highway Dept. #5</u>

Bluegrass
Brome grass
Rye grass
Red top
Timothy
White clover
Birdsfoot trefoil

<u>USFS Wildlife Mix</u>

Chewing fescue
Medino clover
Alsike clover
Bluegrass
Rye grass

<u>AMAX Native Seed Collection</u>

Chenopods	(lambs quarters)
Chrysanthemum	(daisy)
Convolvuus	(bindweed)
Lynchnis	(campion)
Melilotus	(sweet clover)
Moldavica	(dragonhead)
Phleum	(timothy)
Potentilla	(cinquefoil)
Oenothera	(primrose)

Lake, west of Ely. It is likely that such cover of pioneer tree species with very little herbaceous ground cover is the highest possible revegetation goal for untreated piles with steep slopes and coarse materials. More continuous and structurally diverse vegetation cover may be possible with the amelioration of the surface before planting, but self-sustaining communities probably cannot be expected for at least 50 yr.

Human uses of waste rock piles would appear to be limited, although adequately topsoiled and contoured surfaces reduced to less than a 35% slope could be developed as ski slopes. It is probable that such development may still require revegetation with perennial herbaceous cover to stabilize the surface.

2.9.1.4 Smelter and Refinery Sites--The major reclamation issue affecting smelter/refinery sites (20 ha in the Regional Study's models) is the avoidance of contamination. Such sites are often characterized by highly compacted soils contaminated with heavy metals from fugitive sources. Within 5 to 10 km of the site, metal contamination and SO_2 fumigations during periods of control equipment malfunction could reach levels causing visible damage to the vegetation.

If good housekeeping procedures are not followed or if breakdowns are frequent, revegetation of disturbed areas immediately surrounding a smelter may involve major steps including mechanical loosening of soils, addition of organic matter to raise the cation exchange capacity, liming, and fertilization with inorganic nitrogen, phosphorous, and potassium fertilizers to compensate for slowed nutrient cycling caused by heavy metal loading. Once soil conditions are modified, vegetation should be easier to establish than in areas with adverse physical conditions which subject the plants to drought or heat stress (such as the steep slopes of waste rock piles). Seeding and planting will be necessary to re-establish vegetation in disturbed areas.

In view of the extensive soil preparation needed for revegetation at contaminated smelter/refinery sites, alternative future land uses such as industrial sites or transportation facilities may be favored. Removal of the building structures would be necessary under any circumstances. In some cases development such as redesigning, paving or new construction may be necessary for site conversion.

2.9.1.5 Processing Plant Sites--Impacts at processing plant sites fall into 2 major classes: visual impacts and contamination of the environment by particulate heavy metals. Careful siting and plant design which enhance "good housekeeping" procedures can reduce these impacts to a minimum.

Pre-siting visual analysis of alternative plant sites can produce viewscapes such as that in Figure 19, from any selected angle of view and distance. Such analyses suggest that potential sites should be considered on the basis of the following criteria (BRW 1978):

1) siting at the lowest practicable elevation relative to the surrounding topography

2) siting as far as possible from important observer viewpoints

3) interruption of the line of view from observer to plant by natural objects

4) siting in locations with infrequent viewpoints

5) siting in already disturbed locations

In addition to these siting criteria, design of the facility should bear in mind the following considerations:

1) size and shape of the plant relative to topographic features and the surrounding vegetation

2) color and texture of the plant relative to surrounding topographic features and vegetation

3) dispersal or concentration of components such as office buildings, service areas, and parking lots

The influence of these considerations on the visual impact of a facility is illustrated in Figure 20.

Figures 19 and 20

As is illustrated by Figure 21, the effectiveness of visual screening is greatest when the screen is located close to the observer, regardless of distance from the object to be screened. For example, the 20 X 10^6 mtpy mine model assumes an average stockpile height of 61 m with a slope of 21.8°. Maximum height of mature native trees in the area averages near 30 m. Mature trees planted near the base of a stockpile would be effective to a distance in the range of 100 m of the pile, whereas mature native conifers near expected points of observation such as roads, overlooks, and lakes could effectively screen the pile from the view of an observer 900 m (approximately 1/2 mi) away.

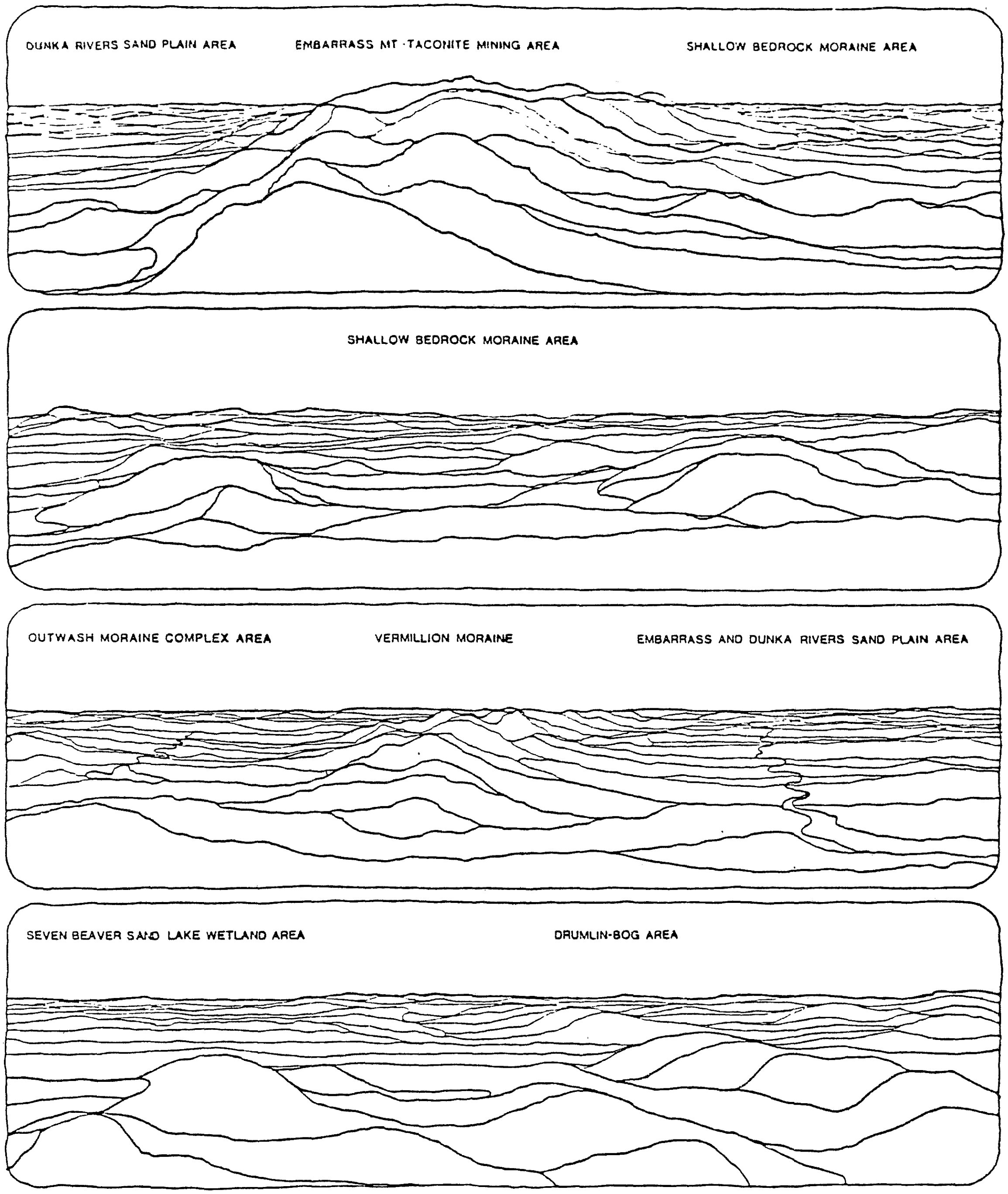
Figure 21

Because Forest Service management practices provide for an uncut buffer zone along all public roads, screening generally would be provided for all viewers looking toward the mining operation from these roads in wooded areas. It seems likely that visual screening would only be necessary as a landscaping feature between certain areas of the operation itself. On-site, year-round screening could best be provided by native conifers, such as white spruce, which have been rated as tolerant to pollution in the Sudbury area (Driesinger and McGovern 1970).

As is the case with smelter/refinery sites, unless good housekeeping procedures are followed, plant sites are likely to be characterized by a great deal of soil

FIGURE 19

EXAMPLES OF VIEWSCAPES WHICH AID VISUAL ANALYSIS



SOURCE : BRW, 1978

FIGURE 20

PLANT SITING WITH AND WITHOUT REGARD TO VISUAL IMPACT

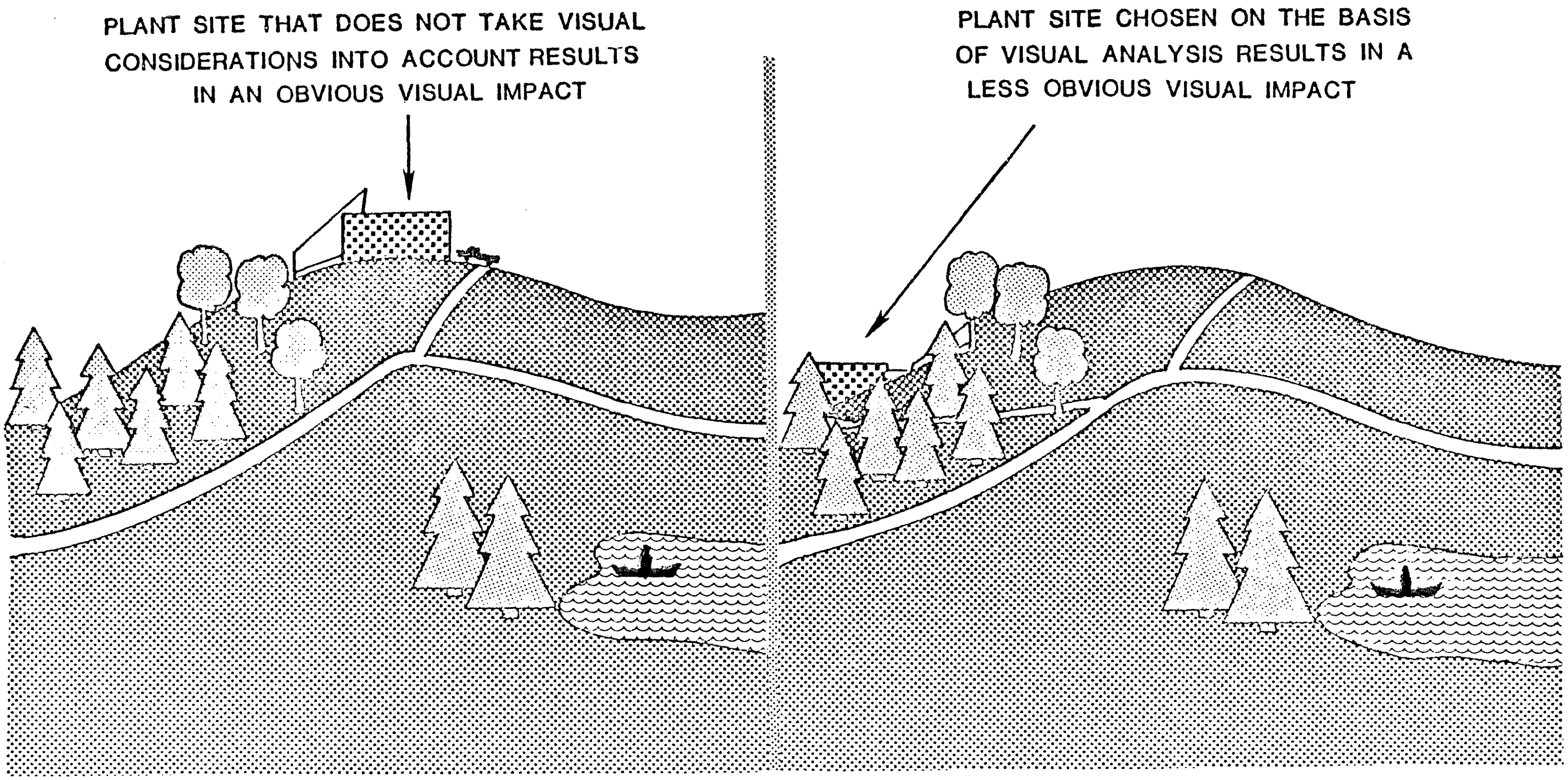
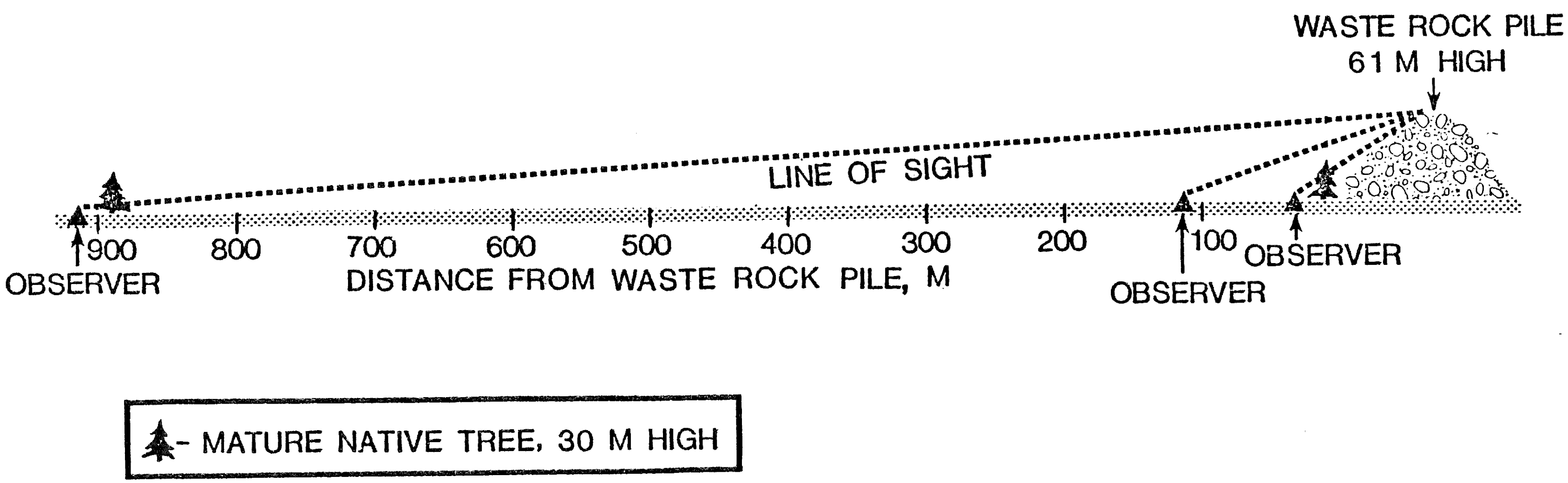


FIGURE 21

EFFECTIVENESS OF VISUAL SCREENS



compaction and heavy metal contamination from fugitive particulates and concentrate spills. Reclamation goals and methods of amelioration are likely to be similar to those for smelter/refinery sites. Conversion of the site to another industrial use may be the most economical and easily attainable reclamation goal. If revegetation is planned, buildings and associated facilities such as parking lots would need to be razed.

2.9.1.6 Underground Mine Sites--Underground mine sites require surface facilities such as headframes, conveyors and buildings. Insofar as is possible, the siting and design criteria applicable to plant sites should also be applied to these facilities. Upon abandonment, underground mine sites present the added consideration that access to shafts must be controlled. If the shafts and mined areas are not affected by underground sources of water, military storage areas or underground waste disposal are possible uses. If the shafts themselves are not converted to a new use, waterproof, and vandal-proof permanent sealing is required before the surface can be developed for any other use. Other developments such as conveyor systems, railroads and buildings would need to be razed or converted to another industrial use. Because of the competence of the Duluth Gabbro, surface subsidence is not expected in areas overlying underground mines. Should such subsidence occur, the overlying landscape could develop irregular and broken surfaces requiring stabilization and revegetation by methods discussed for waste rock piles and tailing basins. Because such areas might constitute public hazards, they would probably require fencing.

2.9.1.7 Undisturbed Watershed--The area designated as "undisturbed watershed" may not be truly undisturbed but may be influenced by fugitive particulates or accidental fumigations. If their biological characteristics are studied at the outset, such areas may be used as research areas to monitor impacts. Litter decomposition may be reduced in areas subject to heavy metals loading, with concomitant increases in litter depth and decreases in nutrient cycling. Such changes could be expected to affect forest growth so that intensive timber production would probably not be possible on company lands where the risk of impacts is high. Undisturbed areas may be managed throughout the life of the operation for the production of forest products and wildlife, or it may be left in its "natural" state except for its proximity to mining operations and haul roads. Such undisturbed lands generally provide a visual buffer around open pits, plants, and storage piles, and may serve the added function of providing seed sources for natural invasion of revegetated areas by native species.

2.9.1.8 Overburden Piles--In zones 1 through 4, overburden piles will probably be a temporary feature on the landscape because of the usefulness of overburden either as fill or as topdressing for other reclamation activities. Even where overburden is limited and is stockpiled for future use in reclamation, dust lift-off may be a problem. Temporary surface stabilization such as chemical or annual vegetative cover could be used to reduce dust lift-off. Of the materials available, topsoil, peat, and clay may provide the best absorbents for heavy metals. Clay materials deposited by the St. Louis sublobe in the western part of zone 7 would be especially valuable absorbents of heavy metals because of their higher cation exchange capacities. The usefulness of overburden as topdressing will vary with its texture. Coarse sands and gravels, which constitute a large portion of the overburden in development zones 3 and 4 would be less suitable as topdressing for rock piles than finer materials because of their lower cation exchange capacity and coarser texture. On the other hand, coarse materials may be used as construction materials and the incorporation of coarse materials into slimes of the tailing basin might help develop a more loamlike material.

Segregation of the developed soil layer from the parent material during the course of excavation would provide a source of topsoil for final dressing of the tailing basin.

Topdressings of 20 to 122 cm have been suggested for rock piles (Farmer et al., 1976, Vogel, 1977) whereas revegetation of tailing basins in the Sudbury area have been successful where topdressings were 15 cm. deep (Michelluti, 1974).

Information on depth of the overburden in the copper-nickel resource zone is incomplete. A maximum depth of 61 m has been reported in bedrock depressions west of Birch Lake and minimum depths of less than a meter prevail in the area adjacent to the BWCA where bedrock outcrops are common. Average depth to bedrock is approximately 20 m in the Toimi Drumlin Field and gradually diminishes to near zero north of Birch Lake.

A model based on measured depths of surficial materials in the Study Area (Olcott and Siegel 1978) suggests that overburden is likely to be a significant waste product of open pit mining in zones 5 and 7 (see Table 26). On the other hand, as can be seen from the table, underground mining generates no overburden and till may have to be obtained from borrow pits to meet reclamation needs of an underground mine in all zones.

One suggestion for overburden pile construction proposes that the overall pile should be no steeper than a 5:1 slope, with a series of short segments, each with a slope not exceeding 3:1. At a maximum of every 30 ft change in elevation, such slopes would be interrupted by a terrace sloped toward the interior of the pile to contain runoff and encourage infiltration.

The backsloped terraces required by this proposed regulation would not have the same adverse environmental impact on overburden piles as on waste rock piles as overburden should not have the same potential for leaching heavy metals. In certain areas of the resource zone where significant outcropping of Duluth Gabbro occurs, metal concentrations of overburden are quite high. Depending on soil chemistry, this material could also present leaching problems. On the other hand, if surface materials were fine-textured, such as the clays in the western part of zone 7, drainage might be poor and ponding could be expected.

2.9.1.9 Slag Piles--Slag piles, like overburden piles, are a valuable source of fill, construction material, or stabilizer. Because of the high temperatures of the smelting process, slag is essentially an inert glasslike substance, which presents an adverse physical environment for growth.If it is quenched and ground into a chosen size for construction material it will be less inert than if it is dumped and allowed to harden in-situ. The finer it is ground, the less inert the slag is likely to be. The Regional Study's 20 X 10^6 mtpy model anticipates production of 15 X 10^6 mt of slag over the life of the operation.

Slag has been used as a physical stabilizer on tailing (Dean and Havens 1973). In addition to its usefulness as stabilizer it can be used as fill in constructing roads and dikes. It is likely that the amount of slag produced will exceed the demand and that slag piles will need to be reclaimed. Slag is not amenable to revegetation and would require topsoiling similar to that used on waste rock piles. The Regional Study's models (Volume 3-Chapter 1) suggest that 0.02 X $10^6 m^3$ of top dressing will be needed to reclaim the slag piles resulting from each of the 3 models producing 100,000 mtpy metal (12.35 X 10^6 mtpy underground, 16.68 X 10^6 mtpy combined, and 20.00 X 10^6 mtpy open pit). Although slag piles may require fertilizer and stabilization, they are less likely to require liming than waste rock piles because of their more inert nature.

2.9.1.10 Haul Roads--Haul roads are a significant feature of the landscape associated with the total mining operations but may become less important in the future as rising petroleum costs encourage mining companies to convert to covered conveyor haulage systems. During the operation of a mine and associated facilities, the control of airborne particulates associated with haul roads is a major reclamation concern. Approximately 75% of all particulates are expected to arise from haul roads (Volume 3-Chapter 3, section 3.6.2.2). Studies in the New Lead Belt of Missouri (Wixson and Jennett 1975) indicate that the areal extent of impacts from road dust may be limited, with the distribution of particulate metals in leaf litter falling off drastically beyond 100 m of the road. Use of covered conveyor systems could significantly reduce the impact of airborne particulates arising during transport.

Temporary stabilization methods such as watering are useful in keeping down dust on temporary roadways within the open pit. Watering haul roads requires continual application for effective dust control. Erie Mining Company (Dickinson 1978) has used both No. 5 road oil and lignon sulfonate with success. Although the oil application is more durable than the sulfonate, it does provide a more slippery surface. Costs of both additives are compared in Table 24. Abandoned roadways can be revegetated with cover crops such as birdsfoot trefoil or roadside grass mixes such as the Minnesota Highway Department #5 (see Table 30). The comparative costs of stabilization methods are discussed in section 2.9.1.2. Reclamation goals can choose to maintain some of these roads as public roadways, perhaps even to upgrade them as access roads to recreational facilities. Other roads may be retained in undeveloped condition as trails for jeeps, snowmobiles, and offroad vehicles. Abandoned haulroads through undisturbed watershed can be expected to revert to swathes invaded by weedy species and brush. Forest Service guidelines encourage the maintenance of openings that provide food and runways for wildlife on Forest Service lands. The choice of leaving roadbeds rather than seeking to revegetate them will depend on their location.

Haul roads that are part of waste rock piles may be developed as access ramps for wildlife but may require special stabilization against erosion because their gentler grades may interrupt the overall contour of the piles and provide opportunities for gullying on the uphill side. Local surface runoff may concentrate in old roadbeds because their compacted soils have less permeability. If this runoff is to be avoided, roadbeds will require differential loosening.

2.9.1.11 Reservoirs--Reservoirs may be necessary to store water collected from watersheds as make-up water for processing. Management of the reservoir during the course of operation would depend partially on reclamation goals. If the goal is to maintain the reservoir as a usable lake or pond, the only allowable water source would be the watershed and tailing basin overflow water would be stored elsewhere. If the reclamation goal is eventually to fill the reservoir and revegetate it, tailing basin return make-up water can be stored in it. In the latter case, reclamation procedures will be similar to those for tailing basins. Waste materials such as slag or waste rock could be dumped into the drained reservoir site before it is reclaimed.

2.9.2 References

Aaseng, N.E. 1978. Problems and approaches to the revegetation of mine wastes. Regional Copper-Nickel Study, Minnesota Environmental Quality Board.

Antonovics, J., A.D. Bradshaw and R.G. Turner. 1971. Heavy metal tolerance in plants, in J.B. Cragg (ed.) Advances in ecological research, Vol. 7. Academic Press, London and New York.

BRW (Bather-Ringrose-Wolsfeld-Jarvis-Gardner, Inc.). 1978. Copper-nickel mining visual analysis and design criteria. Prepared for the Regional Copper-Nickel Study, Minnesota Environmental Quality Board.

Blake, G.R. 1975. Appraisal of taconite tailings as a medium for plants. Draft Environmental Impact Statement Tech. Appendix. Reserve Mining Company's proposed on land tailing disposal plan. PE108-E117.

Brown, R.W. and R.S. Johnston. 1976. Revegetation of an alpine mine disturbance: Beartooth Plateau, Montana. USDA For. Ser. Res. Note. INT-206.

Chosa, J.A. and S.G. Shetron. 1976. Use of willow cuttings to revegetate the "slime" areas of iron mine tailing basins. Mich. Tech. Univ. Ford Forestry Center Res. Note 21.

Dean, K.C. and R. Havens. 1973. Methods and costs for stabilizing tailing ponds. Presented at Amer. Mining Congress Mining Convention/Environment Show, September 9-12, 1973. Denver, CO.

Dean, K.C., R. Havens and M.W. Glantz. 1974. Methods and costs for stabilizing fine-sized mineral wastes. USDI Bur. Mines Rep. Invest. 7896.

Dean, K.C. and M.B. Shirts. 1977. Vegetation for acidic and alkaline tailing in Thames, J.L. (ed.) Reclamation and use of disturbed land in the Southwest.

Deeley, D.J. and F.Y. Borden. 1973. High surface temperatures on strip-mine spoils in Hutnick, R. and G. Davis (eds.) Ecology and reclamation of devastated land, Vol. 2. New York: Gordon and Breach.

Dickinson, S.K. 1972. Experiments in propagating plant cover at tailing basins. Min. Cong. Jour., October issue.

-------. 1975. Revegetation of taconite tailing. Mineral Waste Stabilization Liaison Committee, Vail, Colorado, August 7-8, 1975.

-------. 1978. Mineland stabilization. Univ. of Minn. and AIME Annual Symposium, Duluth, Minnesota, January, 1978.

Dickinson, S.K. 1978. Personal communication.

Dickinson, S.K. and D.G. Youngman. 1971. Taconite tailing basin reclamation-a phase of multiple resource management. 32nd Ann. Min. Symp.

Down, C.G. and J. Stocks. 1977. Environmental impact of mining. John Wiley and Sons, New York and Toronto.

Driesinger, B.R. and P.C. McGovern. 1970. Sulfur dioxide levels and resultant injury to revegetation in the Sudbury area during the 1969 season. Dept. of Energy and Resources Management. Sudbury, Ontario.

Eger, P., B. Johnson and G. Hohenstein. 1979. 1978 DNR/AMAX field leaching on and reclamation program. Progress report on the leaching study. MDNR, Division of Minerals, St. Paul, MN.

Farmer, E.E., B.Z. Richardson and R.W. Brown. 1976. Revegetation of acid mining wastes in central Idaho. USDA For. Serv. Res. Paper INT-178.

Flambeau Mining Corporation. 1976. Mining permit application for mining the Flambeau copper deposit, Ladysmith, Rusk County, Wisconsin.

Gadgil, R.L. 1969. Tolerance of heavy metals and the reclamation of industrial waste. J. Appl. Ecol. 6.

Golder, Brawner and Associates. 1978. Report to State of Minnesota Environmental Quality Board on Copper-Nickel Project-engineering aspects of tailing disposal.

Goodman, G.T., C.E.R. Pitcairn and R.P. Gemmel. 1973. Ecological factors affecting growth on sites contaminated with heavy metals in Hutnick, R. and G. Davis (eds.) Ecology and reclamation of devastated land, Vol. 2. Gordon and Breach, New York, NY.

Jones, L.M. 1972. Vegetative establishment on iron mine tailings, dam berms, and waste rock dumps. M.S. Thesis, Mich. Tech. Univ.

Leisman, G.A. 1957. A vegetation and soil chronosequence on the Mesabi Iron Range spoil banks. Minnesota Ecol. Monog. 27.

Michelluti, R.E. 1974. How to establish revegetation on high iron-sulphur mine tailings. Can. Min. J. 10.

Molz, F.J. and V.D. Browning. 1977. Effect of vegetation on landfill stabilization ground water, Vol. 15, No. 6.

Morrison, W.R. and L.R. Simmons. 1977. Chemical and vegetative stabilization of soils. Bur. Rec. Rep. Rec.-ERC 76-13. Bureau Reclamation, Denver, CO.

Olcott, P.G. and D.I. Siegel. 1978. Physiography and surficial geology of the Copper-Nickel Study Region, northeastern Minnesota. U.S. Geol. Survey. Water Resources Investigations 78-51. Open-file report.

Olson, J. 1978. The effects of heavy metals on the germination and radicle growth of some forest plants in northern Minnesota. Plan B paper, College of Forestry, Univ. of Minn.

References continued

Prather, J.G. 1973. Vegetative stabilization of reclaimed copper stamp sands. M.S. Thesis, Mich. Tech. Univ.

Shetron, S.G. and R. Duffek. 1970. Establishing vegetation on iron mine tailings. J. Soil and Water Conserv. 25(66).

Shirts, M.B. and J.H. Bilbrey. 1976. Stabilization methods for the reclamation of tailing ponds. Presented at the landscaping and land use planning as related to mining operations seminar. Australisian Instit. Min. Met. Adelaide, Australia, March 29-April 4, 1976.

Smith, R.A.H. and A.D. Bradshaw. 1970. The reclamation of toxic metalliferous wastes. Nature, Lond. 227.

Vogel, USDA Southeastern Forest Experiment Station. 1977. Personal communication.

Whitby, L.M. and T.C. Hutchinson. 1974. Heavy metal pollution in the Sudbury mining and smelting region of Canada. Environ. Cons. 1(3).

Wixson B.G. and J.C. Jennett. 1975. The new lead belt in the forested Ozarks of Missouri. Env. Sci. and Tech. 9(13).

Young, C.A. 1969. The use of vegetation to stabilize mine tailing areas at Copper Cliff. Can. Min. J. 90(6).