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REGIONAL COPPER-NICKEL STUDY  
PROBLEMS AND APPROACHES IN THE  
REVEGETATION OF MINE WASTES

Minnesota Environmental Quality Board

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July 11, 1978

PRELIMINARY DRAFT REPORT, SUBJECT TO REVIEW

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# PROBLEMS AND APPROACHES IN THE REVEGETATION OF COPPER-NICKEL MINE WASTES

## INTRODUCTION

Background--Depending on the mine model used it is estimated that the mining of copper-nickel ore in the Regional Copper-Nickel Study Area (Study Area) will require the disposal of 129 to 1,134 million metric tons of waste rock and lean ore and 117 to 484 million metric tons of tailings over a 30 year period. In addition, 19 to 25 million cubic yards of glacial overburden will be excavated. This material will require from 951 to 5,548 acres for its storage and disposal. A summary of the extent of the various mining waste materials for five different mining models is given in Table 1.

A reclamation program will be required to restore the disturbed landscape. This will involve two steps; an immediate goal of minimizing adverse impacts on the surrounding environment, and a long term goal of returning land to productivity in harmony with surrounding natural land use. The first priority of reclamation involves the immediate stabilization of waste surfaces to prevent air quality problems due to blowing dust, and water quality problems due to leaching of toxic substances. Aesthetics are also a consideration. The ultimate goal of reclamation is to establish maintenance-free native plant communities that will continue to stabilize the area and minimize adverse environmental impacts. Returning the land to a condition suitable for the management of timber, wildlife and/or recreational purposes will be encouraged and in some cases may be required. Appendix A contains estimates of revegetation costs (1977 dollars) for various end results.

Purpose--The purpose of this paper is to discuss the problems that could  
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Study Area. A discussion of revegetation techniques used to overcome these problems and results obtained from revegetation programs is also included. This report will provide information on the probable types of vegetation and their rates of establishment that could be expected to revegetate the various mining wastes.

Approach--Because mine waste reclamation research has been largely coal-orientated a limited amount of literature dealing specifically with copper-nickel wastes is available. Of the pertinent information reviewed the majority deals with copper rather than nickel mine wastes. An attempt was made to review reclamation studies in areas with climate, vegetation, and soil conditions similar to those found in the Study Area. However, due to an almost total lack of such studies, information from iron and taconite revegetation work in Minnesota and Michigan was used when applicable. Because tailings pose the biggest problem from a reclamation viewpoint they are dealt with in greatest detail.

The literature reviewed dealt almost exclusively with short-term studies with an emphasis on immediate site stabilization by revegetation. Few studies are at the point of considering long-range reclamation problems, approaches, and goals. This is understandable, however, for large scale reclamation efforts have been attempted only recently. Much immediate concern centers around the prevention of dust problems.

### TAILINGS

Background--Most of the literature reviewed deals only with copper tailings, for information on copper-nickel or nickel tailings is almost non-existent. Information specific to copper tailings revegetation was obtained from three areas; southwestern United States, Michigan, and Sudbury, Canada, but studies

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studies in the southwest deal predominately with revegetation efforts in a desert vegetation type they make up the majority of the available information on copper tailings. Revegetation research on taconite and iron tailings was used to supplement information relating to physical problems associated with tailings in an environment similar to that of the Study Area.

Characteristics--Copper tailings are fine grained residues generated by crushing, grinding, and concentrating processes. Composed largely of siliceous materials, the particles range in size from fine sand (<150 microns) to fine silt or clay (<2 microns) (Shirts and Bilbrey 1976). Modern milling processes have presently reduced the average particle size so that often 50% are less than 74 microns (O'Neil 1977). As a result copper tailings lack the coarser particles (coarse sand to gravel) found in taconite tailings.

Although there are several tailing discharge schemes, the basins discussed in the literature generally conform to the following description. Tailings are deposited as a water slurry into a basin formed by the natural landscape and /or constructed earthen dams. Basins range in size from 40 to several thousand acres. The deposition of tailings by water movement results in a separation of tailings by particle size into three general areas, each having their own physical characteristics. The coarser particles settle out first near discharge points at the periphery of the basin and form a coarse-textured outer ring. The finer material is carried towards the center of the basin. A slime zone forms in this depression as a result of ponding water which allows fine colloidal materials to settle out. The slow meandering of the slurry over the gradual slope of the basin results in areas of inter-stratified layers of differing particle size forming between the slimes and coarse sands. Dams are built up at periodic intervals during the life of

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a basin using the coarse tailings near the outer edge. The dam slopes are generally  $\leq 50\%$ .

Discharge points are rotated around the basin to facilitate even filling. As a result certain areas of the basin may be "dormant", and length of exposure of tailings will vary with the rate and method of spigot rotation.

Other tailing disposal schemes that would result in physical characteristics of the basin differing from those of the traditional approach may also be utilized. For example, the deposition of tailings from the center of the basin instead of the periphery would result in a raised central area composed of coarse tailings. The finer particles and slimes would be concentrated in an outer ring along the side of the dam. If cyclone separators are used the coarser tailings would be separated out and used in dam construction prior to deposition into the basin. The finer material, discharged as a slurry, would be separated out by particle size in the usual manner. The result would be a basin with a less extreme range in tailing textures, although some gradation of coarse to finer particles will still occur.

Other tailing discharge schemes that are less likely to be employed include the deposition of tailings into an area without dikes or dams, and the deposition of tailings into a basin submerged in water. The former would probably result in a greater separation of particles, whereas the latter would possibly result in a more homogeneous textured basin.

In summary, physical characteristics of tailings basins may vary, depending on the disposal scheme used. Even with similar methods of

vary considerably from site to site, because ore mineralogy and milling processes vary.

It is difficult to generalize about the chemical properties of copper and nickel tailings. Iron sulfides are often associated with copper and nickel ore deposits. When these acid generating compounds constitute a significant portion of the ore, the low tailing pH that is often characteristic of copper and nickel tailings will result. As with physical characteristics, the chemical composition of tailings (i.e. concentrations of salts, phytotoxic substances, nutrients, etc.) may vary considerably from site to site because of varying ore mineralogy. Also, great variability in characteristics may occur within a tailings basin (Lukulich 1977).

Factors Inhibiting Revegetation--Eight factors have been identified from the literature reviewed that could pose a threat to successful revegetation of copper and nickel tailings:

- 1) erosion
- 2) undesirable physical structure of slimes
- 3) water deficiency
- 4) heat stress
- 5) nutrient deficiencies
- 6) heavy metal phytotoxicity
- 7) salinity
- 8) damage by wildlife

On most sites several of these factors are present, and it is their synergistic interactions that work to inhibit plant establishment and growth (Peterson and Nielson 1973).

Erosion--Wind--Sandblasting or burial of plants by abrasive tailings has been identified by many researchers as one of the most difficult problems to overcome in the establishment of vegetation on tailings basins (Jones 1972, Prather 1973, Dean and Shirts 1977, Peterson and Nielson 1973). Several wind erosion problems often exist because of the absence of wind breaks over a vast and relatively flat topography composed largely of unconsolidated sands that are particularly susceptible to aeolian transport. Without some form of surface stabilization, much seed and fertilizer may also be blown away.

Water--prior to the establishment of adequate cover of well-rooted plant species, the steep slopes of tailing dams and their lack of a normal soil structure make them very susceptible to erosion. This is a particular problem where intense precipitation events produce heavy surface runoff. Although erosion is not considered severe by most researchers, Dickinson (1972) states that a major concern in revegetating tailings dams in northeastern Minnesota is the control of surface runoff in order to prevent washouts that require regrading and replanting. Within the tailings basin, water erosion was reported to be a problem in Michigan (Chosa and Shetron 1976) where rain falling on slimes that were too saturated to be planted resulted in gullyng of surrounding planted areas.

Undersirable Physical Structure of Slimes--Although all tailings lack the desirable physical structure normally found in agricultural and forest soils, the physical characteristics of slimes present an unusually difficult medium for plant establishment. Slimes, which are composed of the finer particulate fraction of tailings, concentrate in the bottoms of basins and are characterized by highly restricted water permeability. The poor drainage characteristics of slimes result in dewatering problems. In some cases as

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much as a third of a tailings basin may go unplanted until sufficient time for drying has occurred (Jones 1972). Drying may take several years to occur after deactivation of the basin (Chosa and Shetron 1976). Once the slimes have drained, there continues to be poor drainage that can be exacerbated by high water tables. These result in severe puddling following rainfall and survival of plantations may be reduced by as much as 50% (Jones 1972). In cases where an "impervious" basin is constructed to minimize contamination of ground water by leachate, these problems may be accentuated.

Problems also result from the lack of air-filled pore spaces through which oxygen can diffuse. Poor soil aeration results in high CO<sub>2</sub> concentrations, and hinders proper root development (Blake 1975). In addition a crust often forms at the tailings surface when it dries. These crusts may inhibit seed germination and further decrease soil-air interaction. Slime problems are characteristic of most tailings basins and have been studied in copper and iron tailings basins by Jones (1972), Michelluti (1974), Dean et al. (1973), and Chosa and Shetron (1976).

Water deficiency--In contrast to slimes, the coarse particulates that cover much of the outer periphery of tailings basins and dams in typical dispersal schemes present a substrate particularly susceptible to water deficiencies. The problem is magnified by the high surface temperatures and winds that characterize tailings basins and result in high evaporation rates. Water deficiencies on slopes are particularly severe due to loss of precipitation by surface runoff and the higher incidence of solar radiation on south-facing slopes.

These factors can combine to reduce the effectiveness of rainfall in areas with normally adequate precipitation. Plant germination and survival on droughty tailings is dependent upon the random occurrence of sufficient precipitation. As the length of time between periods of rainfall increases, the more drought susceptible species begin to thin out and surviving species show poor growth (Blake 1975). Also, susceptibility to other environmental stresses is greatly increased. Revegetation efforts that have been successful for a number of years can be severely retarded during long periods of drought. Although water deficiency is particularly acute in the southwest, it has also been a significant factor in occasional setbacks experienced in Michigan (Shetron and Duffek 1970) and Sudbury, Canada (Peters 1975).

Heat Stress--The possibility that high surface temperatures may be important in inhibiting plant establishment on tailings has been raised by Ludeke (1973) in the southwest and Dickinson (1972) in Minnesota. Most in-depth studies dealing with this problem have been coal-oriented. Results, however, appear to be applicable to mine wastes in general.

Heat stress limits plant germination and growth and may be caused by extremely high temperatures and severe temperature fluctuations. Both causes stem from the extremely high thermal conductivity of tailings. This gives rise to a surface environment that can easily be heated to extreme temperatures and is susceptible to extreme temperature fluctuations over short periods of time (Deely and Borden 1973).

The abnormally high thermal conductivity of tailings is due to their lack of organic matter and their low moisture content during rainless periods. Also, large amounts of solar radiation reach the surface in the absence of insulation either in the form of plants or litter. Slope, aspect, and tailings color can also greatly influence the amount of radiation absorbed

or reflected. A steep south-facing dam slope composed of dark colored tailings would be expected to have highly elevated soil temperatures. These factors can result in surface temperatures high enough to place a physiological stress on low-lying plants and can depress photosynthesis (Gates 1965, cited by Ludeke 1973). On very light surfaces intense solar radiation is reflected to the plant causing increased heat stress, which in extreme cases can be fatal. Dark surfaces absorb heat and result in excessive ground temperatures causing mortality in germinating seeds and heat girdling of stems at the ground/stem interface of established plants (Deeley and Borden 1973, Shirts and Bilbrey 1976). Soil-surface temperatures of 50° C (122° F) may be lethal to young plants. Deeley and Borden (1973) report that surface temperatures in this range can occur on many kinds of materials characteristic of disturbed lands. Dickinson (1972) measured temperatures as high as 61° C (142° F) on the slopes of a taconite tailings dam in Minnesota and concludes that moisture and surface temperature controls are necessary for proper germination and growth.

Severe temperature gradients may be an even greater problem than high temperatures. Such gradients occur in spring; particularly on light colored surfaces, which reflect much of the solar radiation. Surface temperatures may reach 40-50° C while root temperatures remain near freezing. Severe gradients can also occur on partly cloudy days where the change from full sunlight to shade may result in drops of 30° C in 5 minutes (Deeley and Borden 1973).

Nutrient Deficiencies--Chemical analyses of available plant nutrients have shown that copper tailings are characteristically deficient in nitrogen, phosphorous, and/or potassium. Severe nitrogen deficiencies were reported

in nearly all cases. Deficiencies for P were generally found whereas K deficiencies were less common (Nielson and Peterson 1973). Even with the addition of fertilizers, nutrient deficiencies usually develop within a few months to several years. These continued deficiencies are attributed to two factors; low availability and loss by leaching. Nutrient availability for plant use is dependent upon soil pH. Under increasingly acidic conditions (i.e., pH < 5.5) these nutrients become less soluble or are bound by other elements (e.g., Al, Fe) through pH related reactions. This results in reduced availability for plant use. In addition, with the low cation exchange capacity due to lack of organic matter and clay size particles (< 2 microns) and the high rate of water percolation in the coarser-textured areas, the nutrients are weakly bound (Blake 1975). Rapid leaching of N and K results, although P is relatively immobile. Nitrogen deficiencies are most common, because relatively large quantities are required by plants, and N compounds are particularly prone to leaching. Also, unlike P or K, which may be replenished by weathering of minerals, soil nitrogen comes primarily from microbial activity and organic matter, both of which are lacking in tailings. It is the continual and excessive loss of nutrients that poses a major obstacle in obtaining self-sufficient plant communities (Young 1969). Deficiencies of the other macronutrients--magnesium, calcium, iron, and sulfur--have not been reported.

Supply of micronutrients is generally considered to be adequate, although chemical analysis for these elements has not been done routinely. In some cases deficiencies of micronutrients were suspected (Michelluti 1974), although chemical analyses were not carried out and/or individual elements identified.

Heavy Metal Phytotoxicity--Several researchers have suggested that toxic levels of heavy metals may occur in copper tailings basins. Metals that may occur include Cu, Ni, Pb, As, Fe, Al, Zn, Mg, and Mn (Courtin, et al. 1974, Ludeke 1977, Shirts and Bilbrey 1976). However, of the literature reviewed only Ludeke (1977) had identified toxic symptoms in species planted on tailings. He reported dwarfing and root malformation due to Cu and chlorosis due to Mn. The effects of Cu toxicity are often lethal and are believed to be a major factor limiting plant growth and establishment. Other metal toxicities are suspected but, because symptoms are not well documented, little is known of their importance. On the other hand, many researchers either make no mention of heavy metals problems, are unable to separate heavy metal toxicity from other effects, or conclude that concentrations are too low to be toxic. Others suspect marginal toxicity but dismiss it as secondary to other environmental stresses and/or assume it can be readily alleviated by general soil amelioration practices.

Peterson and Nielson (1973) report that very little data on limits of toxicity of heavy metals to various plants and practically no information on synergistic toxicities are available. Table 2 shows test results and indicates the variability in the levels at which toxicity has been reported. Differences result from a number of factors. Various plant species are reported and these differ in their susceptibility to heavy metals. The actual availability of metals may vary depending upon pH and the amount of organic matter present. Also, the presence of more than one toxic metal may have a synergistic effect that greatly lowers the concentration levels at which toxic effects occur.

The primary factors that determine whether or not heavy metal toxicity will occur are the initial concentration of a metal in tailings and its availability.

Relatively high levels of copper and nickel would be expected, for extraction processes are only 65-90% efficient. The amount remaining in tailings varies among extraction methods. However, the absence of toxicity problems following liming and fertilization suggests that the toxicity of the Cu and Ni concentrations present may often be marginal, at worst, under normal soil conditions. A more important factor in heavy metals toxicity is the availability of toxic cations. This is dependent upon solubility, which is largely determined by soil reaction (pH). In general, as pH falls below 5.5, solubility increases. Because copper tailings are often acidic, there is a high probability of high levels of available Cu, Ni and other metals. In highly acid tailings even metals that are present in normal (total) concentrations may become toxic (Whitby and Hutchinson 1974). Heavy metals phytotoxicity is thus linked directly to pH extremes.

Tailings pH is influenced by chemical processing and mineralogy. The ore beneficiation process generally produces a basic effluent and normally will not result in acid generation (although some acids are released in the tailings slurry). The major cause of low pH is the presence of acid-forming minerals characteristicly found in copper deposits. Iron sulfides, generally in the form of pyrite ( $\text{FeS}_2$ ) and less commonly pyrrhotite ( $\text{Fe}_2(\text{SO}_4)_3$ ), oxidize to form sulfuric acid ( $\text{H}_2\text{SO}_4$ ):

1.  $\text{FeS}_2 + \text{Fe}_2(\text{SO}_4)_3 + \text{H}_2\text{O} \rightarrow 3\text{FeSO}_4 + 2\text{S}$
2.  $2\text{S} + 3\text{O}_2 + 2\text{H}_2\text{O} \rightarrow 2\text{H}_2\text{SO}_4$

Because the water used to discharge tailings is constantly recirculated and has low biological and chemical oxygen demands, it is generally highly oxygenated. Thus tailing water provides sufficient amounts of oxygen for the conversion of S to  $\text{H}_2\text{SO}_4$ . Even when tailings are dry, moist air provides

$\text{Fe}_2(\text{SO}_4)_3$  constitute a major portion of the tailings, pH may fall to less than 3.0.

Salinity--Excessive concentrations of soluble salts have been found to be present in several tailings basins. The accumulations are thought to come from two sources:

1. high salt concentrations in the ore body being processed, and
2. high salt concentrations in the water used for processing.

Salt concentrations may be further increased by evaporation as a result of recycling the water (Ludeke 1977). Also, salt buildups can develop in soils with normal salt concentrations when infiltration is impeded and surface evaporation is high. Capillary action results in the movement of dilute salt solutions from the interior to the surface of the tailings.

High salinity creates high osmotic potentials in the tailings. These result in "physiological drought" despite adequate soil moisture. Water stresses develop that may result ultimately in the desiccation of plants (Michelluti 1974).

Salinity in tailings is a problem primarily in the southwest, where high salt concentrations occur naturally in the ore and evaporation is particularly rapid. Studies in Canada and the eastern United States indicate that high salinity may become a problem in more humid climates if rapid evaporation results in salt accumulation near the tailing surface (Michelluti 1974, Davis 1977).

Damage by Wildlife--Girdling of shrubs by rodents and trampling of grasses by ducks and geese have reportedly caused injury and death to plants

established in tailings (Ludeke 1977, Dickinson 1972). Damage, however, is usually confined to slight reductions in plant stocking or vigor and usually does not significantly influence overall revegetation success.

#### APPROACHES TO TAILING AMELIORATION

Each tailings basin must be evaluated independently and procedures are designed to alleviate the major problems identified. General agricultural practices are usually employed to modify tailings characteristics to resemble normal soils. A yearly analysis is made of the vegetation requirements on these "synthetic soils", and corrections are made accordingly. Approaches to some of the more serious problems are outlined below.

Neutralization--Alteration of pH for the purpose of maximizing available plant nutrients and minimizing toxic effects of heavy metals has been a standard practice in acid tailings basins. Generally a pH of 6-8 is the most desirable range for plant establishment. Agricultural limestone ( $\text{CaCO}_3$ ) and less often burnt lime ( $\text{CaO}$ ) have been used as neutralizing agents. Rates of application vary depending upon the amount of sulfides present in tailings. Although one or two applications of lime may neutralize tailings, effects are often temporary. A coarser grind of limestone, which breaks down more slowly, has been used to lengthen the buffering period (Young 1969). The continued oxidation of sulfides can require the addition of limestone at periodic intervals. Many researchers have claimed success in neutralization and revegetation of extremely acid tailings. However, these studies have been of relatively short duration, usually less than 10 years, and long term neutralizing requirements are difficult to predict.

Fertilization--Frequent applications of fertilizers have been used to improve fertility (Jones 1972). The rate and frequency of application are tailored for

various species depending on soil analyses for individual sites (Shetron and Duffek 1970).

The timing of various fertilizer applications has been manipulated to stimulate plant growth. Initial applications that are low in N but high in P and K have been used to develop the strong root systems necessary for plant survival in hostile environments. As growth progresses, concentrations are increased to stimulate top growth (Michellitti 1974).

Applications of slow-release fertilizers are best over long time periods, for N and K leach rapidly during periods of heavy rainfall (Michellutti 1974). On the other hand, the immobility of P has necessitated disking following fertilization to mix it in the rooting zone (Dickinson 1972). Precautions must be taken to avoid over-fertilization. The addition of large quantities of nutrients may increase the osmotic potential of tailings making water less available to plants. Also, toxic effects can result when heavy metals are solubilized by the ammonia present in some fertilizers (Dean, et al. 1973).

As with acidity, the possibility of nutrient deficiencies recurring in the years following initial treatment is high. Young (1969) reports that even after grass has been established, annual maintenance in the form of fertilization may be required. Other researchers report that grass cover may be established with fertilization required only during the first few years (Dickinson 1972, Gordon 1969). Studies have not, however, been of sufficient duration to assess long term effectiveness.

Whether or not the required levels of nutrients are maintained in the soil following fertilization depends upon the rate of nutrient loss and immobilization

relative to inputs from nitrogen-fixing organisms and the physical and /or chemical weathering of tailings. Tailings weather slowly and loss by leaching under acidic conditions is typically rapid. Ideally, once vegetation is sufficiently established, plant recycling of nutrients will minimize loss due to leaching and result in the establishment of a self-sustaining community.

Irrigation--Irrigation has been of great benefit where plant establishment is prone to failure due to undependable rainfall. Irrigation has been used to improve revegetation success on tailings, particularly on dam slopes (Ludeke 1977, Young 1969). Watering has also been used to leach toxic heavy metals and salts out of the root zone (Nielson and Peterson 1973, Dean, et al. 1973). This, however, is undesirable where contamination of ground water can result.

The use of irrigation in revegetation efforts has been largely confined to the arid southwest, although Young (1969) reports its use in Canada where dust control is a severe problem. In northeastern Minnesota, Dickinson (1972) concludes that irrigation is not justified, for droughts severe enough to curtail revegetation success occur infrequently.

Application of Non-Organic Tailings Stabilizers--The application of soil stabilizers to prevent or minimize surface erosion, especially on the steep slopes of dams, has been employed by nearly every tailings revegetation project. Both physical and chemical stabilizers have been used, often in combination. Physical stabilizers include crushed rock, slag, plastic netting, or any restraining material that holds down the fine tailings dust and makes it less prone to erosion by wind or water. These stabilizers are used primarily in areas where severe climatic or toxic conditions have prevented tailings revegetation.

Chemical stabilizers include any chemical used to interact with fine-sized tailings to form a crust. They are designed to prevent blowing dust and reduce the erosive power of falling rain while still absorbing water. Chemicals are also used on unreclaimable land or where only temporary stabilization is required. Chemicals can be modified to retain moisture and not inhibit seed germination and growth so that they can be used in conjunction with plantings (Dean, et al. 1973). Chemical binders and sewage sludge have been combined with tailings to form pellets that are spread over tailing basins to a depth of 3-4cm. These pellets are .3 to 1.0cm in diameter and provide not only a less erodable surface but also a more favorable environment for root growth and development (Dean and Shirts 1977).

Chemical stabilizers have been most successful when used in combination with mulches. An asphalt mixture applied to hay and straw has been used to prevent seed and mulch from blowing and washing away by Peters (1975) in Canada, by Jones (1977) in Michigan and by Dickinson (1977) in Minnesota.

Addition of Organic Matter other than Soil--The addition of organic matter greatly improves tailings as a medium for plant establishment and growth.

The benefits of organic matter include:

1. decreasing the heat conductivity thereby moderating surface temperature extremes,
2. increasing the water holding capacity,
3. decreasing the surface evaporation rate,
4. increasing the cation exchange capacity thereby reducing loss of nutrients by leaching,
5. introducing complex-forming chelates that tie up toxic heavy metals making them less available to plants,
6. lowering of the bulk density resulting in more favorable water and air relationships for plant roots.

7. increasing the buffering capacity making tailings less subject to drastic changes in pH,
8. improving "soil structure" thereby decreasing the erosive power of rainfall and surface runoff,
9. providing favorable conditions for establishment of soil micro-organisms,
10. and, providing an additional source of nutrients, primarily nitrogen, as decomposition proceeds.

Organic matter has been added to tailings through the application of both mulches and sewage sludge. Mulch has been applied directly to tailings surfaces in the form of hay, woodchips and bark, or a slurry of woodfiber. It is particularly useful in providing protection from surface erosion and modifying microclimate for seed germination. Occasionally mulches have been disked into the upper few inches of tailings. Mulches composed mostly of cellulose will require additional inputs of nitrogen to maintain a proper C/N ratio in the soil. Although the benefits of mulching are significant, revegetation costs are greatly increased. With waste disposal becoming a problem, the practice of adding sewage for the renovation of tailing sites has been tested. The advantage of sludge is its high nutrient contents. Heavy metal contamination is, however, a potential problem. Also, Shirts and Bilbrey (1976) report that sludge layer buried near the surface acts as an oxygen consumer during decomposition. This reduces the rate of oxidation and acid generation, thereby preventing tailings pH reductions.

Peat is a third source of organic matter. Its high water holding and cation exchange capacities and its high complex-forming tendencies towards Cu cations are of particular interest. Studies by Goodman, et al. (1973) demonstrate the ameliorating effects of peat on toxic mine wastes.

Additions of Soil or Till--The placement of a soil or glacial till covering has been shown to be successful in the revegetation of problem tailings.

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Davis (personal comm., 1977) believes that in some instances it is better to work with covering material than to try to fertilize and/or lime tailings directly. Michelluti (1974) used soil coverings in Canada and reports that the best results were obtained when at least 6" (15cm) of covering material were added, although even 2" (5cm) were greatly beneficial. Best plant growth was obtained with loamy soils, but any type of soil was better than none. Within a few months pH of top dressing dropped to as low as 3.5, about the same as the underlying tailings. No detrimental effects to vegetation were observed, however. The results were thought to be due to the favorable medium provided by the soil for the establishment of young plants when they are most susceptible to adverse conditions. As the roots developed they were able to successfully invade the inhospitable tailings environment. Although the extent of rooting decreased when the tailing surface was reached, the plants were well enough established to survive. Other benefits of soil can be attributed to the presence of clays, which increase water holding capacity, cation exchange capacity, and possibly micronutrients that are not provided by fertilizers.

Generally, the terms soil and till are used interchangeably and refer to any loose and in consolidated material above the bedrock. Occasionally topsoil is separated from subsoil. The uppermost (15-20 cm) layers of soil are especially beneficial as a final covering of waste materials because of their organic matter and seed content.

Species Selection--Extensive testing of the suitability of various plant species for revegetation of tailings has been an integral part of most revegetation research programs. Depending on regional climate, geology, vegetation, and the physical and chemical characteristics of the tailings, the criteria for plant selection by researchers has generally been based

on the following:

1. tolerance to pH extremes (especially low),
2. tolerance to heavy metals,
3. tolerance to salinity,
4. drought resistance,
5. tolerance to poor soil aeration,
6. winter hardiness,
7. ability to develop a dense fibrous root system capable of resisting erosion,
8. ability to germinate and root quickly,
9. productivity potential (organic matter production),
10. availability of seed and planting stock,
11. ease of propagation,
12. minimum maintenance requirements,
13. ability to reproduce vegetatively
14. efficiency in nutrient recycling and soil formation, and
15. compatibility with other reclamation and natural volunteer species.

No single species fits all the criteria given or would do equally well on all the different environmental conditions found in a tailings basin. With variations in tailings texture, moisture content, slope, aspect, and surface chemistry, a variety of species with varying growth habits and requirements is most desirable (Ludeke 1977). Table 3 lists species that have been used for revegetation purposes in Minnesota, Michigan, and Sudbury, Canada.

Additional considerations in species selection that have been brought up in the literature include compatibility with planned end use of the revegetated area and the desirability of using only native species. Generally, these considerations have been ignored in the initial stages of revegetation for

stabilize the site as quickly and economically as possible. Generally, introduced or weedy plant species are more ecologically adapted to becoming established on the highly disturbed sites. The use of only native plant species requires more extensive site treatments (fertilizing, mulching, etc) and a greater period of time to become well established. Also, large quantities of native seed are usually not readily available.

Second, once non-native plant species have become established, moderating temperature and moisture regimes and a build up of nutrients result in a site more conducive to invasion by native species. Disturbance species are often short-lived annuals and do not compete so well under less extreme environmental conditions. Therefore, succession tends to favor native species.

The rate at which succession proceeds on mine wastes has been inadequately quantified, however, and the establishment of native species may occur only gradually over long periods of time. If revegetation objectives include the rapid establishment of native species, the planting of exotics may be undesirable.

Selection of species for immediate stabilization of tailings has emphasized grasses and herbs. Species with root systems that are adapted to the stabilization of erodable material and the recycling of nutrients are the best. The strategy generally used in revegetation is to plant a mixture of annuals and perennials. The annuals act as a nursing crop, germinating and rooting quickly. They thus provide cover and protection for the more desirable perennials that are longer lasting and self-perpetuating. Annuals and biennials are also used on portions of active tailings basins where

Legumes have been given special attention because of their ability to fix nitrogen. Developing adequate nitrogen supplies is essential for the establishment of self-sustaining, maintenance-free plant communities.

Trees and shrubs have been used to a lesser extent in the earlier stages of reclamation. In Michigan, Jones (1972) found that of 32 tree and shrub species tested only 5 were successful. He concludes that most of the species used were not adapted to pioneer sites. Some researchers have suggested deferring tree and shrub plantings until tailings have been sufficiently stabilized by grasses and legumes. Others, however, have reported successful establishment of trees on the tailings basins or surrounding dikes (Dickinson 1972, Gordon 1969). Willows have been successfully planted on tailings slimes (Chosa and Shetron 1976).

On particularly toxic tailings, cryptogams, including mosses, lichens, and algae, have been used with some success in the southwest, but they were found to be no better than grasses in reclaiming the severest environments. In areas with high metal concentrations, the planting of stock originating on old waste sites has been suggested (Goodman, et al. 1973).

Species found in such areas appear to evolve genetic tolerance to high metal concentrations.

Introduction of Microorganisms--Several studies have looked into the possibility of introducing soil microorganisms to improve plant establishment and vigor. Tailings lack microbial populations normally found in soils and usually contain only bacteria that oxidize Fe and S (Ludeke 1973b).

Of major concern in the long-range goal of self-sufficiency is the introduction of rhizobium inoculated legumes. The legumes and rhizobium form a symbiotic association that allows the latter to fix nitrogen.

The introduction of self-sufficient nitrogen fixing bacteria is also possible but of less significance. Nitrogen-fixing activity is markedly curtailed when pH drops below 5.5 (Buckman and Brady 1975). Legumes have been successfully inoculated on taconite tailings where acidity is not a problem (Dickinson 1972), but copper-nickel tailings could pose problems.

Many fungi form symbiotic associations with higher plants called mycorrhizae. These fungi either invade plant roots (endomycorrhizae) or live on root surfaces (ectomycorrhizae). They increase the roots' ability to absorb water and nutrients, including normally unavailable phosphorus. Researchers have begun to recognize the potential of inoculating various plant species prior to planting. Aldon and Springfield (1977) and Peters (1975) have attributed the much improved growth of certain species on tailings to mycorrhizal inoculations. Ectomycorrhizal fungi, which are associated with conifers, are wind dispersed. They quickly invade mine wastes, and seedlings need not be inoculated. Endomycorrhizal fungi, on the other hand, are associated with hardwoods, and only move through the soil. They must therefore be introduced into mine wastes. Species-specific relationships must be known before an inoculation program can begin (Vogel, personal commun. 1977).

The addition of decomposer microorganisms or the improvement of conditions to enhance their colonization of tailing basins should be encouraged for a lack of decomposers could, over a period of time, result in an immobilization of plant nutrients in litter. Important factors influencing colonization include moderation of temperature extremes and the availability of adequate moisture. An adequate carbon source is required to guarantee survival (Neuman 1973).

## REVEGETATION RESULTS

Researchers are nearly unanimous in their assessment that the methods and know-how exist for the successful revegetation of all but the most hostile tailings environments. The only total failures have occurred in the arid southwest, although occasional setbacks occur in nearly every research program.

Results of revegetation efforts indicate that vigorous grass and herb cover can usually be established in one or two years (Peters 1975, Jones 1972, Grandt 1977, Dickinson 1972, Michelluti 1974, Shetron and Duffek 1970). Reduction of plant cover, however, can be expected to occur at irregular intervals due to prolonged or even temporary droughts that occur during critical growth periods. Although most studies have been carried out on relatively small plots, blocks as large as 100 acres have been successfully revegetated (Young 1969). Annual grasses have provided adequate winter cover within a few weeks when planted in the fall (Peters 1975).

Several studies have noted soil development in revegetated tailings. Development of an organic rich A horizon in copper tailings has been reported as early as two to three years after planting (Young 1969). On taconite tailings, indicators of soil development were observed within six years of planting (Dickinson 1972). The only quantitative measurements available indicate that an A horizon develops to a depth of 1.25cm in eight to ten years on copper tailings in Canada (Peters 1975).

Invasion of native plants, primarily aspen (Populus tremuloides) and birch (Betula papyrifera), within a few years of planting has been reported by Jones (1972), Dickinson (1972), and Peters (1975). Specific information on invasion and growth rates is not available, however. This makes difficult the task of predicting rates of reforestation under natural conditions.

Although the outlook for tailings revegetation appears to be optimistic, progress towards the overall reclamation objective of producing a maintenance-free community is less certain. Several researchers suggest that the application of fertilizers and/or limestone may be required at periodic intervals or even yearly (Young 1969, Peters 1975, Chosa and Shetron 1970).

Based on studies of severely toxic slag piles, a more pessimistic outlook may be expected on mine wastes that have higher concentrations of heavy metals. Goodman, et al. (1973) conclude that although successful vegetative cover can be maintained with annual fertilization, regression will almost certainly occur after five or six years unless additional applications of organic matter are made. On the other hand, Michellutti (1974) claims that, through the application of lime and fertilizer, vegetation can be established and maintained on even the most severely acidic tailings. His research is of insufficient duration to adequately assess long term success, however.

#### ASSESSMENT OF MINNESOTA TAILINGS

Heavy Metal Concentration--The possibility of phytotoxicity due to heavy metals appears to be minimal based on an analysis of tailings processed from ore taken at the INCO test site near Ely, Minnesota. Total concentrations of Cu and Ni were found to be as low or even lower than those of soil samples taken near the Gabbro contact (See Table 4). The concentrations determined in both cases, however, are total and not available for metals.

An approximation of availability of these elements was obtained from chemical analysis of tailing water. The results, which represent an underestimate of values obtained through normal laboratory techniques, ranged from 0 to .04 ppm for Cu and 0 to .15 ppm for Ni (Table 5).

Germination tests of several native tree species on the tailings failed to produce signs of heavy metal toxicity (Olson 1978). A growth

reduction for some species was observed on certain tailings, but reductions were thought to be caused by unknown factors other than Cu and Ni toxicity.

The heavy metals present are not likely to be highly soluble, for tailings from Minnesota are expected to be neutral in pH. This is due to the low percentage of pyrite in the ore and therefore low  $\text{SO}_4^{=}$  production. In addition, the tailings have a high buffering capacity due to the presence of Ca-Al silicates in the plagioclase. Even if all the pyrite is oxidized it is thought that there is sufficient buffering capacity to tie up the  $\text{SO}_4^{=}$  and prevent production of  $\text{H}_2\text{SO}_4$ .

Nutrient Status--It is expected that the Minnesota tailings would have deficiencies of macronutrients typical of most tailings. The lack of extreme acidity should lessen nutrient deficiency problems, however, making their correction much easier.

Particle Size Distribution--Preliminary analyses of particle size distributions indicate that the Cu-Ni tailings (INCO) are more homogeneous in texture than some of the tailings discussed in the literature. Particles in Cu-Ni tailings are all <420 microns and lack the coarse sand and fine gravel found in taconite tailings (see figure 1).

They also have a smaller percentage of clay and silt particles (<.05 microns) (<50% versus >60% for taconite). It also appears from Figure 1 that taconite tailings have a greater clay content.

The lack of the coarser sized particles typically found in taconite tailings may make the outer ring of the basin less droughty. Also, the small percentages of clay may reduce the areal extent of slimes thereby reducing the dewatering problem.

If a cyclone separator is used, the removal of particles >74 microns would leave only very fine sand, silt and clay to be disposed of in the basin. The resulting soil texture would be less subject to drought but the higher concentration of clays may increase dewatering problems.

#### WASTE ROCK AND LEAN ORE DUMPS

Background--Very few studies have examined the problems of reclaiming copper-nickel waste rock and lean ore dumps. Most of the data dealing specifically with copper wastes are from the Rocky Mountain area. Extensive research on non-ferrous metal wastes, including copper, has also been conducted in Great Britain. Reports on the revegetation of taconite and iron ore waste rock in Minnesota and Michigan are also of value, for the vegetation, climate, and geology of these areas are comparable to those of the study area. Because these sites are easily revegetated, however, little has been published. Information on the reclamation of other mining overburden materials including coal spoils was reviewed although no extensive search was attempted. Rock overburden dumps and lean ore stock piles are considered together in this paper because of the similarity in physical characteristics and the absence of information specific to lean ore stockpiles.

As with tailings, most reclamation studies on overburden wastes are of short duration. This makes long term predictions difficult. Also, the emphasis of most reclamation programs has been on manipulating disturbed areas to protect water quality. As a result revegetation efforts are often oriented towards minimizing water problems rather than maximizing land productivity.

Characteristics--Waste rock and lean ore vary in their physical and chemical characteristics depending upon mineralogy and mining processes. Generally they consist of fragmented bedrock ranging in size from boulders to fine sand

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particles with varying amounts of unconsolidated till. The material is dumped in piles up to 61m (200 ft) in height. Slopes are often very steep (up to 64%). Slope stability varies from site to site and depends upon the physical and chemical characteristics of the rock.

#### Factors Inhabiting Revegetation

Many of the factors inhabiting revegetation on waste rock and lean ore piles are similar to those of tailings and therefore are not discussed in detail. Also, because legislation (see NR 401-411) requiring contouring and covering of these wastes with soil or till is likely, the problems associated with the hostile environment or bare rock piles will be dealt with only briefly.

#### Heavy Metal Phytotoxicity

The problem of toxic concentrations of heavy metals occurring in mine wastes has been discussed by Johnston, et al. (1975) and Brown and Johnston (1976) for overburden wastes in the western United States, and by Goodman, et al. (1973) for slag in the United Kingdom. The severity of the problem is related to the acidity of the material, a factor that influences cation availability. The toxicity problem is generally confined to lean ore piles, although "hot spots" or pockets of high metal concentrations may be present in the overburden material.

#### Nutrient Deficiencies

Although nutrient deficiencies would not be as great a limiting factor in waste rocks compared to tailings, nutrient levels may be low enough to result in poor establishment and growth of plants. Availability of plant nutrients is also reduced by adverse environmental factors such as drought (Johnston, et al. 1975)

complete burial of plants established on these areas. Also, injury due to wind scouring by fine particles can occur on the tops of piles (Goodman, et al. 1973).

#### Water Deficiencies

Water stress is very likely during critical periods in the summer because such coarse material characteristically has low water holding capacity. Steep slopes would be very susceptible to water stress because runoff rates are high. Evaporation rates are high due to unobstructed air movement and high incidences of solar radiation on exposed surfaces (Johnston, et al. 1975).

#### Heat Stress

The extremely high heat conductivity of bedrock can result in high surface temperatures and sharp temperature fluctuations. These factors can be expected to both inhibit germination and, on established plants, cause damage to meristematic tissue (Deely and Borden 1973).

#### Compaction

Surface compaction of the finer particulate material due to grading by heavy equipment, may inhibit seed germination and growth and reduce water permeability. Liesman (1957) and Borovsky (personal commun. 1977) reports that compaction is a major factor in delaying natural invasion and establishment of pioneer plant species on iron ore overburden.

#### Approaches To Revegetation

A limited amount of research has been carried out on revegetation of waste rock and lean ore. Several researchers have presented suggestions for possible site improvement techniques. Although most are subject to economic constraints, long range planning of the disposal of mine wastes can greatly

reduce costs. Lean ore stockpiles will require special considerations because of their temporary nature. O'Neil (1977) suggests that it may be unwise to adopt costly and/or permanent redevelopment schemes on such stockpiles. Adjustments in revegetation techniques may have to be implemented so that future recovery of the ore is not is not greatly hindered. The serious contamination problems presented by lean ore stockpiles cannot be ignored, however.

### Contouring

Contouring of rock piles in order to reduce steepness of slope and blend landscape with surrounding topographic features has been suggested as the first step in reclaiming mine wastes (Rodiek, et al. 1976). This may greatly improve slope stability and promote more favorable water relationships by reducing surface runoff. Also, the accessibility to the area by equipment for revegetation purposes is greatly improved. Because grading can result in soil compaction, it should be followed by surface manipulation.

Recontouring, however, also has problems. Reducing the steepness of slopes increases the area covered by mine wastes and greatly increases reclamation costs. Also, Dickinson (1977) reports that erosion is greater on sloped waste piles when no provisions are made for surface drainage.

### Covering with Overburden

Davis (1977) suggests that planning the order in which the various wastes are deposited is the key to successful reclamation. Because soil, till, and non-toxic, unconsolidated material usually must be excavated to get at the ore body, the possibility of modifying the mining process to utilize these materials to cover mining wastes shows great promise. The advantages of soil or till rather than unmodified rock as a medium for plant establish-

rooting media, and amelioration of temperature extremes. Also, soil allows plants to become established in an environment free from the toxic effects of underlying wastes.

Based on a draft of proposed Minnesota regulations it is likely that a till covering will be required for at least waste rock piles. Vogel (personal commun. 1977) suggests that 61 to 122 cm of "soil" covering will probably be needed for piles that are composed primarily of boulders. Less would be required for less-coarse material. Farmer, et al. (1976) report that a top dressing of soil to a depth of 20 cm is highly beneficial on very acid and infertile copper-cobalt wastes in Idaho. On non-toxic overburden that is composed of at least 20% fines ( $\leq$  20 microns) Hutnick (personal commun. 1977) believes that a soil covering is not required for successful revegetation.

There may be a possibility of toxicity problems to deep rooting plants once they have penetrated through the top dressings into waste rock material. Vogel (personal commun. 1977) reports that pine trees have died after 10 years on soil-covered coal spoils. Although the exact cause of mortality remains unknown, it is suspected that death may be due to underlying toxic wastes. This contradicts Michelluti (1974) who speculates that once plants are established they are able to successfully survive more hostile conditions.

#### Addition of Fertilizers

Nutrient deficiencies determined by soil analyses have been corrected by the application of fertilizers (Farmer, et al. 1976; Brown and Johnston, 1976). Optimum results were obtained when fertilizer was used in conjunction with topsoiling. The application of sewage effluent is presently

### Incorporation of Organic Matter

The addition of organic matter would greatly increase water holding capacity, decrease surface evaporation, moderate temperature extremes, stabilize surface erosion, and make toxic metals less available to plant roots. Organic matter in the form of sewage sludge and domestic refuse has been effective in ameliorating heavy-metal contaminated mining wastes in Swansea, Wales (Goodman, et al. 1973). Mulches in the form of straw, hay, wood chips, and shredded bark have been used extensively on coal spoils in eastern United States (Grim and Hill 1974). Rodick, et al. (1976) report the satisfactory use of a combination of a petroleum-based compound and woodfiber on copper overburden dumps in Arizona. The use of an adhesive is particularly beneficial where mulches are frequently blown away by high winds.

The use of organic matter on lean ore piles may be restricted for it may disrupt the floatation process in future beneficiation.

### Surface Manipulation

Various manipulation practices may be carried out on surfaces of mining wastes to make them more favorable for plant establishment. These include reducing compaction by loosening surface materials and modifying the microrelief to form shallow depressions that collect moisture, fine-sized soil particles, and wind dispersed seeds. Various treatments tried on coal wastes include;

- 1.) furrow grading--parallel ridges .6 to .9 m in height produced by successive passes of a bulldozer with an angled blade.

- 2.) gouging--a surface pattern composed of many depressions

15-20 cm deep, accomplished by a specially constructed

machine.

- 3.) dozer basins--large depressions designed to accomplish goals similar to those of terracing without the attendant precision, hazard and expense.
- 4.) deep chiseling--a surface treatment that loosens compacted soil to a depth of 15 to 20 cm and creates a series of parallel surface furrows.
- 5.) off-set listering--a surface configuration of alternately arranged elongated pits approximately 15 cm deep and 1.2 m long (Grim and Hill 1974, Hodder 1977).

All five treatments are attempts to ameliorate surface conditions to encourage germination and rapid growth of seedlings, reduce erosion, and alleviate soil compaction.

#### Revegetation Results

Information on the revegetation of copper mining waste rock is minimal. Satisfactory results were obtained by both Farmer, et al. (1976) and Brown and Johnston (1976) in the west when mining wastes were topsoiled and fertilized. Farmer, et al. (1976, p. 15) conclude that "revegetation of raw mining wastes, even with inputs of lime, fertilizer, and mulch does not appear to be a desirable alternative" to topsoiling in the Rocky Mountain region. Also, Rodick, et al. (1976) report excellent grass and herbaceous cover along with erosion control on recontoured and mulched mining overburden in Arizona. These results, however, are for only one or two years, and it is not known if continued maintenance will be required in the future. Farmer, et al. (1976) suggest that the answer to this question lies partly in the complex chemistry of acid sulfide wastes.

obtaining a maintenance-free plant community is even more questionable. Studies by Goodman, et al. (1973) on zinc and copper slag piles in the United Kingdom found that although acceptable vegetation cover can be established on the most toxic wastes (e.g. these containing Zn) with the use of sewage sludge, annual fertilization will be required. In addition, they predict that regression will almost certainly occur if additional organic matter is not added.

A more optimistic outlook may be expected on overburden that lacks severe phototoxicity problems. Jones (1972) obtained good grass cover simply from the seed present in the soil used to cover iron ore overburden in Michigan. Where sufficient fines were not present, hydroseeding with fertilizer was carried out. Dickinson (1977) also reports satisfactory results on taconite overburden covered with till.

An extensive study by Leisman (1957) on the natural invasion of plants on mining wastes in the iron range of northeastern Minnesota indicates how rapidly vegetation can become established on non-phytotoxic waste rock and lean ore piles. On the latter, where the bulk of the material is 7.5 to 15.0 cm in diameter, complete vegetation cover was obtained within 31 years. Trembling aspen (Populus tremuloides) and balsam poplar (Populus balsamifera) were the dominant species and averaged 10.5 m in height. The numerous microhabitats provided by the coarse-textured surface and the lack of competition by ground-cover vegetation were believed to make lean ore substrate-suitable for germination of these two species. Growth rates were extremely low and the trees were usually deformed and susceptible to insect and fungal attacks. The herbaceous ground cover was very sparse and patchy.

This was thought to be due to the high Fe and S content of the lean ore. Leisman could not explain why herbaceous but not woody vegetation would be

effected by the concentrations present. This observation, however, corresponds to current research that has found that grass and herbs generally have a lower tolerance to toxic substances than woody plants (Hutnick, personal commun., 1977).

Leisman's studies of plant succession on iron ore overburden composed largely of glacial till show the advantages of using till as a planting medium. Overburden areas were completely covered with vegetation in only 13 years, with 60% of the area covered with woody species. Trembling aspen was the dominant species. Within 32 years an aspen canopy was observed, and after 51 years the thickness of the organic layer had increased to 1.25 cm and the A<sub>1</sub> horizon to a depth of 4.4-6.3 cm. No signs of regression in plant vigor were reported.

Leisman estimates that complete tree cover can be expected within 25 years if aspen is planted at 50 foot intervals. This would occur without any site amelioration, although the application of fertilizers would greatly increase the rate of growth.

A more recent study of natural succession on iron ore waste piles in northeastern Minnesota was carried out by Borovsky (personal commun. 1978). In agreement with Leisman (1957), Borovsky found that the rate of plant invasion and resulting species composition of these piles depends on the topography of the waste piles (height above surrounding landscape) as well as the type and proximity of the surrounding vegetation. Generally he found that within 25 years a dense cover of predominately "noxious weeds" typical of disturbed sites is established. Trembling aspen and/or balsam poplar clones were prevalent within 35 years and after 40 to 50 years immature aspen was nearly continuous. The shrub cover, however, was not well developed.

Borovsky suggests that succession to an aspen forest may be altered by frequent occurrences of fire. He found that fires started in the highly

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flammable herbaceous material are not uncommon on waste piles located near population

centers. Although an occasional fire may stimulate aspen sprouting, a high fire frequency will set back or totally eliminate aspen from these sites. This may result in the waste pile becoming sod bound, thus making invasion by trees and shrubs very difficult.

#### Assessment of Cu-Ni Waste Rocks and Lean Ore

Presently very little information that would be of value in assessing potential revegetation problems is available on the properties and characteristics of waste rock and lean ore. Also, because the chemical composition of lean ore is not now known, this material is included in the discussion with waste rock. Estimates of the amounts of lean ore and waste rock generated by five separate hypothetical mining operations is given in Table 1.

#### Particle Size Distribution

All that can be said at this time is that the rock material will be less than 4 feet in diameter.

#### Phytotoxicity Potential

No phytotoxicity is expected from the waste rock.

No data are available on lean ore.

#### Nutrient Analysis

No data are available.

#### Topography of Stock Piles

Based on the present mining models, as many as 13 stockpiles (see Figure 1) will be required. The piles would be approximately 61m (200 ft) high, with 2.5:1 slopes (21.3°). Each would cover about 150 acres. The piles will

be benched and the upper surfaces will have gradual slopes. Orientation of the waste rock piles with respect to sun angle may affect revegetation success. The steepest slopes, which are the most difficult to vegetate, should face north.

#### Assessment of Overburden in the Study Area

From the literature it is apparent that the application of overburden or till on waste rock is highly desirable. A preliminary draft of DNR reclamation regulations indicates that the use of overburden covering may be required. The following discussion assesses the availability and suitability of the overburden in the Study Area.

#### Availability

Information on depth of overburden along the gabbro contact in the Study Area is incomplete. A maximum depth of 61 m (200 ft) has been reported in bedrock depressions west of Birch Lake. A minimum depth of 1 m or less occurs extensively in an area adjacent to the BWCA where extensive bedrock outcrops occur. The average depth to bedrock is approximately 20 m (60 ft) in the Toimi drumlin field and gradually diminishes to near zero north of Birch Lake. Depths range considerably, however, depending on the presence of glacial moraines and bedrock depressions.

It is estimated that 270,000 yd<sup>3</sup> of overburden will be required to cover each waste pile to a depth of one foot. This is based on calculations of a truncated pyramid-shaped waste pile with a base of 2,640 feet. The amount of overburden available (Table 1), based on a 30 foot average depth, appears to be adequate for this task. Open pit mining in an area where overburden is lacking, however, may greatly hinder revegetation efforts. Additional effort and expense may have to be expended in these areas for satisfactory revegetation.

Characteristics

The two major types of till that occur in the Study Area were deposited by the Rainy Lobe and the St. Louis Sublobe of the late-Wisconsin glaciation. The Rainy deposits cover nearly all of the Study Area and are composed primarily of non-calcareous sand and gravel. These coarse materials contain much less silt and clay than the overburden found in iron ore waste rock areas studied by Leisman (1957). Therefore, the relatively rapid rates of invasion and establishment of aspen noted by Leisman may not apply to the Study Area.

The deposits left by the St. Louis Sublobe, an off-shot of the DesMoine Lobe, cover a very minor portion of the Study Area in the southwest corner. The overburden in this area consists of fine textured lake deposits that would be particularly advantageous for revegetation purposes.

The type of glacial deposit rather than its source may be more important from a revegetation standpoint. The use of alluvial deposits that have high silt and clay contents would provide a much more desirable planting medium than coarse outwash material. Also, peat soils would be highly advantageous for plant establishment.

SUMMARY

This report presents a discussion of problems associated with the revegetation of mining wastes (i.e. tailings, waste rock, overburden).

Particular emphasis has been placed upon examining problems associated with copper-nickel wastes, but examples from other activities (e.g. iron, taconite and fossil fuel mining) are also cited. Both physical and chemical factors are discussed. The latter are generally specific to individual metals that are mined and often pose the greatest problems in heavy metals mining. Few examples that have conditions similar to those to be encountered in northeastern Minnesota are available for study.

Problems associated with physical factors are more universal, and many of the problems encountered in taconite mining in Minnesota will also arise in copper-nickel mining.

A number of approaches to revegetation are evaluated. These include alteration of the physical environment (recontouring of waste piles, systematic sorting of tailings) as well as methods for ameliorating harsh chemical conditions. Although emphasis has been placed upon examining conditions necessary for higher plant growth, we have attempted to treat the site as an integrated unit. Thus, the establishment of a self-sustaining plant community depends upon the development of a soil microflora capable of decomposing organic matter and recycling essential elements.

Finally, mining waste and overburden characteristics that are unique to the Study Area are examined. The suitability for plant growth of test tailings is discussed, and the availability of overburden for top

dressings is evaluated. The report, as a whole, is meant to be a reference paper, which, when combined with mining models, will serve as a basis for evaluating potential problems and opportunities of mining waste revegetation in northeastern Minnesota.

Table 1. SUMMARY OF CU-NI WASTES

Mine type	Under ground	Open pit	Under ground	Underground Open pit	Open pit
Mine size ( $10^6$ MT/yr)	5.35	11.33	12.35	16.68	20.00
Mine Life (yrs)	30	30	30	30	30
Waste Type	AMOUNT OF WASTE				
Overburden ( $10^6$ yd <sup>3</sup> )	--	19	--	19	25
Waste rock ( $10^6$ MT)	12	368	28	380	650
Tailings ( $10^6$ MT)	117	274	269	391	484
Lean ore	?	?	?	?	?
TOTAL WASTE					
( $10^6$ yd <sup>3</sup> )	0	19	0	19	25
( $10^6$ MT)	129	642	297	771	1,134
	AREA TO BE REVEGETATED (ACRES)				
Overburden	0	137	0	137	173
Waste rock and lean ore stock pile	51	1,119	96	1,155	1,988
Tailing pond	900	1,980	1,947	2,765	3,387
TOTAL AREA COVERED	951	4,766	2,043	4,057	5,548
No of waste rock piles (200' high) 50 x $10^6$ MT/pile	1	8	1	8	13

Table 2  
Results of Copper and Nickel Toxicity Studies

Source	Metal	Conc. (ppm)	Method of Conc. determination	Media	Effects
Whitby and Hutchinson (1974)	Ni	2	known quantity of metal	soil-H <sub>2</sub> O extract on filter paper	-reduced root elongation by nearly 70%
	Ni	10			-almost complete inhibition
	Cu	2			-reduced root elongation by 30%
	Cu	15	salts added		-nearly 100% reduction in root elongation
Goodman, et al. (1973)	Cu	>.5	H <sub>2</sub> O soluble	water culture	toxic (undefined)
	Ni	2	H <sub>2</sub> O soluble		toxic (undefined)
Dean, et al. (1974)	Cu	1000	known quantity of metal	tailings	-little effect
	Ni	>100			-toxic (undefined)
	Cu-Ni-Zn	10	salts added		-toxic effect "evident"
	Cu-Ni-Zn	100			-toxic effect "pronounced"
Olsen (1978)	Cu	75-200	known quantity of metal salts added		- $\geq$ 75% reduction in mean radicle length
	Ni	50-100			

Table 3.

List of some of the species planted on tailings in Minnesota, Michigan, and Sudbury, Canada

		Source				
		1	2	3	4	5
<u>Grasses</u>						
<u>Agropyron</u> sp.	wheatgrass					X
<u>Agropyron cristatum</u>	crested wheatgrass			X		X
<u>Agropyron elongatum</u>	tall wheatgrass					X
<u>Agropyron intermedium</u>	intermediate wheatgrass	X				X
<u>Agropyron smithii</u>	western wheatgrass	X				X
<u>Agrostis alba</u>	red top	X				X
<u>Agrostis tenuis</u>	colonial bentgrass		X	X		
<u>Andropogon gerardii</u>	big bluestem	X				
<u>Avena</u> sp.	oats			X		X
<u>Bromus</u> sp.	brome grass		X	X		
<u>Bulbittis dactyloides</u>	buffalo grass					X
<u>Dactylis glomerata</u>	orchardgrass				X	X
<u>Echinochloa crus-galli</u>	Japanese millet					X
<u>Festuca</u> sp.	fescue	X				
<u>Festuca arundinacea</u>	alta tall fescue					X
<u>Festuca elatior</u>	tall fescue					
<u>Festuca rubra</u>	red fescue		X	X		X
<u>Festuca ovina</u>	sheep fescue		X			
<u>Hordeum</u> sp.	barley					X
<u>Lolium</u> sp.	cougar ryegrass					X
<u>Lolium multiflorum</u>	rye grass				X	X
<u>Panicum virgatum</u>	switch grass					X
<u>Pharus arundinacea</u>	read canary grass	X				X
<u>Phleum pratense</u>	timothy			X	X	X
<u>Poa compressa</u>	Canada bluegrass			X		
<u>Poa pratensis</u>	Kentucky bluegrass			X		X
<u>Secale cereale</u>	annual rye			X		
<u>Setaria italica</u>	millet	X				
<u>Stipa viridula</u>	green needle grass					X
<u>Legumes</u>						
<u>Forbs</u>						
<u>Astragalus</u> sp.	milk vetch	X				
<u>Coronilla varia</u>	crown vetch	X				X
<u>Lathyrus japonicus</u>	beach pea					X
<u>Lotus corniculatus</u>	birdsfoot trefoil	X				X
<u>Medicago sativa</u>	alfalfa	X	X	X	X	X
<u>Melilotus</u> sp.	sweet clover	X	X	X		
<u>Trifolium hybridum</u>	alsike clover	X				X
<u>Trifolium pratense</u>	red clover	X				
<u>Trifolium repens</u>	white clover		X		X	
<u>Vicia americana</u>	purple vetch					X
<u>Shrub and Trees</u>						
<u>Caragana arborescens</u>	Siberian pea	X				X
<u>Robinia pseudoacacia</u>	black locust	X			X	X
<u>Other</u>						
<u>Linaria dalmatica</u>	dalmatian toadflax					X

Table 3 cont.

		Sources				
		1	2	3	4	5
Verbascum thapsus	mullein					X
<u>Shrubs</u>						
<u>Alnus glutinosa</u>	European black alder	X				
<u>Alnus rugosa</u>	tag alder					X
<u>Amelanchier</u> sp.	service berry	X				
<u>Comptonia peregrina</u>	sweet fern					X
<u>Prunus pensylvanica</u>	pin cherry					X
<u>Prunus virginiana</u>	choke-cherry					X
<u>Rosa</u> sp.	rose					X
<u>Salix</u> sp.	willow	X				
<u>Shepherdia</u> sp.	silverberry	X				
<u>Vaccinium</u> sp.	blueberry					X
<u>Trees</u>						
<u>Betula papyrifera</u>	paper birch					X
<u>Elaeagnus angustifolia</u>	autumn olive	X				
<u>Elaeagnus umbellata</u>	Russian olive					X
<u>Larix decidua</u>	European larch					X
<u>Pinus banksiana</u>	jack pine	X			X	
<u>Pinus resinosa</u>	red pine	X			X	
<u>Populus</u> sp.	hybird poplars	X				X
<u>Populus alba</u>	white poplar					X
<u>Populus balsamifera</u>	balsam poplar					X
<u>Populus grandidentata</u>	large-toothed aspen					X
<u>Populus tremuloides</u>	trembling aspen					X
<u>Sorbus</u> sp.	mountain ash					X
<u>Thuja occidentalis</u>	eastern white cedar	X				X

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

Table 4.

Total Cu & Ni Concentration (ppm) in tailings and soils.

One-stage Grind Tailings		
	<u>Cu</u>	<u>Ni</u>
Amax 9002	362	334
" 9003	360	270
Dunka Pit 9002	419	182
Inco Pit 9002	297	302

Two-stage Grind Tailings		
	<u>Cu</u>	<u>Ni</u>
Amax 9002	161	287
" 9003	195	285
" 9004	217	214
Dunka Pit 9002	135	219
Inco Pit 9002	122	273
US Steel Pit 9002	124	266

Field Values			<u>Cu</u>	<u>Ni</u>
Normal*) soil }	range		2-100	10-1,000
	mean		20	40
Amax Mineral Soil organic }	range		29-1,200	2-660
	range		1-1,300	20-3,800

\*Bowen (1966)

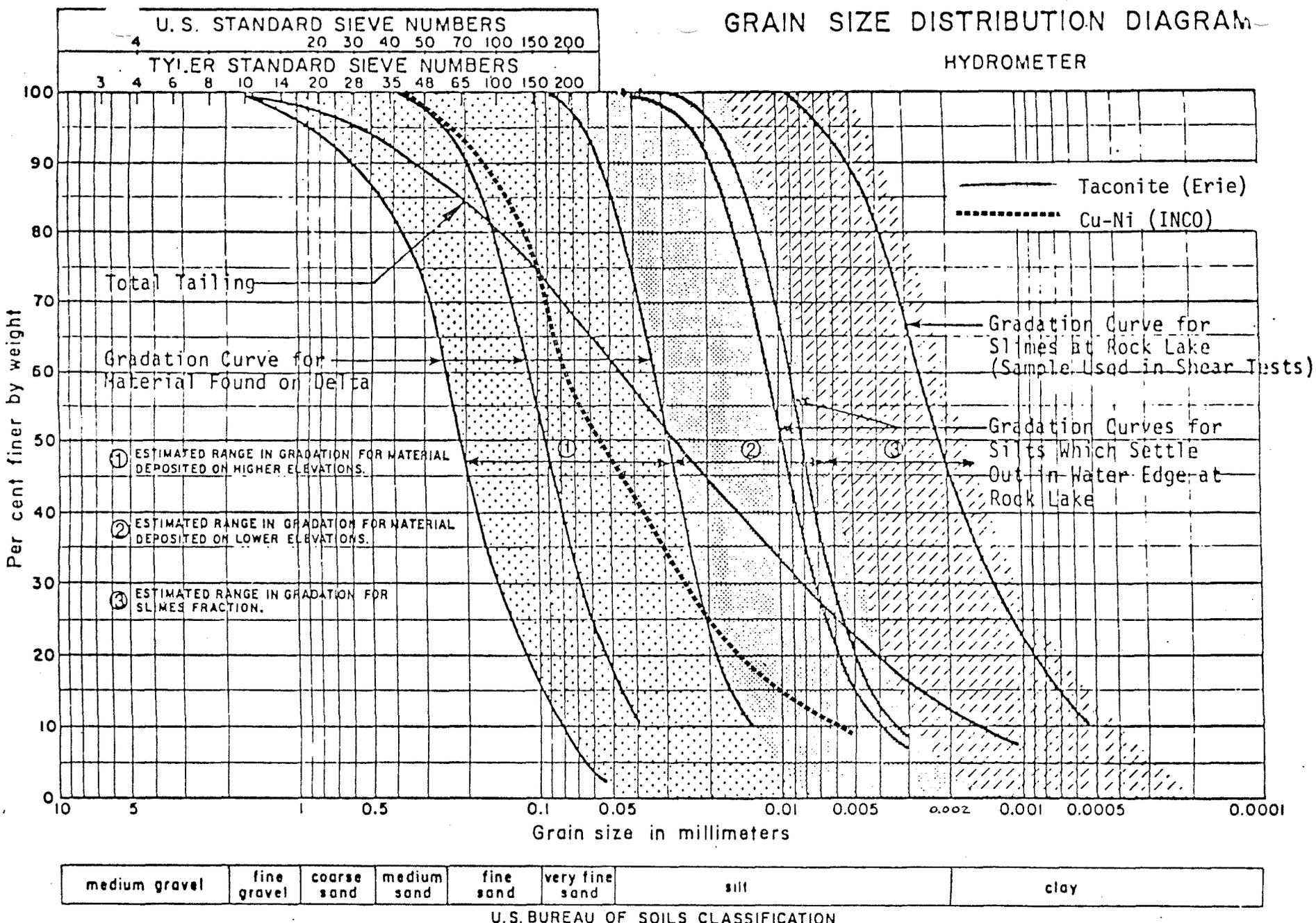
Table 5.

Estimated Available (water soluble) Cu and Ni in tailings.

## Tailings

One-stage	Cu	Ni
Amax 9002	0.02	0.15
9003	0.02	ND
Dunka 9002	0.02	ND
Inco 9002	0.01	ND

Two-stage	Cu	Ni
Amax 9002	0.02	ND
9003	0.04	ND
Dunka 9002	0.01	ND
Inco 9002	ND	ND
US Steel	0.01	ND



**FIGURE 1**  
GRADATION CURVE COMPARING TACONITE AND Cu-Ni TAILINGS

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APPENDIX  
RECLAMATION COSTS \*

		cost/acre (labor & materials)		time to success**
		slopes	interior	
<u>dust control:</u>				
no action	wasterock	0	0	>50 years
	overburden	0	0	>20 "
	tailings	0	0	>20
	plant site	0	0	>10
chemical	wasterock	150	130	0
stabilizer	overburden	150	130	0
	tailings	150	130	0
	plant site	na	130	0
fertilizer	wasterock	160	75	>5
	overburden	70	60	3
	tailings	160	75	3
	plant site	na	60	3
seeding	wasterock	160	55	>5
	overburden	70	60	1
	tailings	160	55	2
	plant site	70	60	1
mulching	wasterock	300	300	4
	overburden	na	na	na
	tailings	300	na	2
	plant site	na	na	na

wildlife habitat/ forest cover:

In addition to costs indicated above through the mulching step. This operation is done the second year, before a sod forms.

tree/shrub				
planting	all sites	150	170	wildlife 5 forest cover 30

\* Cost estimates are based on information from Sam Dickenson at Erie Mining Company; they should be within 10-20 percent of costs for a copper-nickel operation.

\* Time to success relates to the accomplishment of the defined purpose. Estimates for the "action" options for dust control should be within 1-3 years of actual time; for the wildlife habitat/forest cover and no action options the estimates are probably within 10-20%.