

***Using Municipal Biosolids to Reclaim Iron and Steel
Slag Disposal Sites in the
Illinois-Indiana Urban Initiative Area: A Literature Review***

by

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Chemical Symbols and Acronyms Used in This Literature Review

Chemical Symbols

Ag – silver	Fe – iron	Pb – lead
Al – aluminum	Hg – mercury	S – sulfur
As – arsenic	K – potassium	Sb – antimony
B – boron	Li – lithium	Se – selenium
Ba – barium	Mg – magnesium	Si – silicon
Be – beryllium	Mn – manganese	Sn – tin
C – carbon	Mo – molybdenum	Ti – titanium
Ca – calcium	N – nitrogen	Tl – thallium
Cd – cadmium	Na – sodium	V – vanadium
Co – cobalt	Ni – nickel	W – tungsten
Cr – chromium	P – phosphorus	Zn – zinc
Cu – copper		

Acronyms

AB-DTPA and DTPA – chelating reagents used as soil extractants

AMSA – Association of Metropolitan Sewerage Agencies

ASTM – American Society for Testing and Materials

BF – blast furnace

BOF – basic oxygen furnace

BOP – basic oxygen process

BOS – basic oxygen steelmaking

CCE – calcium carbonate equivalent

CCL – ceiling concentration limit

CEC – cation exchange capacity

Acronyms (cont'd)

CFR – Code of Federal Regulations

dS/m – decisiemens/meter

EAF – electric arc furnace

EC – electrical conductivity

EP – extraction procedure

EQ – exceptional quality

ESP – exchangeable sodium percentage

FGD – flue gas desulfurization

HERA – human health and ecological risk assessment

HEW – U.S. Department of Health, Education and Welfare

HI – hazard index

IIUIA – Illinois-Indiana Urban Initiative Area

kg/ha – kilograms/hectare

LNAPL – light non-aqueous phase liquids

MCL – maximum contaminant levels

meq/100 g – milliequivalents/100 grams

meq/L – milliequivalents/liter

MLE – most likely exposure

mmho/cm – millimhos/centimeter

mt/ha – metric tons/hectare

MSD – Metropolitan Sanitary District

MWRDGC – Metropolitan Water Reclamation District of Greater Chicago

NSSS – National Sewage Sludge Survey

Acronyms (cont'd)

PCB – polychlorinated biphenyls

PCL – pollutant concentration limit

POTW – publicly-owned treatment works

ppb – parts per billion

ppm – parts per million

RME – reasonable maximum exposure

SAR – sodium adsorption ratio

SMCL – secondary maximum contaminant levels

TCLP – toxicity characteristic leaching procedure

TDS – total dissolved solids

USEPA – U.S. Environmental Protection Agency

WRP – water reclamation plant

WWTP – wastewater treatment plant

I. Using Municipal Biosolids to Reclaim Iron and Steel Slag Disposal Sites in the Illinois-Indiana Urban Initiative Area: A Literature Review

Introduction

The purpose of this literature review is to investigate the technical and environmental feasibility of using municipal biosolids (i.e., sewage sludge) and other organic materials to reclaim former slag disposal sites in the Illinois-Indiana Urban Initiative Area (IIUIA). The literature review covers four major parts: (1) a brief summary of the background of iron and steel manufacturing in the IIUIA, types of slag deposits, and the quality of surface and groundwater in the area; (2) an overview of iron and steel slag chemistry and uses; (3) site assessment and considerations for slag fill site reclamation; and (4) technical and environmental aspects for reclamation of slag fill sites in the IIUIA using municipal biosolids.

The purpose of section one is to briefly familiarize the reader with the IIUIA and some historical background of the industrial development which occurred. While the goal of this literature review is to evaluate the potential of using municipal biosolids for reclamation of iron and steel slag disposal sites, a number of waste disposal activities in the IIUIA during the past have contributed to environmental pollution problems facing today's society. These problems have been documented by several recent investigations that are briefly summarized in this section.

Section two provides some general background and understanding of iron making, smelting and steelmaking processes that produce iron and steel slags as by-products. The chemical characteristics of these slags and their potential uses are described, as well as some human health and ecological risk assessment results pertaining to the current uses of these by-products as valuable resources. Other waste residuals that come from the iron and steelmaking industry and may also be at slag disposal sites are discussed. This information should be helpful for determining what reclamation or remediation options would be best to use for sites containing slag deposits.

Section three explains site assessment techniques that can be applied to reclaim or remediate different types of disturbed lands. Challenges that have been encountered when establishing vegetation on slag sites and reclamation techniques that have been used at these and other sites are discussed, including vegetation selection and management.

The final section discusses how municipal biosolids have been used for reclamation of many types of disturbed lands. While very few articles and studies could be found in the literature on specifically using biosolids on slag disposal sites, experiences and knowledge gained from a wide variety of reclamation projects suggests that biosolids, or biosolids combined with other available by-products, can be successfully utilized to reclaim iron and steel slag disposal sites in the IIUIA.

The IIUIA

The IIUIA comprises the Calumet Region which occupies portions of Northeast Illinois (or Southeast Chicago) and Northwest Indiana and covers the area shown in Figure 1. The Calumet area surrounds Lake Calumet and includes the Calumet River, and portions of the Grand Calumet and the Little Calumet Rivers. Prior to urbanization, large portions of this area consisted of shallow bodies of surface water, wetlands, and sand dunes as shown in Figure 2. As early as the 1860's, developers foresaw the transformation of Chicago's southeast side into a mighty industrial center. In 1869, the Corps of Engineers initiated modifications at the mouth of the Calumet River to make it a more secure anchorage. This was the first in a long series of harbor improvements that allowed industries to line the river banks. The Calumet region grew into one of the premier industrial districts in the country. During the twentieth century, iron and steel manufacturing operations expanded into Northwest Indiana. Since the early twentieth century, the IIUIA has been home to one of the largest areas for iron and steel production in the world. (Colten, 1985)

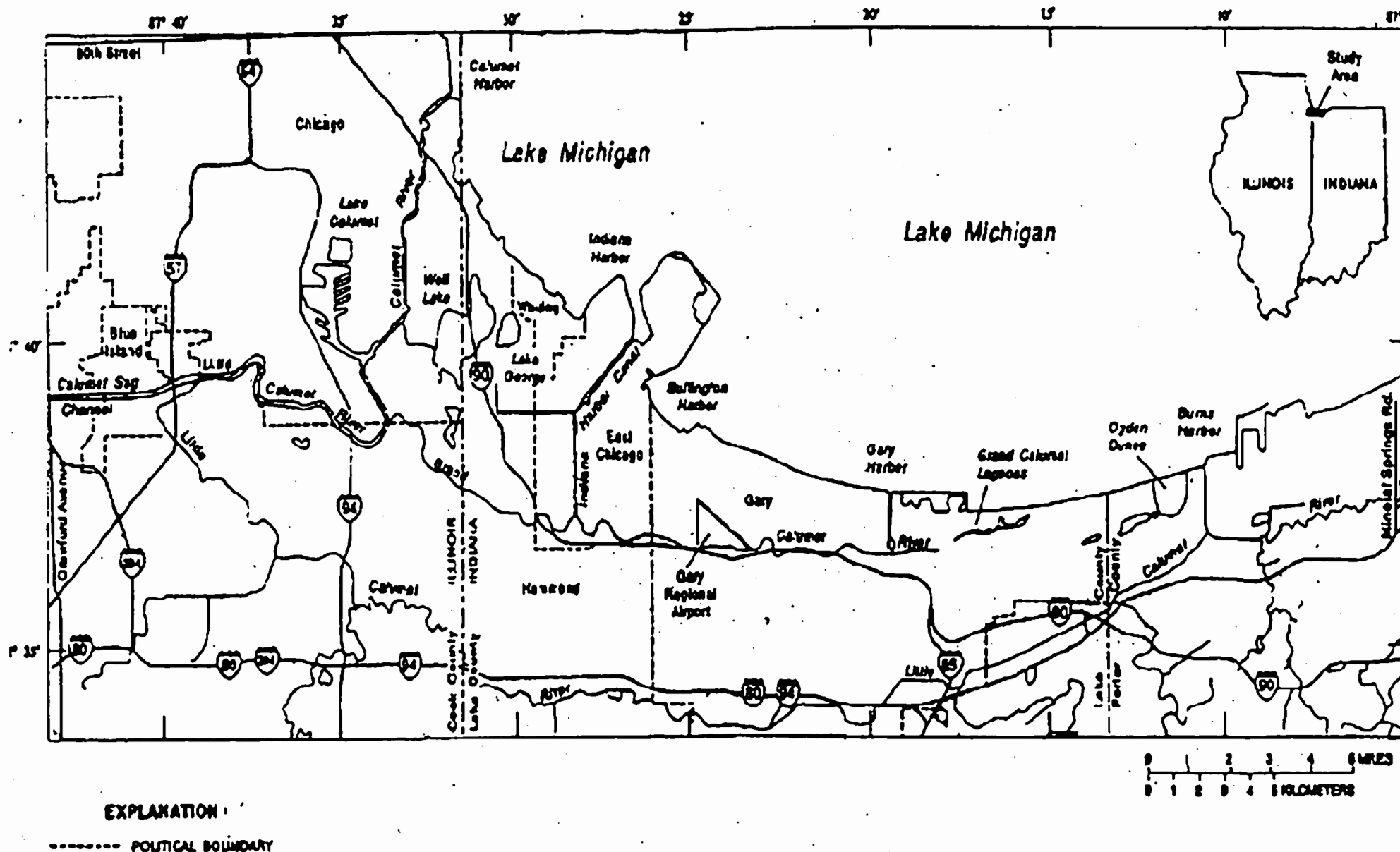
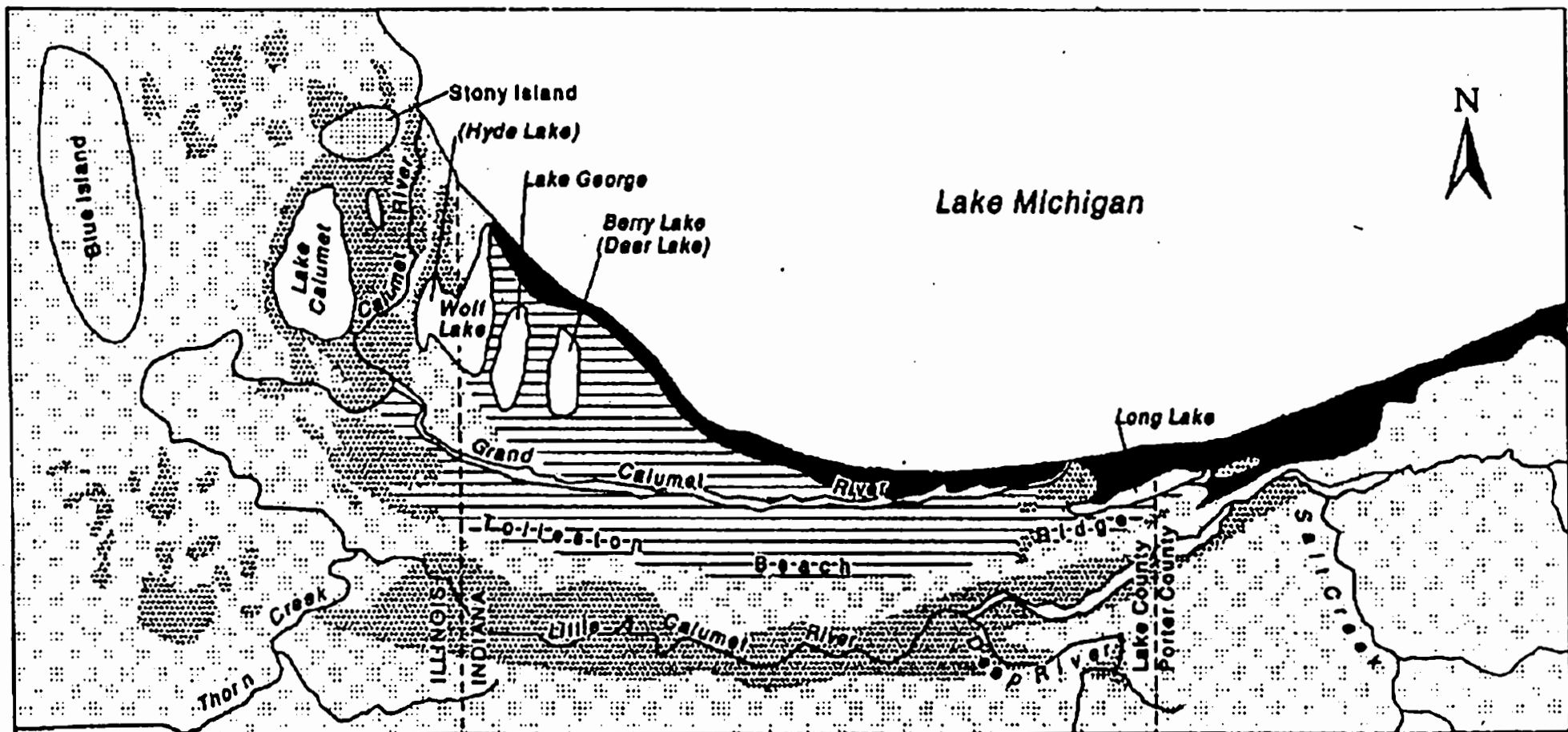


Figure 1. Illinois-Indiana Urban Initiative Area (IIUIA) which comprises the Calumet Region of Northeastern Illinois and Northwestern Indiana (Fig. 1, Kay et al, 1997).



Modified from Michigan Academy of Science, Arts and Letters, Vol. 36 (1950).

0 5 MILES
0 5 KILOMETERS

EXPLANATION

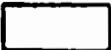
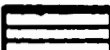
	WATER		BEACH RIDGES WITH INTERSPERSED WETLAND
	WETLAND		DRY LAND--Dunes, beach ridges, moraine islands, bedrock ridge
	DUNE WITH INTERSPERSED WETLAND	(Hyde Lake) (Deer Lake)	NAME AND LOCATION OF LAKE THAT APPEARS AFTER 1840

Figure 2. Physiographic features, surface-water bodies, and selected political boundaries prior to 1840 in the Calumet Region of Northeastern Illinois and Northwestern Indiana (Fig. 8, Kay et al, 1997).

Historical Analysis of Industries and Waste Disposal Practices in the IUIA

The historical analysis of the industrial development in the Calumet area by Colten (1985) and his chronology of waste disposal practices over a 100 year plus time period from 1869 to the early 1970s helps provide an appropriate background for this literature review. Colten's chronology helps to identify the types of wastes that were commonly produced in the IUIA prior to 1970 and prior to effective environmental protection laws which now require industries to properly treat and dispose of their waste residuals. This chronology has also aided more recent studies to characterize the current environmental conditions and potential for reclamation or remediation of iron and steel slag disposal sites. While other historic accounts have also been written about the Calumet area, as noted in "The Remedial Action Plan for the Indiana Harbor Canal, the Grand Calumet River and the Nearshore Lake Michigan—Stage One, January, 1991," the study by Colten (1985) seemed to provide an appropriate and useful accounting of the historical geography of the Lake Calumet industrial complex, as a starting point for our literature review. Colten discussed three separate time periods (1869-1921, 1922-1940 and 1940-1970) for his historical analysis of the Calumet area, which we have attempted to highlight for the reader.

The Period of 1869 - 1921

The leading industrial activity in the Calumet region was the manufacture of iron and steel and processing the finished metal into rails, wire, and other products. Before 1900, most steel in the Calumet area was produced using Bessemer furnaces, but by 1919 the Open Hearth technique surpassed the Bessemer. This newer technology consumed more scrap metal, although the type of waste remained similar. (Colten, 1985)

The steel mills produced large quantities of phenols and cyanides and expelled them into the water courses adjacent to their operations. Pickle liquors (sulfuric acid solution used to remove rust from steel form) were also produced in large volumes by plants processing finished steel. Various chemical, paint and oil manufacturers also contributed to the waste production.

And another waste product produced by most operations in the area was fly ash, since coal was the primary fuel for manufacturing power. (Colten, 1985)

Two methods for disposing of industrial wastes prevailed throughout the period before 1921. Liquid wastes were directed into nearby water bodies, usually untreated, although in some situations they were diluted with noncontact wastewater. Solid refuse was removed to vacant land near the factory and dumped. Concern about the hazardous quality of industrial by-products was limited, as health authorities directed most of their attention to the problems of biological wastes, both domestic and industrial. Land disposal of solids was a viable method for industries to enlarge or improve their property in the marshy environs of the Calumet region. The most dramatic effect on the local environment was the encroachment on the wetlands. (Colten, 1985)

The Period of 1922 - 1940

Two major waste management changes occurred in the Calumet region during the early 1920s. First, the construction of the Calumet Sewage Treatment Plant resulted in some of the liquid industrial effluents receiving treatment rather than being directly discharged. However, in 1925 only 14 out of the 123 factories in the area were connected to the sewage treatment plant, so most liquid wastes were still dumped untreated into the nearest stream. Second, the Cal-Sag channel was opened to divert industrial and municipal sewage away from Lake Michigan, a source of potable water supplies. (Colten, 1985)

The Illinois Legislature passed legislation in 1927 giving the Metropolitan Sanitary District (MSD) authority "to control and regulate the discharge of industrial wastes", which led to some modifications in disposal methods. For example, construction of holding tanks or storage ponds at Interlake Iron, Wisconsin Steel, and Republic Steel to reduce effluent discharges to the Calumet River were reported in 1930. While some industrial plants in Illinois began cooperating to voluntarily eliminate their wastes, the same was not happening in Indiana. Although Indiana statutes restricted industrial discharges into rivers and streams, they exempted the Gary, Whiting, and Hammond areas. (Colten, 1985)

During the twenties and thirties, industries began looking at ways to reduce waste volumes. Increased use of Open Hearth furnaces helped to increase the consumption of scrap metal in larger proportions than with the Bessemer furnaces. Other projects to reduce waste volumes included construction of benzol recycling facilities at coke plants and finding ways to make use of by-products, such as using slag in building materials and as an ingredient in fertilizers. The Open Hearth furnaces of the Calumet region produced a basic slag also suitable for use in Portland cement. Although steel mills sold some slag for these various uses, the rest was trucked to marshes and dumped. (Colten, 1985)

Throughout the 1920s and 1930s, the Army Corps of Engineers continued to periodically dredge the navigable channel of the Calumet and transfer the spoil to Lake Michigan. In an effort to protect potable water supplies taken from Lake Michigan, the U.S. Government delineated an authorized dumping ground 12 miles offshore and 9 miles from the nearest water intake. Dredge spoil was also pumped behind a slag dike to create land for dock facilities at the south end of Lake Calumet. Thus, the Corps contributed to the disposal of these solid wastes into Lake Michigan and to the use of dredge spoils for continued land building. (Colten, 1985)

During the early thirties, the American economic depression helped to significantly decrease the amount of wastes being produced. Encouraged by federal incentives and local ordinances, industries in the Calumet area also installed treatment facilities for their wastes. While area residents faced exposure to hazardous substances daily from nearby factories, polluted waterways and waste disposal areas, the greatest human exposure during this period of time occurred at the workplace. (Colten, 1985)

The Period of 1940 - 1970

The period from 1940 to 1970 witnessed a change from water disposal to land disposal of industrial wastes. Federal authorities entered the field of industrial pollution control in 1948 with the passage of the Water Pollution Control Act. Both Illinois and the MSD enacted statutes

in the 1940s and 1950s to regulate industrial wastes, prohibiting waste disposal in state and MSD waters. (Colten, 1985)

However, stream pollution persisted and worsened during the 1960s, once again threatening the water quality in Lake Michigan. Eventually, the US Department of Health, Education and Welfare (HEW) decided to evaluate water quality in the Calumet area. While many industries provided some treatment before releasing their effluents, the HEW study concluded that the streams of the Calumet region were severely polluted with both industrial and domestic sewage.

Both the Army Corps of Engineers and the MSD pressed industries to clean up their waste discharges without much success. Ordinances passed in 1951 and 1962 to require wastes to be treated before discharge, and give the MSD authority to require discharge permits for industries, were only partially effective. Finally, in 1970, the MSD was able to make satisfactory progress in reducing waste discharges and cleaning up the Calumet River system. The Sewage and Waste Control Ordinance of 1969 stated, "There shall be no discharge of any sewage, industrial waste, or other wastes of any kind into the waters of Lake Michigan." Under the authority of this law, the Sanitary District filed suits against several industries in 1970 to bring about needed pollution control improvements. (Colten, 1985)

Sanitary landfills became the favored method for disposal of solid wastes after 1945, since wastes that were covered daily posed fewer health hazards than open dumping or disposal into surface waters. Although land disposal had been regulated since the 1940s, it received little legislative attention until much later. State laws in 1966 forbid open dumping and burning and encouraged the use of sanitary landfills. In 1967, Federal regulations forced the Corps of Engineers to halt lake disposal of dredge materials contaminated with industrial wastes. Subsequently, the Corps designated 11 sites in the Calumet area to receive dredge spoils which also became repositories for the increasing quantities of industrial wastes. These sites were located predominantly in marshes and swampy areas, bringing huge areas of wetlands into use as

disposal sites. Therefore, while the shift in waste disposal from surface waters to landfills had positive effects on water pollution, it resulted in negative impacts on wetlands and a noticeable reduction in the biological diversity of the Calumet area. (Colten, 1985)

Summary

In his summary, Colten (1985) pointed out that "When considering the record of hazardous waste production and irresponsible disposal in the area, it must be remembered that, although shocking by today's standards, few of the hazards were understood fully at the turn of the century." Nevertheless, these past disposal practices suggest there is a good probability that wastes previously disposed in the IIUIA may be disturbed when abandoned industrial sites, closed plants or other disposal areas are considered for remediation or Brownfield reclamation to develop new land uses.

Therefore, identifying past land uses as much as possible and attempting to characterize current land conditions and water quality will be important for properly addressing any potential hazards that may still exist for proposed new land uses in the IIUIA. The next section summarizes some of the studies that have been conducted in the Calumet area during the past 10-15 years to characterize these environmental conditions.

Recent Investigations of Geohydrology, Water Quality and Fill Deposits

Several recent reports have been published to investigate current geohydrology, water quality and fill deposit conditions in the Calumet region of Northeastern Illinois and Northwestern Indiana. What has been documented by these reports will help provide guidance as to how remediation techniques should be conducted, when sites within the IIUIA are considered for new land uses that can improve the quality of life for individuals living nearby or within remediated sites, e.g., using remediated sites for recreational use. Insights provided by these reports are briefly described in their chronological order.

Geohydrology and Water Quality of the Calumet Aquifer (Fenelon and Watson, 1993)

The purpose of the investigation by Fenelon and Watson (1993) was to evaluate the potential for discharge of groundwater contaminants into the Grand Calumet River, Indiana Harbor Ship Canal or Lake Michigan surface waters, located in Northwestern Indiana. This major urban-industrial area contains three large steel mills, a major petrochemical processing plant, several large petroleum-storage facilities, forging and foundry facilities, food and paper industries, and a coal-fired electricity plant. The six major types of land use in this area are residential land (40%); commercial areas or light industry (25%); steel industry (15%); petrochemical industry (10%); and parks and agricultural areas (10%). The residential land is occupied primarily by the cities of Gary, Hammond, East Chicago, and Whiting, and the main drinking water supply for these cities is Lake Michigan. (Fenelon and Watson, 1993)

A variety of chemicals that are, or have been, widely used in the residential land areas and could potentially contaminate groundwater include gasoline, oil, lead paint, pesticides, and road-deicing salts. The potential contaminants from the commercial and light industries include industrial chemicals, solvents, heavy metals, aviation fuel, and sewage. A wide variety of chemicals, mostly organic in nature, are used and produced in the refinery area which include benzene, toluene, and xylenes, lead products, phenols, aluminum chloride, and acid and caustic substances. Most of the petrochemical industry areas are near the Indiana Harbor Ship Canal. Park land was not expected to be a source of groundwater contaminants unless located on former burial sites of waste by-products, and agricultural land could potentially be a source of nutrients and pesticides. (Fenelon and Watson, 1993)

The steel industry land-use area includes almost 75 percent of the 25 miles of Lake Michigan shoreline property. Much of this land located within one-half mile of the shore is lake-fill, composed of slag and industrial refuse. This land is intensively developed, generally lacking in vegetation, and covered with buildings, railroads, pavement, and piles of slag, coke, or ores that are associated with the steel industry. Many of the chemicals produced in a steel mill come from the production of coke, the fuel source of blast furnaces. By-products of coke-making

include ammonia, sulfate, naphthalene, light oil (i.e., benzene, toluene, and xylenes), phenols, cyanide, and heavy solvents. Materials used for the production of steel and by-products of the process include alloy metals, slag, lime, chloride and oil. (Fenelon and Watson, 1993)

Water quality data were obtained for samples collected from 35 wells located in five of the different land use types (no. of wells in each type given in parentheses) -- residential (4), commercial/light industry (15), steel industry (7), petrochemical industry (6) and parks (3). The highest median concentrations of inorganic ions and the most detections of organic compounds generally occurred in water samples from wells on the steel and petrochemical land-use areas. Water from wells in the commercial and light industrial land-use areas generally had median chemical concentrations that were lower than from wells in the steel and petrochemical areas and greater than those in well water from residential and park land-use areas. (Fenelon and Watson, 1993)

Fenelon and Watson (1993) concluded that: (1) of the four major groundwater sinks in the Calumet aquifer (which include the east branch of the Grand Calumet River plus the Indiana Harbor Ship Canal, the carbonate bedrock beneath the Calumet aquifer, Lake Michigan, and municipal sewers), the east branch of the Grand Calumet River plus the Indiana Harbor Ship Canal generally receive the greatest chemical loads from groundwater, whereas Lake Michigan generally receives the smallest loads and (2) groundwater probably contributes more than 10 percent of the total chemical load of ammonia, Cr, and cyanide to the Grand Calumet River, while only contributing 1 to 3 percent of the total streamflow.

Shallow Ground-Water Quality and Hydrogeology of the Lake Calumet Area (Roadcap and Kelly, 1994)

The purpose of Roadcap and Kelly's (1994) study was to determine the presence and extent of hazardous organic compounds in the groundwater, look at groundwater-surface water interactions, and examine wetland and surface water quality. In this study groundwater samples were obtained from 21 monitoring wells encircling Lake Calumet on four separate occasions

between April 1991 and June 1992. The water chemistry revealed an area of extreme chemical heterogeneity, and almost all the water samples exhibited contamination, from slight to severe. Types of inorganic contamination included total dissolved solids (TDS) greater than 500 mg L⁻¹, extremely alkaline pH, total organic C concentrations greater than 100 mg L⁻¹, and high concentrations of Fe, ammonium, fluoride, and several toxic heavy metals, including Ba, Cr and Mn. Several other minor elements not considered to be toxic were also detected at elevated levels, including Al, Li, Ti and B. (Roadcap and Kelly, 1994)

A number of volatile and semivolatile organic compounds were also found in several wells. Organics found in the greatest concentrations (i.e., greater than 1,000 ppb or 1 ppm) included dichloroethylene, vinyl chloride, benzene, toluene, naphthalene and phenols. Roadcap and Kelly (1994) suggested that sources of these inorganic and organic chemical contaminants likely included landfill leachates, road salt runoff, petroleum spills, fly ash deposits, and burial of steel mill slag and concrete and probably other sources. They also concluded that the intense human activity in the area of Lake Calumet had severely degraded the water quality.

Geohydrology and Occurrence of Nonaqueous Liquids on Groundwater in NW Indiana and the Lake Calumet Area (Kay et al, 1996)

The purpose of this investigation was to characterize the geohydrology and to determine the location and extent of light-nonaqueous-phase liquids (LNAPL's) on the water table in the urban and industrialized Lake Calumet area. The four hydrologic units of concern are surface-water bodies, the Calumet unconsolidated sand aquifer, the Silurian-Devonian carbonate aquifer, and the unconsolidated silt and clay till confining unit which separates the two aquifers. These are the units most affected by industrial and waste-disposal activities. The most important surface-water bodies are Lake Michigan, Lake Calumet, Wolf Lake, Lake George, the Calumet River, the Grand Calumet River, the Little Calumet River, and the Calumet Sag Channel. (Kay et al, 1996)

Hydrogeologic studies indicated that the water-table configuration generally is a subdued

reflection of the surface topography. The general water-table configuration is affected in some areas by recharge from landfill leachates and ponded water or by discharge into sewer lines and excavations and pumping from shallow wells. Comparison of surface-water and groundwater levels indicates the general direction of groundwater flow is toward the major surface-water bodies, but surface water also may be discharging to groundwater in several areas. Vertical hydraulic gradients indicate the potential for downward flow from the Calumet aquifer to the confining unit and from the confining unit to the Silurian-Devonian aquifer over most of the study area. (Kay et al, 1996)

LNAPL's were detected in several (18) wells near the petrochemical facilities in Indiana and at several gas stations and a few industrial or waste-disposal facilities in Illinois and Indiana. No LNAPL's were detected in any well that was not near a refinery, gas station, industrial facility, or waste-disposal facility. (Kay et al, 1996)

Groundwater Quality in the Calumet Region (Duweliuss et al, 1996)

The purpose of this investigation was to continue the study by Kay et al (1996) to describe regional groundwater quality in the Calumet Region. Water samples were collected from 128 wells in June, 1993 that were screened in one of four geohydrologic units: the surficial sand aquifer (Calumet aquifer); the clay confining unit; confined sand aquifers within and beneath the confining unit; or the carbonate-bedrock (Silurian-Devonian) aquifer. Samples were analyzed for general water-quality properties, common ions, 17 trace elements and cyanide, volatile and semivolatile organic compounds, pesticides and polychlorinated biphenyls. (Duweliuss et al, 1996)

The largest concentrations of trace elements and organic compounds were detected in samples from wells located in or near industrial areas or areas of waste disposal. However, water from several wells located in residential areas had relatively large concentrations of trace elements. All water samples contained at least one trace element, and all water samples except

one contained Ba (127).¹ In addition to Ba, As (69), Pb (68), Hg (69), and Tl (71) were detected in more than half of the samples. Aluminum (54), Ni (36), Se (32), V (41), and Zn (43) were detected in 25 to 50 percent and Co (14), Cu (31) and cyanide (17) were detected in 10 to 24 percent of the water samples. Trace elements detected in less than 10 percent of the samples included Ag (0), Cd (1), Sb (2), Be (2), and Cr (11). The MCL (Maximum Contaminant Levels)² was exceeded in only one sample for the concentration of Cr and the SMCL (Secondary Maximum Contaminant Levels)³ was exceeded in 29 samples for Al and in one sample for Cu.

Fourteen volatile organic and 23 semivolatile organic compounds on the U.S. Environmental Protection Agency's target compound list were detected in 20 and 56 samples, respectively. The most frequently detected volatile organic compounds were acetone, benzene, toluene, and xylene. The MCL concentrations were exceeded for benzene in 11 samples and for vinyl chloride in two samples. Phenol, phenanthrene, and naphthalene were the semivolatile organic compounds detected most frequently, and only the benzo[*b*]fluoranthene MCL was exceeded, occurring in one sample. A total of 18 pesticide compounds was detected in 29 samples, the most frequently detected being endrin aldehyde (in 14 wells) and *p,p'*-DDT (in 9 wells). Compounds containing polychlorinated biphenyls were detected in three samples, exceeding the MCL in two of these samples.

Characterization of Fill Deposits in the Calumet Region (Kay et al, 1997)

The purpose of this investigation was to characterize the fill deposits in the heavily industrialized Calumet region of Northwestern Indiana and Northeastern Illinois. The fill deposits are a mixture of steel-industry wastes (primarily slag), other industrial wastes, municipal

¹ Numbers in parentheses indicate the number of wells in which the trace element was detected.

² MCL's are concentration limits for certain substances in water delivered to customers of public water systems which consider risk to human health, technological considerations, and economic costs (Duwelius et al, 1996).

³ SMCL's are suggested concentration limits for substances in water that do not result in adverse health effects but may limit the use of water because of unpleasant taste, odor, or color (Duwelius et al, 1996).

solid waste, dredging spoil, construction debris, ash and cinders, natural materials, and biological sludge. These deposits are concentrated along Lake Michigan; from the Lake Calumet area to east of the Indiana Harbor Ship Canal; along the Calumet, Little Calumet, and Grand Calumet Rivers; and along the Calumet Sag channel. Industrial wastes and municipal solid waste were used as fill near Lake Calumet. Steel-industry wastes, primarily slag, were used as fill along Lake Michigan, Wolf Lake, Lake George, parts of Lake Calumet, and parts of the Calumet and Little Calumet Rivers. Dredging spoil is located along the rivers, and in abandoned river channels, landfills, and tailing ponds. Cinders, ash, construction debris, and natural materials are scattered throughout the area. A total volume of 2.1×10^{10} cubic feet of fill (mostly steel-industry waste) was calculated to be present in the Calumet region in 1996, covering an area of about 60.2 square miles. (Kay et al, 1997)

Steel-industry waste, mainly slag, is the most voluminous fill material (of the eight types of fill categorized in this study) in the Calumet region, and has been the principal fill material in this area since the early 1900's. These wastes cover over 30.6 square miles of the region, have an estimated volume of about 1.3×10^{10} cubic feet, and consist mainly of slag, although foundry sand and casting bricks also were used as fill. Using computer-processed multispectral satellite digital imagery, slag deposits at the surface were identified and delineated. Using this method, about 6,600 acres of surficial slag were delineated, although deposits covered with substantial amounts of vegetation, buildings, etc. would not be detected, so this estimate of slag acreage was considered conservative. (Kay et al, 1997)

Disposal of fill materials in lakes, wetlands, and on dry land over the past century have degraded groundwater quality in many areas and affected the viability of the remaining lakes and wetlands. The fill deposits that are most likely to affect surface-water and groundwater quality, if located above or within the Calumet aquifer and/or near a surface-water body, are industrial wastes, municipal solid waste, and steel-industry wastes. Groundwater in contact with slag and other steel-industry wastes may have high pH and elevated concentrations of metals, cyanide, and volatile and semivolatile organic compounds. (Kay et al, 1997)

Hydrology and Chemical Characteristics of Slag-Affected Groundwater (Bayless et al, 1998)

The purpose of this investigation was to examine geochemical processes in a glacial aquifer that is receiving drainage from an overlying slag deposit. In addition to this site-specific study, a statistical analysis of regional water quality was done to compare groundwater in wells affected versus not affected by slag. This analysis showed that wells screened in slag generally had groundwater with relatively higher pH and specific conductance values and relatively higher concentrations of alkalinity, dissolved solids, suspended solids, total organic C, Ca, K, Na, chloride, Al, Ba, and possibly higher Mg, sulfate, Cr, Co, Cu, cyanide, Mn, Hg, Ni and V.

Summary

The historical background by Colten (1985) helped identify types of wastes that were produced and discarded in the IIUIA from 1869 to 1970. The methods of waste disposal utilized prior to passage and enforcement of environmental regulations that required proper waste disposal practices, left a legacy of pollution that has been well-documented by a number of recent investigations, several of which have been cited and discussed above. In addition, the study by Kay et al (1997) has helped to characterize the major fill deposits that are prevalent in the IIUIA and the size of areas occupied by these fill deposits. Steel industry waste, mainly slag, was found to be the principal fill material making up >60% of the fill deposits by volume and >50% of the surface land area occupied by fill deposits of waste residuals.

This literature review provides resource information to help provide guidance as to how municipal biosolids might be used to reclaim some of the land surface where steel industry slags are present. This reclamation should not be expected to correct all of the surface and groundwater pollution problems that has been previously-documented. As the above investigations have documented, a variety of past industrial land uses and disposal practices have impacted surface and groundwater quality throughout the IIUIA that will have a lasting effect. However, reclamation of steel slag disposal sites would be expected to provide the opportunity for more positive land uses to be established, such as commercial areas and light industry or parks and other recreational areas.

References cited in the following sections are intended to represent the literature which identifies and discusses (1) principal factors that need to be considered for accomplishing reclamation of iron and steel slag disposal sites and (2) types of research pertinent to this review topic. Our goal was to have this literature review provide useful reference information that could be utilized for implementing practices and procedures to accomplish reclamation of iron and steel slag sites in the IIUIA. We were able to find several references dealing with the challenges of trying to revegetate sites having iron and steel slag deposits present. However, very little published information was found on using municipal biosolids for this type of reclamation. Therefore, we have reviewed and discussed many publications reporting on the utilization of biosolids for reclamation of other disturbed lands, since we believe these other reclamation experiences, knowledge and technology have relevance to using municipal biosolids to reclaim iron and steel slag disposal sites in the IIUIA.

Section II. Properties of and Problems with Iron and Steel Slags and Other Slag Site Wastes

Introduction

Practically all steel products are made at the present time by the sequence of steps shown in Figure 3. Iron-bearing materials containing principally iron oxides (iron ore, pellets, sinter, etc.) are reduced to molten iron (called pig iron) in the blast furnace. During this process, the iron absorbs from 3.0 - 4.5% carbon from the coke⁴. Iron containing 3.0 - 4.0% carbon can be used to make iron castings (called cast iron), but most pig iron will be used to make steel which contains considerably less than 1.0% carbon. The excess carbon is removed by controlled oxidation of mixtures containing molten pig iron and melted iron and steel scrap in steelmaking furnaces to produce carbon steels of the desired carbon content. Various elements may be added singly or in combination to the molten steel, during or after the carbon-removal process, to produce alloy steels. (USS, 1985)

Iron Making and Smelting Process

The Blast Furnace (BF) is charged with: (1) iron bearing material [e.g., iron ore (oxides and carbonates of iron; oxides of silica and alumina), sinter and pellets, etc.]; (2) flux (limestone and/or dolomite); (3) fuel (coke); and (4) air to produce pig iron and slag (Richards et al, 1993; USS, 1985). The chemical reactions within the BF occur at a temperature of 1300 to 1600 °C to reduce iron oxides to iron; the silica and alumina compounds combine with the Ca of the flux to form the slag (Lee, 1974). Other wastes/by-products are flue dusts, ash and refractory linings, as shown in Table 1 (Richards et al, 1993). Blast furnace slag is defined by the American Society for Testing and Materials as "the nonmetallic product consisting essentially of silicates and aluminosilicates of calcium and other bases, that is developed in a molten condition simultaneously with iron in a blast furnace" (USS, 1985).

⁴ Coke, a primary product of the coal carbonization process, exists in a highly reduced form and has robust structural properties. In the blast furnace, coke provides heat, reducing power (in the form of carbon monoxide) and the structural support that keeps the unmelted burden materials from falling into the hearth (Richards et al, 1993; USS, 1985).

FROM RAW MATERIALS TO FINISHED MILL PRODUCTS
(EXCLUDING COATED PRODUCTS)



Figure 3. Flow diagram showing the principal process steps involved in converting raw materials into the major product forms, excluding coated products (p. 2, USS, 1985).

Figure 3

Table 1. Processes, raw materials, products, and wastes involved in the production of steel (p. 267, Richards et al, 1993).

Process	Raw Materials	Product	Wastes & By-products
Iron ore mining		Iron ore	Waste rock
Iron smelting (in blast furnace)	Iron ore Limestone Coke Air	Pig iron	Blast furnace slag Flue dusts Ash Refractory linings
Steelmaking	Pig iron and/or steel and iron scrap	Steel	Steel slag Flue dusts Refractory linings
Iron casting	Pig iron Coke Molding sand	Cast iron	Foundry slag Molding sand
Processing of steel metals	Crude steel	Steel products	Spent acids and alkalis, hydroxide sludges, spent plating solutions, mill scale, oils, solvents, paints, non-ferrous
Coal carbonization	Coal	Coke Coal gas	Tars Benzole & Naphthalene Ammoniacal liquors Spent oxide Sulfate

Types of BF Slags

Slag comes from the furnace as a liquid at temperatures about 1480 °C (2700 °F) and resembles a molten lava. Depending on the manner in which the molten slag is cooled and solidified, three distinct types of BF slag can be produced (USS, 1985):

1) Air-cooled slag - - Solidification of the molten BF slag takes place under the prevailing atmospheric conditions, after which cooling may be accelerated by spraying water on the solidified mass. The crystalline structure of this slag is similar to natural igneous rocks, and the slag can be crushed, screened to desired sizes, and used as aggregates. The bulk specific gravity (dry basis) of air-cooled slag used as coarse aggregate generally falls within the range of 2.0 to 2.5. Typical unit weight (compacted) of crushed and screened air-cooled slag, graded as ordinarily used in concrete, is usually in the range of 1120 to 1360 kg m⁻³ (70 to 85 lb ft⁻³). Air cooled slag is highly resistant to the action of weathering, and high temperatures have very little effect on the slag. (USS, 1985)

2) Expanded slag - - Molten BF slag is treated with controlled quantities of water to accelerate the solidification and increase the cellular or vesicular nature of the slag, producing a lightweight product. The solidified expanded slag is crushed and screened for use as a lightweight aggregate. Expanded slag is either angular and roughly cubical in shape, or spherical with a minimum of flat or elongated fragments. The unit weight of the expanded slag (loose) usually ranges from about 800 to 1040 kg m⁻³ (50 to 65 lb ft⁻³) for the fine aggregate, and from about 560 to 800 kg m⁻³ (35 to 50 lb ft⁻³) for the coarse aggregate. Expanded slag has the same durability characteristics of air-cooled slag. (USS, 1985)

3) Granulated slag - - Molten BF slag is quenched quickly in water, so little or no crystallization occurs. The physical structure of the granulated grains may vary from a friable popcorn structure to grains resembling dense glass. Granulated slag may be crushed and screened, or pulverized for various applications. (USS, 1985) Granulated slag has marked hydraulic properties when ground to a powder. If this powder is mixed with an alkaline activation agent, such as lime or Portland cement, it can be used for the manufacture of a number of cements. (Lee, 1974)

Chemical Characteristics of BF Slags

Blast furnace slag consists of silicates and alumino-silicates of lime. The major mineral component is melilite which is a solid solution of gehlenite ($2\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{SiO}_2$) and akermanite ($\text{CaO}\cdot\text{MgO}\cdot 2\text{SiO}_2$). Melilite is a stable mineral with good strength properties and is responsible for the good engineering properties of BF slag when used as road stone, fill material and concrete aggregate. Other minerals commonly found in BF slag are listed in Table 2. While these specific minerals can be found, the overall chemical composition of BF slag is shown in Table 3. (Richards et al, 1993; Lee, 1974; USS, 1985)

The elemental content of BF slags being generated in the mid-1990's by 11 blast furnace operations in the U.S. is shown in Table 4. The BF slag data were reported by ChemRisk (1998b) for The Steel Slag Coalition and are compared to typical average (Dragun and Chiasson, 1991) and median (Bowen, 1979) concentrations found in soils. Elements that are higher in BF slag than in soils are Ca, Mg, S, Be, Cr, Mn and Se.

Table 2. Commonly occurring minerals in blast furnace slag (p. 6, Lee, 1974).

Mineral	Formula	Analysis (per cent by mass)			
		SiO ₂	Al ₂ O ₃	CaO	MgO
Gehlenite ¹	2CaO•Al ₂ O ₃ •SiO ₂	21.9	37.2	40.9	
Akermanite ¹	2CaO•MgO•2SiO ₂	44.1		41.1	14.8
Wollastonite	CaO•SiO ₂	51.7		48.3	
Dicalcium silicate	2CaO•SiO ₂	34.9		65.1	
Rankinite	3CaO•2SiO ₂	41.7		58.3	
Merwinite	3CaO•MgO•2SiO ₂	36.6		51.2	12.2
Anorthite	CaO•Al ₂ O ₃ •2SiO ₂	43.2	36.6	20.2	
Monticellite	CaO•MgO•SiO ₂	38.4		35.8	25.8
Spinel	MgO•Al ₂ O ₃		71.8		28.2

¹ These compounds form a continuous series of solid solutions known as melilite.

Table 3. Composition ranges of blast furnace slags (p. 334, USS, 1985).

Silica (SiO ₂)	32 - 42%
Alumina (Al ₂ O ₃)	7 - 16%
Lime (CaO)	32 - 45%
Magnesia (MgO)	5 - 15%
Sulfur (S) ¹	1 - 2%
Iron Oxide (Fe ₂ O ₃)	0.1 - 1.5%
Manganous Oxide (MnO)	0.2 - 1.0%

¹ Principally in the form of calcium sulphide.

Table 4. Comparison of elemental concentrations in slags to background concentrations in soils.

Element	Background in Soils ¹		Mean Concentrations in Iron & Steel Slags ²		
	D & C	Bowen	BF(11) ³	BOF(17) ³	EAF(45) ³
- - - - - mg/kg - - - - -					
Aluminum (Al)	70,995	71,000	41,245	23,841	35,009
Calcium (Ca)	---	15,000	273,855	280,135	250,653
Carbon (C)	---	20,000	2,291	2,600	2,936
Iron (Fe)	---	40,000	17,355	184,300	190,211
Magnesium (Mg)	---	5,000	69,991	55,318	54,460
Phosphorus (P)	---	800	220.(3) ⁴	3,197	1,781
Sulfur (S)	---	700	10,268	1,112	1,891.(44)
Antimony (Sb)	0.67	1	ND ⁵	3.3(6)	4.0(14)
Arsenic (As)	7.2	6	1.3(5)	ND	1.9(5)
Barium (Ba)	588	500	273	75	557
Beryllium (Be)	0.92	0.3	8.2	0.5(1)	1.1(41)
Cadmium (Cd)	---	0.35	ND	2.5(4)	7.6(38)
Chromium (Cr)	53.7	70	132	1,271	3,046
Cobalt (Co)	9.1	8	3.0(7)	3.8(10)	4.8(43)
Copper (Cu)	25.3	30	5.3(6)	30	178
Lead (Pb)	19.4	35	3.6(2)	50	28
Manganese (Mn)	555	1,000	5,527	32,853	39,400
Mercury (Hg)	0.09	0.06	ND	0.07(7)	0.04(8)
Molybdenum (Mo)	0.97	1.2	0.8(2)	11.(8)	30.(44)
Nickel (Ni)	18.5	50	1.4(2)	4.9(16)	30
Selenium (Se)	0.39	0.4	3.9(9)	15.(14)	18
Silver (Ag)	---	0.05	ND	9.1(9)	8.4(35)
Thallium (Tl)	2.2	0.2	ND	7.2(2)	11.(1)
Tin (Sn)	1.29	4	1.6(3)	6.5	10
Vanadium (V)	80.6	90	54.2	992	513
Zinc (Zn)	60	90	20.4	46.(16)	165

¹ D & C = mean concentrations taken from Dragun and Chiasson (1991); Bowen = median concentrations data taken from Bowen (1979).

² BF(Blast Furnace), BOF(Basic Oxygen Furnace), and EAF(Electric Arc Furnace) data taken from ChemRisk (1998b, 1998a, 1998c, respectively).

³ Number of samples tested for each slag type is in parentheses.

⁴ The number in parentheses following a concentration is the number of samples testing positively.

⁵ ND = the element was not detected in any of the slag samples.

Steelmaking Process

The manufacture of steel involves the removal of excess quantities of C and Si from the iron by oxidation. The steelmaking process also includes the addition of other constituents that are necessary for imparting special properties to the steel (Lee, 1974). Steel is an alloy of carbon and iron containing generally less than 0.5% C. Alloy steels contain metallic elements other than Fe, such as Cr (present at 14% in stainless steel), Ni, V, Mo, Mn, Co and W. Pig iron and/or steel and iron scrap are used to produce steel in a batch process where impurities present in these iron-containing materials are removed. Then measured quantities of carbon and other elements are added to produce steel of the type required. The amount of steel slag generated is much less than that of BF slag from iron making. Other waste materials also produced during steelmaking include flue dusts and refractory linings, as shown in Table 1. (Richards et al, 1993)

Modern steelmaking processes began in the mid-1850's with the Bessemer Process, the oldest steelmaking process. It is an acid process, where only iron ore low in S and P could be used, since these elements were not removed by this process. As high quality ores were depleted, the acid process was eventually replaced by the Thomas Process, a basic version of the Bessemer process. Addition of a lime-rich flux is used to remove unwanted elements from steel. This process was used in Europe, so P-rich ores from France, Belgium, Luxembourg and Germany could be used to make steel. However, the Thomas Process never was adopted in the U.S. (Richards et al, 1993; USS, 1985)

In the early 1900's, an open hearth process called the Siemens process, or sometimes referred to as "Siemens-Martin", surpassed the Bessemer process in the U.S. The basic open-hearth furnace had the advantages of being able to produce steels of many compositions, as well as being able to use large proportions of steel and/or iron scrap. (Richards et al, 1993; USS, 1985)

The basic oxygen steelmaking process (called BOP in the U.S. and BOS in Europe) uses oxygen rather than air in the furnace. (BOF, which means Basic Oxygen Furnace, is the furnace

where the steelmaking process occurs and is another commonly used term.) While the basic open-hearth process dominated steelmaking in the U.S. for many years, the BOP has now become the leading steelmaking process in the U.S., as well as in Europe. Another process, electric steelmaking [Electric Furnace (EF) or Electric Arc Furnace (EAF)], uses electricity to provide the energy for melting a charge of iron and steel scrap to produce steel of the desired quality. The role of each steelmaking process since 1955 is shown in Figure 4. (Richards et al, 1993; USS, 1985)

Chemical Characteristics of Steel Slags

Unlike BF slag that may be air-cooled or water-cooled (expanded or granulated), the majority of steelmaking slags are air cooled. Steel slags contain more iron (present as free metal and as oxides) than BF slags, which makes them more dense, and contain very little sulfur compared to BF slags (see Table 4). Their chemical composition tends to be more variable than for BF slags, even from the same steelmaking process.

Steel slags may derive from the acid Bessemer process or from the basic processes of open-hearth, BOP (or BOF) and electric furnace (EF or EAF) steelmaking processes. Slags from acid processes contain silica with some lime, but these are likely to not be encountered much due to the predominance of basic steelmaking processes since the early 1900's. Basic steel slag is high in lime and contains calcium silicates, solid solutions of Ca oxide and ferrous oxides and calcium ferrite. Free, uncombined lime (CaO) and magnesia (MgO) may also be present, particularly in slags from BOP steelmaking. Typical composition ranges for steel furnace slags are shown in Table 5. (Richards et al, 1993; USS, 1985)

The modern day elemental content of BOF and EAF steel slags was determined in the mid-1990's by the Steel Slag Coalition (ChemRisk, 1998a, 1998c). Slag samples from 17 BOF and 45 EAF steelmaking plants were analyzed and their mean concentrations are shown in Table 4. When comparing these steel slag concentrations with background soil concentrations, elements having higher levels than soil include Ca, Fe, Mg, S, P, Sb, Cd, Cr, Cu (EAF only), Pb, Mn, Mo, Se, Ag, Sn, Tl, V, and Zn (EAF only).

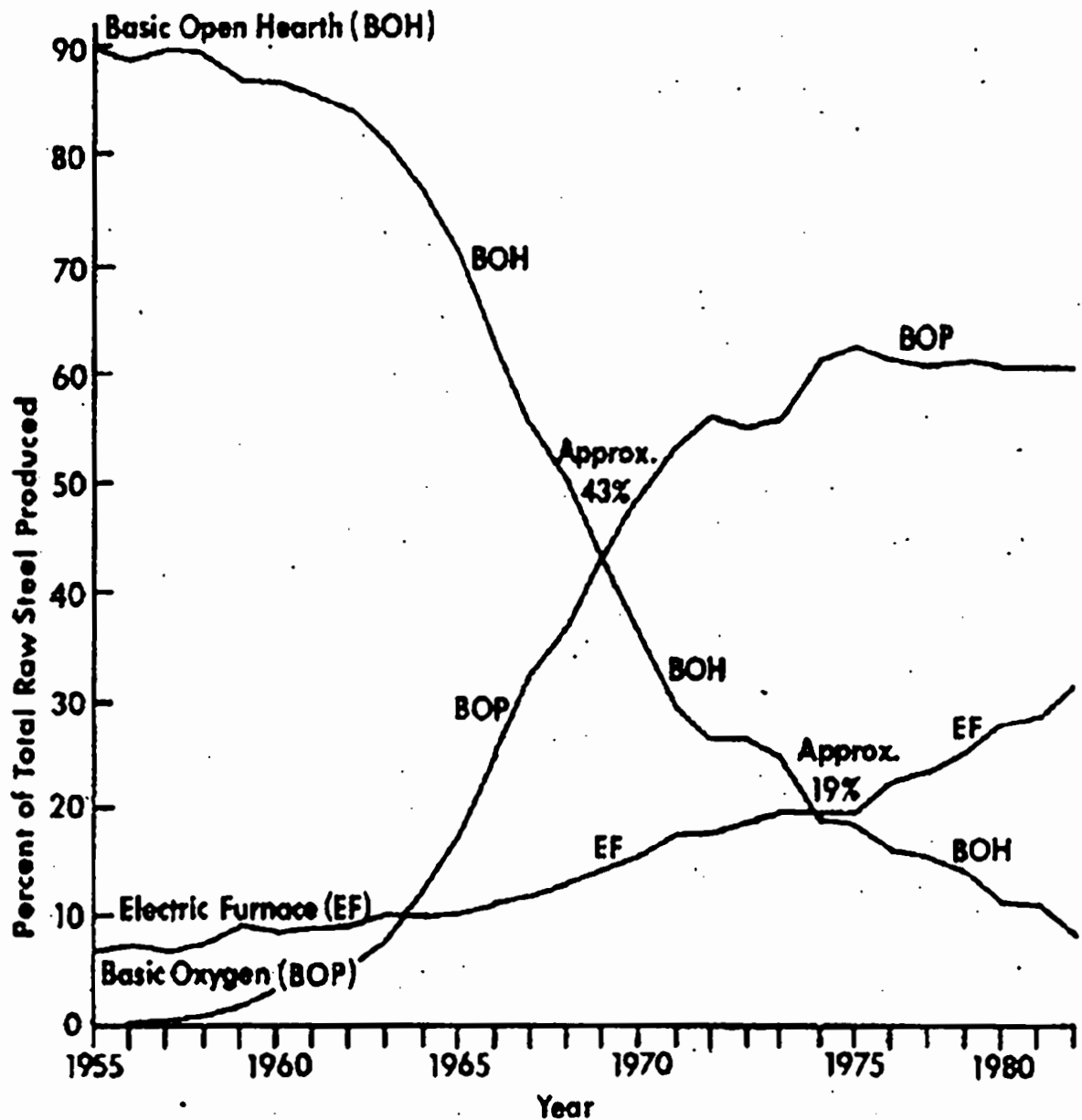


Figure 4. Proportions of total annual raw-steel production by the three principal steel-making processes in the United States, since the introduction of the basic oxygen process in 1955 (p. 34, USS, 1985).

Figure 4

Table 5. Composition ranges of steel furnace slags (p. 38, Lee, 1974).

Silica (SiO_2)	10 - 20%
Alumina (Al_2O_3)	3 - 4%
Lime (CaO)	40 - 50%
Magnesia (MgO)	2 - 9%
Sulphur (S) ¹	0.2 - 0.9%
Iron Oxide (as FeO or Fe_2O_3)	12 - 20%

¹ As elemental sulfur and not as an oxide form.

Different Uses of Blast Furnace and Steel Slags

Blast-furnace slag has been very successfully put to many commercial uses. Production of BF slag in 1988 by 26 U.S. iron processing facilities totaled 18.8 million metric tons. Surveys indicated that 14.4 million metric tons of BF slag were sold and/or used in the U.S. in 1988 at an average price of \$6.97 per ton for an estimated value of >100 million dollars. Also in 1988, 24 of the 26 steel mills in the U.S. generated more than 13.2 million metric tons of steel slag, of which approximately 1.8 million metric tons were recycled to blast furnaces for further recovery of the iron they contained. The U.S. Bureau of Mines reported that over 5.1 million metric tons of steelmaking slags were sold or used in the U.S. in 1988 at an average price of \$3.16 per ton for an estimated value of 16.1 million dollars. The remaining 6.3 million metric tons of steel furnace slag were presumably stockpiled. (USEPA, 1990a)

+

Uses of Blast Furnace Slags

Blast furnace slags, crushed and screened, have physical properties that make it particularly suitable as an aggregate, both coated and uncoated. Their rough surface texture provides good frictional properties and good adhesion to bituminous and cement binders, a low coefficient of thermal expansion and a high fire resistance. As aggregate, BF slag also has a relatively high water absorption due to its high porosity. (Lee, 1974)

In 1988, 90% of the BF slag produced by 26 U.S. iron processing facilities (i.e., 16.9 million metric tons) was air-cooled. This air-cooled BF slag was utilized in the U.S. for the following purposes -- road base (57%), concrete aggregate (12%), fill (10%), asphaltic concrete aggregate (7%), and the final 14% for railroad ballast, mineral wool, concrete products, glass manufacture, sewage treatment, roofing, and soil conditioning. (USEPA, 1990a)

The following are examples of how BF slags have been used in the past and are currently used:

1) roadbases - - used successfully for many years in road bases, either in the form of wet-mix or dry macadam, as tar or bitumen macadam, and as lean concrete (Lee, 1974).

2) concrete aggregate - - used extensively in the United States. The National Slag Association (Wayne, PA; www.taraonline.com/nationalsla_qassoc/main.html) has details of hundreds of structures made with slag concrete. An examination of such structures that have been in place for periods of 30 to 50 years has revealed no examples of excessive weathering or deterioration from breakdown of the slag, even under adverse environmental conditions.

3) railway ballast - - used for many years throughout the world for this purpose, and it continues to give excellent performance.

4) medium for biological percolating filters - - BF slag used as a medium in percolation filter beds provides an extended surface for decomposing organisms, including bacteria and fungi, that bring about the purification of polluted liquids supplied to the filter.

5) medium for germinating seeds - - Hamzah (1986) found out that Daikyo soil (water crushed slag) from iron manufacturing in Japan was a good alternative medium for the purpose of germinating *Calamus manan* seeds.

6) liming material - - Blast furnace slag has been used to lime soils as early as the 1920's. White (1928) and White et al (1937) reported on the use of BF slags to lime acid soils in Pennsylvania. Results of experiments based on the yields of 200 field plots through a period of nine years and supplemented by laboratory and greenhouse studies, led to the conclusion that BF slag had the same crop producing values as pulverized limestone, when applied to the soil on the basis of equal units of lime oxides and similar degree of fineness (White et al, 1937).

Crane (1930) compared limestone and BF slag obtained from Youngstown, Ohio in greenhouse and laboratory tests. On the basis of calcium carbonate equivalency, the two materials had nearly the same effect on red clover growth and soil reaction (i.e., acid neutralizing value) using a Gray silt loam soil. Naftel (1942) observed in greenhouse and field experiments that crimson clover made outstanding yields where BF slags were the source of lime on a Norfolk sandy loam soil. Naftel concluded that this growth response was due to the boron contained in the slag. Blast furnace slag has been effective in liming acid soils in India and increasing the yield of wheat in a pot experiment (Dafta et al, 1972).

7) use of slags for water purification - - Dimitrova (1996) characterized the Cu, Ni and Zn ion removal processes by BF slag from the "Kremikovtsi" metallurgical works in

Bulgaria. Ungranulated BF slag was found to be an effective sorbent for Cu, Zn and Ni ions in a wide range of ion concentrations and pH values.

8) use for waste stabilization - - Albino et al (1996) evaluated the use of BF slag in a matrix with gypsum and portland cement for its ability to reduce mobility of contaminants (Cd, Cr, Cu, Ni, Pb and Zn) in laboratory leaching tests. They concluded that the BF slag has a high potential in the field of waste stabilization due to the formation of ettringite-1, a product having good binding properties. However, the long term release behavior could not be predicted from a single leaching test.

Problems When Using BF Slag

A few problems have occurred in the past when using BF slag that are mostly associated with the S content or high lime content of the slag. Blast furnace slag generally contains about 1.5-2.0% total S which is derived from the coke used in the furnace. High concentrations of water soluble sulfates may result in the formation of sulfoaluminate minerals such as ettringite ($3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 30\text{H}_2\text{O}$). The formation of this mineral is accompanied by an increase in volume of approximately 120%, which may cause ground heave where BF slags are placed. (Richards et al, 1993) However, this expansion problem can be attributed to past practices where slag was improperly handled or cured prior to use. The more sophisticated slag handling techniques used today allow for expansion to occur prior to utilizing slag.

High concentrations of sulfate may also result in the chemical attack of concrete, particularly when the concrete is in contact with BF slag under waterlogged conditions. In addition, wet conditions may create reduced forms of sulfur that will cause discoloration of the slag and odor problems from gases like hydrogen sulfide. Leaching of S compounds from BF slags is the most common water pollution problem associated with the use of slags, particularly if they are placed in situations where water can drain through them. (Richards et al, 1993)

In BF slags that contain excess lime, dicalcium silicate ($2\text{CaO} \cdot \text{SiO}_2$) may form. This compound can cause flaking, or spontaneous disintegration into a fine powder, when it changes

its crystalline structure from the beta (β) to the gamma (γ) form during cooling. This crystalline phase change is accompanied by about a 10% expansion, causing the disintegration of the slag. If this slag were used for concrete structures, building damage could occur due to this expansion (Lee, 1974; USS, 1985).

As noted earlier, these problems can be avoided by utilizing proper handling and curing techniques. The National Slag Association (Wayne, PA) was organized in 1918 to help steel producers develop environmentally sound uses of slag. This effort has helped make BF and steel slags valuable “co-products” of steelmaking rather than disposal problems.

Uses of Steel Slags

In general, the majority of steelmaking slags are used similarly as BF slags, except use is more limited to non-confined applications, due to the expansion (i.e., volume change) potential which can occur with some of these slags (USS, 1985). In 1988, about 40% of the steel furnace slag produced by 24 of the 26 steel mills in the U.S. (i.e., 5.1 million metric tons) was utilized for the following purposes -- road base (46%), fill (25%), asphaltic concrete aggregate (11%), and the final 18% for railroad ballast, ice control, and soil conditioning. (USEPA, 1990a)

Examples of how steelmaking slags have been used in the past and are currently used include:

1) as aggregate - - Like air-cooled BF slags, steelmaking slags exhibit excellent skid-resistant properties and are used in road stone, sealed with an asphalt coating to exclude water (Richards et al, 1993). Steel slag has a higher frictional coefficient than does the BF slag, and it often gives the combination of high strength and high resistance to polishing, which makes it particularly suitable as an aggregate of surface dressings or for coated chippings in asphalt on heavily-trafficked roads, especially at sites where the risk of skidding is a serious problem (Lee, 1974). Steel slag is also used as a railroad ballast but is not used as an aggregate for concrete.

2) as a fertilizer - - Slag from the basic Thomas processes, used widely in Germany and France, was rich in phosphate and was valued as a fertilizer. Since oxygen steelmaking has

replaced the Bessemer process in these areas, and low phosphate ores have replaced the high phosphate ore, phosphate was added to some steel slag so that it could be sold as a fertilizer (Richards et al, 1993). Basic slag, probably from the basic open-hearth furnace process, was utilized in some long term continued field experiments in Illinois (Snider, 1934). This slag was assumed to contain about 9% P and was found to be as good as superphosphate as a source of P for plant growth. However, basic steel slags (other than the Thomas slags) typically contain less than 3% P, so the slag used in this study was unusually high.

With the possible exception of superphosphate, basic Thomas slag was viewed as a leading phosphatic fertilizer in the world by Datta and Motsara (1970) and was found to be superior to superphosphate in acid soils. This superiority was attributed to the slag's water insoluble form of P, liming effect, and silica content (Datta and Motsara, 1970). Basic steel slags used in a pot experiment of wheat in India were shown to increase the soil pH and Bray P1⁵ available P (Datta et al, 1972).

3) liming material - - The first basic slag used as a soil conditioner was from the Thomas-Gilchrist steelmaking process in England in 1884 (USS, 1985). The use of the basic slag from BOP steelmaking as a dolomitic liming agent for pastureland in the Basque region in northern Spain was investigated by Rodríguez et al (1994). Slag applications resulted in higher Ca, Mg and P, lower K and Mn plant concentrations, and increased herbage yield.

Pinto et al (1995) also concluded that the use of similar slags in Northern Spain resulted in an increase in soil pH, thereby causing a decreased Al saturation on cation exchange sites in acid soils used for pasture. Complementary studies at one field site on plant and soil heavy metals, with annual application of 10,000 kg slag ha⁻¹ during four years, did not show any accumulation of metals in plant tissue above the safety levels (Pinto et al, 1995).

4) remediation of metal-contaminated soils - - Slags have recently been investigated for their effectiveness in remediating metal-contaminated soils in situ. Thomas phosphate basic

⁵ Bray P1 is a soil fertility test used in the North Central states to estimate how much P is available in the soil for crops and is the basis for recommending how much fertilizer P₂O₅ may be needed to satisfy crop needs.

slag, along with other additives, were investigated for their ability to immobilize Cd and Pb in soils and reduce their bioavailability to plants (Mench et al, 1994). While the addition of lime, or the Thomas phosphate basic slag, did not produce any immobilization of Cd or Pb in the two high pH (pH 7.4 and 7.8) soils used, each material reduced solubility and bioavailability in the acid (pH 4.2) sandy soil contaminated with Pb.

5) water purification - - Granulated slag from steel plants in India contained Fe and Mn, along with other components, in a state suitable for causing electrochemical reduction of ionic species of Hg, Cu, Pb and Zn (Loomba and Pandey, 1993). The extent of removal of these metal ions, when passed through a packed column of steel slag, was found to be directly proportional to the weight of the slag used and the volume of the solution that flowed through the column. This process showed some possibility of application for the removal of these metals from contaminated liquids or wastewater effluents.

Problems When Using Steel Slags

Oxides of calcium and magnesium can react with water to form hydroxides, a reaction resulting in large increases in volume. This expansion is a more common problem than the sulfoaluminate expansion of BF slags and volume changes of detrimental proportions have been observed with some steelmaking slags. Hydration of CaO has been found to be responsible for the expansion of steel slag over the first year subsequent to production, with hydration of MgO a slower long term reaction, responsible for the continued expansion over a number of years. The heat produced by these reactions may also result in spontaneous heating in the slag fill. Therefore, steelmaking slags are now usually weathered in stock-piles to allow the bulk of any volume change to take place prior to its use in construction. (Richards et al, 1993; USS, 1985) These quality-control practices have helped to develop a strong market value for these “co-products” of steelmaking (National Slag Association, Wayne, PA).

Wastes and By-Products from the Iron and Steelmaking Industry

Table 1 lists the potential wastes or by-products generated from iron and steelmaking processes. As was characterized in Section I, these materials have also been deposited as

disposal sites along with iron and steel slags. Consequently, as slag disposal sites are considered for reclamation, other residuals may also be encountered at or near the surface. Therefore, potential animal or human health hazards and environmental contamination problems that may be present at slag disposal sites must be considered when selecting appropriate reclamation techniques that should be used. The following discussion briefly characterizes these various residuals.

Slags

The principal form of by-product from iron and steelmaking is slag, and the various types of slags were described earlier. For a given amount of steel produced from iron ore, the volume of BF slag is much greater than the volume of steel slag. As noted earlier, production of BF slag in the U.S. in 1988 totaled 18.8 million metric tons compared to 13.2 million metric tons of steel slag produced. More current estimates of slag production in the U.S. are likely available from the National Slag Association (Wayne, PA; www.taraonline.com/nationalslagassoc/main.html).

Although slag has become regarded as a useful co-product having value rather than as a waste or by-product material, slag deposits can still be found at old sites. A principal difficulty to revegetate slag heaps has been with those comprised of large blocks and fused slags. The lack of fine-grained particles has meant that moisture holding capacity is negligible, and vegetation has been slow to establish or difficult to maintain. (Richards et al, 1993)

Flue Dusts

Flue dusts consist of the particulate matter removed from the gases emitted by the furnaces of iron and steel production. The coarse grained material trapped by primary catches is usually returned to the blast furnace after sintering⁶. Fine grained dusts, collected in bags, scrubbers, precipitators and cyclones may have been disposed of in lagoons. Excavation of such fine-grained material is likely to produce high concentrations of air-borne dust, a health and

⁶ Sintering is a process which agglomerates fine-grained particles so they can be used in the furnace without impeding the flow of air (Richards et al, 1993).

safety hazard. Chemically, these dusts are likely to be enriched in metals such as As, Cd, Cr, Cu, Pb, Ni, Zn, alkali metals and halides. (Richards et al, 1993) Which metals are present, and how high their concentrations may be, will depend on the types of materials that are processed in the furnaces.

Flue dusts are often the chief source of inorganic contamination at iron and steel sites, and unlike slags, their metal content may be leachable. Dusts from electric arc furnaces frequently contain up to 20% Pb and Zn, originating from the high percentage of scrap metal used in such furnaces. In the USA, electric arc furnace dust is classified as a hazardous waste and must be treated chemically or thermally to remove or stabilize the leachable toxic metals. The free lime content of dusts was found to be the major factor determining metal solubility. (Richards et al, 1993)

Refractory Materials

Materials used to line furnaces can form a significant part of the wastes that can likely be found on iron and steel sites. Refractory materials will usually be contaminated with metals, and those coming from blast furnaces can also contain cyanides. (Richards et al, 1993)

Molding Sand

Sand used to form molds for casting of iron and steel may contain phenolic binders. Foundry and molding sand may also contain steel slag which are subject to expansion and increased risks of ground heaving. Large volumes of this sand, used as a fill material, have been found at some sites. (Richards et al, 1993)

Other Wastes

The processing and treatment of steel results in a variety of other wastes that can include:

- 1) spent pickling acids (liquors containing, typically, 10% unreacted sulfuric or hydrochloric acid and 5% dissolved iron);

- 2) hydroxide sludges, formed by neutralization of spent acid solutions and containing iron sulfate or chloride;
- 3) spent plating solutions;
- 4) galvanizing scums;
- 5) wastes from metallic coating of steel, which may have used Al, Cd, Cr, Cu, Pb, Mo, Ni, Sn, V or Zn;
- 6) emulsified mineral oils from cold rolling of steel;
- 7) waste plasticisers, glues and paints used in coating of steel products;
- 8) selenium used as an additive in ferrous metals to aid casting and improve the machineability of steels;
- 9) asbestos, ash from coal burning, and waste oils and lubricants; and
- 10) areas used for storing scrap will likely be contaminated with materials associated with that scrap, such as paints, oils and non-ferrous metals.

Potential Problems Associated with Iron and Steelmaking Wastes

The potential impact that iron and steelmaking wastes may have on human or animal health and the environment is discussed. Past disposal practices and the impact of these wastes on surface and groundwater quality have been extensively studied and well documented in numerous reports by the U.S. Geological Survey and others. Several of these reports were briefly summarized in Section I. The following summarizes additional potential health and environmental impacts discussed in the U.S. Environmental Protection Agency's Report to Congress (USEPA, 1990a) for "Ferrous Metals Production" and in other selected references.

USEPA Report to Congress Regarding Ferrous Metals Production (USEPA, 1990a)

Chapter 8 on ferrous metals production included discussion pertaining to 28 primary processing facilities that were in operation circa 1990 and accounted for approximately 60% of the domestic steel production. Five of the 28 facilities identified are located in the IIUIA and include Acme Steel Co. (Riverdale, IL), Bethlehem Steel Corp. (Burns Harbor, IN), Ispat Inland Inc. (East Chicago, IN), LTV Steel Corp. (Indiana Harbor, IN) and USX Corp. (Gary, IN). This

report did not discuss the many secondary processors which are predominately electric arc furnaces that primarily use metal scrap for feedstock. However, with the assistance of Gary Allie of Ispat Inland Inc. (personal communication) and the 1998 Directory of Iron and Steel Plants (AISE, 1998), the following electric arc furnaces were identified as being in the IIUIA: A. Finkl and Sons Co. (Chicago, IL), Austeel Lemont Co., Inc. (Lemont, IL), Beta Steel Corp. (Portage, IN), and Calumet Steel Co. (Chicago Heights, IL).

Four mineral processing wastes generated by the ferrous metal production operations and discussed in this Report to Congress are iron BF slag, steel furnace slag, iron BF air pollution control dust/sludge, and steel furnace air pollution control dust/sludge. This Report stated that any potential danger to human health and the environment from these wastes is a function primarily of their composition, the management practices that are used, and the environmental settings of the facilities where these wastes are generated and managed (USEPA, 1990a).

Testing has shown that iron BF and steel furnace slags do not exhibit any of the four characteristics of hazardous waste, i.e., corrosivity, reactivity, ignitability and extraction procedure (EP) toxicity. Slags consist of large solid fragments that are not easily dispersed, and from which contaminants are not readily released. The large particle size of the slag also limits the potential for significant airborne releases. Therefore, the USEPA concluded that the intrinsic hazard of these slags is relatively low. Both iron BF and steel furnace slags are processed, sold, and used extensively for a variety of purposes, such as road base material, fill, asphaltic concrete aggregate, and railroad ballast, as was discussed earlier in this section.

The fact that the USEPA Report (USEPA, 1990b) found iron and steel slags to have a low intrinsic hazard was confirmed by recent human health and ecological risk assessments (HERA) commissioned by the Steel Slag Coalition. HERA's were prepared by ChemRisk (A McLaren/Hart, Inc., Pittsburgh, PA) for BF slag (ChemRisk, 1998b), BOF slag (ChemRisk, 1998a), and EAF slag (ChemRisk, 1998c). Each HERA evaluated the potential for exposure to metals and other inorganic constituents associated with the current uses of each slag type.

Nine exposure scenarios related to the many different types of slag utilization were used to assess potential exposure to occupational (construction, maintenance and industrial workers and farmers) and residential populations. Two exposure levels were used – MLE (most likely exposure) and RME (reasonable maximum exposure). A one in one-million (1×10^{-6}) increased cancer risk level due to potential environmental exposure through air, soil and water media was used for carcinogenic metals and the hazard index (HI) was used for noncarcinogenic metals.

Samples of 11 BF, 17 BOF and 45 EAF slags were collected and analyzed for a large number of elements, as is shown in Table 4. USEPA and ASTM (American Society for Testing and Materials, Philadelphia, PA; www.astm.org) standard methods were used to digest samples and analyze for trace metals, and the TCLP and ASTM leachate procedures were conducted to quantify leaching potential.

These HERA's (ChemRisk, 1998a, 1998b, 1998c) concluded:

- 1) BF, EOF and EAF slags present no significant carcinogenic hazards for potentially exposed populations, including an oral exposure to Be in BF slag;
- 2) no significant noncarcinogenic hazards were identified for populations potentially exposed to BF, EOF and EAF slags, including exposure to dust from BOF and EAF slags high in Mn;
- 3) metals in BF, BOF and EAF slags will not leach to groundwater or surface water nor significantly impact drinking water quality; and
- 4) current uses of BF, BOF and EAF slags are not expected to impact terrestrial biota, and metals contained in these slags are not in bioavailable forms that could bioaccumulate in the food web or bioconcentrate in plant tissue.

Based on test results for iron and steel air pollution control dust/sludges, the USEPA does not believe these wastes are corrosive, reactive or ignitable, but a few sludges exhibited the characteristic of EP toxicity. For iron BF air pollution control dust/sludge, 4 out of 70 samples contained lead concentrations and 1 out of 64 samples contained Se concentrations in excess of

the EP toxicity regulatory levels. For slag air pollution control dust/sludge, only 1 out of 7 samples analyzed contained a selenium concentration in excess of the EP toxicity regulatory levels. Concentrations of the other inorganic constituents tested were below the EP toxicity regulatory levels. (This report (USEPA, 1990a) did not contain extraction results for the more recent TCLP test that is not used.)

None of the facilities having air pollution control dust/sludges that failed the EP toxicity test are located in the IIUIA. Based on an examination of the site-specific conditions at 17 facilities, the current (i.e., circa 1990) management of BF and steel furnace air pollution control dusts/sludges was judged to pose a low threat at some facilities, but a moderate to high threat at others where airborne releases were not properly controlled. All things considered, however, the USEPA concluded that these dusts/sludges pose an overall moderate risk. Therefore, slag site reclamation should include necessary precautions to (1) avoid potential wind erosion, where these dusts/sludges are still present at or on the surface of the site, or (2) prevent the public from coming into contact with these residuals by burying them or removing them from the site.

Public Health Assessments at Sites Containing Iron and Steelmaking Wastes

Public Health Assessments were obtained for two different sites which contained wastes from steelmaking electric arc furnaces. The first is the Florida Steel Corporation site located two miles northwest of Indiantown in Martin County, FL where a steel mill had operated from 1970 to 1982. Wastes present on the site included cooling water contaminated with heavy metals and polychlorinated biphenyls (PCBs) and steel mill by-products (slag, mill scale, and emission control dust) containing heavy metals. Hydraulic fluid contaminated with PCBs was likely the source of PCBs in the cooling water. On-site disposal of sludges and other mill by-products contaminated soil, sediment, surface water and groundwater. (FDHRS, 1992)

Environmental samples were analyzed for all organic and inorganic constituents on the Hazardous Substance List. The highest concentrations of metals were found in soils in the emission control dust disposal areas, with Pb being the principal metal of concern. Lead was

also found in sediments of on-site drainage ditches and in the groundwater located below the site. This site was considered a public health hazard until remediated, due to potential long-term exposures to Pb and PCBs present in contaminated soil and to the presence of Pb in contaminated groundwater. (FDHRS, 1992)

The second site containing steelmaking wastes is the J & L Landfill located in Rochester Hills, Oakland County, MI. Prior to 1951, the site was mined for sand and gravel. In 1951 the Rotary Electric Steel Company bought the site and began disposing slag from its steel manufacturing processes. In 1957 the site was purchased by the Jones & Laughlin Steel Corporation to use for disposal of slag and other wastes, and beginning in 1967, to dispose of dust from its electric arc furnace operations. By 1980, the site had been filled to grade and the landfill was closed. (MDCH, 1996)

The J & L Landfill site was listed on the National Priorities List on March 31, 1989, so a comprehensive field investigation, as part of the Remedial Investigation, was conducted to determine the nature and extent of contamination at the site. The Remedial Investigation Report concluded that surface soil, subsurface soil, surface water, sediment and groundwater at and around the site were contaminated with metals and organic contaminants as a result of previous landfill operations at the J & L Landfill site and at other landfills (at least 10) in the area. (MDCH, 1996)

The Public Health Assessment concluded that the site posed no apparent public health hazard, because no exposure pathways associated with the site were known to be complete that were likely to be of health concern. Although exposures to surface soil contaminants on the site were occurring as a result of persons trespassing on the site, exposure to these contaminants was not likely to exceed levels of health concern, due to the heavy vegetative cover on the site and the relative infrequency of trespassing. Groundwater at the site and in the site area was contaminated as a result of past activities at the J & L Landfill site and other nearby landfills, but

there was no indication that residential wells in the area were being used as a potable water supply. (MDCH, 1996)

Leaching of Metals from Slags

Slags contain metals derived from iron ore, coke, and limestone, and in addition, steel slags may also contain some of the metals used in alloy steels, as was shown for a large number of U.S. slags in Table 4. Total and extractable metal concentrations found in some European BF and steel slags by Barry (1985) were reported by Richards et al (1993) and are shown in Table 6. Because slags have a pH of 10-12 (though this may fall to pH 8 on weathering), this alkaline pH and the complexing of metals with calcium silicates ensure that these metals are not present in soluble forms. For example, the extractants used by Barry (1985) show very low extractable, or soluble, metal concentrations (see Table 6). Richards et al (1993) cited three additional leaching studies which showed that metals are not readily leached from slags.

Principal factors controlling potential leaching of BF and steel slags (i.e., pH, redox and flow) were compared in laboratory tests (availability and column leaching) versus field tests (lysimeter leachates) by Fällman and Hartlén (1994). These authors included a BF slag and a steel slag in their study and concluded that although pH is one of the most important factors controlling leachate composition, redox reactions can influence the pH of a leachate. Results suggested that the much higher S content in the BF slag compared to the steel slag probably led to some oxidation of S compounds that contributed to a decrease in the pH of leachate coming from the BF slag. A decrease in pH (usually below pH 5.0-5.5) can lead to greater solubility of metals and a higher leachability, depending on the metal. For example, metals such as Cd, Cu, Ni and Pb can be bound to sulfide minerals that may be unstable under oxidizing conditions, creating more acidic conditions that may allow these metals to become more soluble. However, other metals, like Fe and Mn, have decreased solubility under oxidizing conditions due to precipitation.

Table 6. Metal contents of blast furnace and steel slags (p. 276, Richards et al, 1993).

Sample:	Blast Furnace Slag				Steel slag		
	A	B1 ¹	B2 ¹	C	D	E	F
<u>Total Concentrations (mg/kg)</u>							
Antimony (Sb)	ND ²	ND	ND	ND	210	64	220
Arsenic (As)	ND	ND	87	3	ND	ND	ND
Barium (Ba)	200	100	200	400	700	70	100
Cadmium (Cd)	10	6	8	9	7	4	9
Chromium (Cr)	162	65	55	60	420	96	752
Copper (Cu)	188	90	60	4,400	32	17	20
Fluorine (F)	9	1	0.8	0.4	9.5	4.8	0.7
Lead (Pb)	63	56	48	61	70	38	80
Magnesium (Mg)	37,360	44,040	54,800	60,980	4,542	20,902	20,370
Manganese (Mn)	18,800	2,580	2,210	3,620	44,900	12,600	43,800
Mercury (Hg)	1.7	ND	ND	ND	ND	ND	ND
Nickel (Ni)	50	20	30	17	140	50	120
Selenium (Se)	24	ND	80	57	ND	ND	16
Thallium (Tl)	23	95	108	90	53	34	58
Zinc (Zn)	780	20	25	1,160	38	41	54
<u>Extractable Concentrations (mg/kg)</u>							
Hot water							
Boron (B)	5.5	3.0	3.0	4.0	3.5	3.0	3.5
0.5M acetic acid							
Copper (Cu)	0.3	0.5	0.8	0.6	0.7	--- ³	0.3
Nickel (Ni)	0.2	0.4	1.6	1.0	3.0	5.0	0.4
Zinc (Zn)	3.6	2.0	3.2	3.4	2.8	8.2	3.2
0.5M EDTA							
Copper (Cu)	0.2	1.3	0.9	1.3	0.1	---	0.7
Nickel (Ni)	1.3	0.9	1.4	1.0	1.8	---	2.0
Zinc (Zn)	8.9	2.7	4.8	2.9	1.0	---	1.2

¹ B1 and B2 are "blind" repeat analyses.² ND = not detected.³ --- = not determined.

Therefore, the degree of solubility of metals contained in iron and steel slags will likely be dependent on conditions present in the environment where these slags are residing. Generally, this solubility will be dependent on the pH of that environment, but the high pH of slag deposits, even after weathering has dropped this pH to about 8.0, greatly minimizes the risk of metals becoming soluble and bioavailable.

Slag as a Possible Source of Feed for Animals

While the earlier discussion has suggested that metals and inorganic constituents present in iron and steel slags will not be a high risk to animals or wildlife, there are two reports we found in the literature which suggest potential problems, if slags are fed to animals. What the risk may be will depend on the quantity consumed and the type of slag that may be fed, as well as the types and concentrations of elements that are present in the slag.

In Northern Sweden, 23 heifers out of 98 cattle died of acute vanadium toxicity in a 10-day period after being fed fresh hay contaminated with basic Thomas slag (Frank et al, 1996). Eight months earlier a pasture had been fertilized with basic Thomas slag containing 3% vanadium, by spreading this slag on the surface without plowing it into the soil. This study concluded that basic Thomas slag fertilizer should be plowed into the soil to prevent any direct consumption of the slag by grazing animals.

To evaluate steelmaking slag as a source of dietary calcium for laying hens, Leach (1985) conducted a study where slag was substituted for limestone in a corn-soybean meal ration containing 20% protein. This resulted in decreased egg production, shell thickness, fertility, and hatchability. The slag material appeared to be an inferior source of Ca for the laying hen and may also have interfered with the utilization of other dietary nutrients. However, analysis of eggs for a number of elements (Ca, P, Na, K, Al, Cd, Cr, Cu, Fe, Pb, Ni and Zn) showed no significant differences between hens receiving diets containing limestone versus slag materials.

Summary

In this section, we have discussed the properties and types of iron and steel slags, their chemical composition, how slags are utilized as valuable resources, and some of the problems that may occur with those uses unless proper handling and curing techniques are followed before those uses. Some discussion of waste residuals that are also produced along with slags and some of the potential health and/or environmental impacts that may be associated with these wastes.

The health and environmental risks appear to be low for slags and generally more of a concern for steelmaking wastes generated along with the slag. For example, hazards at two sites discussed were due to flue dusts and not slags. However, some studies reported in the literature and discussed above do suggest that some metal leaching may occur from slag deposits, depending on environmental conditions, and slag used as a feed source can have negative impacts on animals, depending on the type of slag fed, its elemental composition, and the quantities of slag consumed.

This information suggests a need to assess the slag disposal site to determine what types of residuals are present at or near the surface, what type of human and/or animal exposure may occur for a new land use being considered, and what type of reclamation techniques should be utilized to accomplish the intended land use. These considerations must have as goals:

- 1) protecting any animal and/or human contact that may be hazardous;
- 2) reducing or minimizing any environmental impacts during the reclamation that may result from disturbing slag disposal site residuals; and
- 3) accomplishing the desired vegetative cover for the intended land use.

These considerations will be discussed in the following section.

Section III. Site Assessment and Site Conditions to Consider for Slag Site Reclamation

Introduction

A site assessment is the process by which all relevant information concerning a site is compiled and evaluated to enable the most appropriate reclamation proposals to be produced. Site assessment usually includes (1) a walkover survey; (2) a desk study, with preliminary investigations; (3) detailed investigations and surveys; and (4) analysis of the information collected. (Richards et al, 1993)

The site assessment process should identify the following:

- 1) risks to people or the environment from the site in its present state;
- 2) constraints on the future use of a site, such as poor ground conditions or areas of contamination;
- 3) the opportunities presented by the site, such as ecological or wildlife value or the presence of structures of historical importance;
- 4) structures which could be put to beneficial use; and
- 5) materials which could be put to beneficial use.

Site assessment and future use are closely related. Whilst it is important in the early stages of site assessment to maintain flexibility over reclamation options that might be implemented, some indication of proposed site use will assist the site assessment process and enable appropriate assessments to be made without wasting time and resources. (Richards et al, 1993)

Following site assessment, revegetation efforts and reclamation techniques that have been used for iron and steel slag sites, spoil materials, and other disturbed lands will be discussed. Slag site conditions that pose challenges for establishing vegetation are identified, and factors to consider when selecting the best types of plant species to use for revegetation are provided.

Desk Study

A desk study involves the collection and collation of all relevant information relating to the site and its surroundings. The sources of this information include maps and plans, aerial photographs, industry records, mining records, results of earlier investigations, and utility companies. (Richards et al, 1993)

The information obtained in the desk study will include:

- 1) planning policies related to the site and the surrounding area;
- 2) land ownership and other rights over land;
- 3) current land uses of the site and its surroundings;
- 4) current infrastructure (roads, railways, utility services);
- 5) information on geology, hydrology, hydrogeology, soils and climate;
- 6) all former uses of the site and surrounding area;
- 7) layout of the plant and former process activities;
- 8) waste disposal practices and licenses issued;
- 9) industrial archeology including any unusual or unique site features; and
- 10) any reports on the ecology of the site. (Richards et al, 1993)

Site Investigation

Detailed investigations should aim to identify and quantify the constraints or opportunities which, on the basis of past use, are present in any particular area of a site and which may impinge on the proposed use of the site. A critical appraisal of the information gathered by the desk study and preliminary investigations will enable identification of areas and other aspects of the site in need of detailed investigation. (Richards et al, 1993)

General Site Characteristics

The first stage in considering the revegetation of any site, will be to characterize its physical, chemical, and biological properties (Coppin and Bradshaw, 1982). The assessment of slag tips or heaps presents a number of problems, since a wide variety of different types of slags

of different ages may be present, and cementation of some slags may make it difficult to penetrate the ground with field investigation equipment. (Richards et al, 1993)

The purpose of a detailed site investigation is to determine: (1) which areas of the site are suitable for reclamation; (2) the extent of physical preparations required, e.g., grading and runoff control; (3) the characteristics of the existing soil and the extent to which it must be modified and enhanced in order to support vegetative growth; (4) the environmental qualities of the site and the adjacent areas which require protection, e.g., surface waters, groundwater, etc.; and (5) climatic conditions which will have an impact on the site design and operations. (Sopper, 1994)

Topography

An accurate contour map of the site is needed to provide a basis for (1) delineating which areas have slopes that are too steep for some reclamation operations, (2) regrading the areas if necessary, and (3) designing surface runoff water improvements (e.g., ditches, terraces, berms, etc.). Physical features of the site which usually must be considered in the design of the reclamation project include residences, ponds and lakes, springs, water supply wells, public road rights of way, and the high water mark of streams, rivers and creeks. (Sopper, 1993; 1994)

Hydrologic Properties

The hydrologic properties of the surface material must be carefully considered in the project design. Infiltration rate and soil permeability⁷ (or hydraulic conductivity) are the two most important parameters influencing water movement. Both of these parameters are greatly influenced by soil texture and structure. If the surface material (e.g., spoil, deposits, etc.) is compacted, adverse physical conditions should be corrected, such as by contour chisel plowing the site. (Sopper, 1994)

⁷ Infiltration rate is defined as the rate at which water enters the soil surface, and permeability is the rate at which water moves downward and laterally within the soil profile (Sopper, 1994).

Surface Runoff

Surface runoff occurs when rainfall or snow-melting rates exceed the infiltration capacity of the surface materials. The reclamation design should include preventive measures to control surface runoff to prevent erosion of disturbed surface materials from leaving the site. (Sopper, 1994)

Groundwater

Groundwater quality, depth, and flow should be determined, including depth to the water table, seasonal variation in the water table, existence of any perched water, distance to the nearest domestic well, background quality of the water, and potential use of the water beneath the site. The future use of the groundwater may be a major factor influencing the reclamation techniques used. Depth to groundwater is important because the greater the depth to groundwater, the lower the potential for pollutants to migrate from surface materials into the aquifer. (Sopper, 1994)

Extent of Physical Preparations Required

Determine the need for land reshaping and the size of the fragments in the slag fill. There may be a need to bury large fragments and leave the finer materials on the surface. One thing to worry about is the volumetric instability of the slags. Although slags present at former steel sites may be old, this does not mean that reactions causing expansion will no longer occur. This is particularly so if the slag is disturbed, so that large lumps are broken up, exposing unreacted material to water and bringing materials together in new combinations. Old deposits of slags should be disturbed as little as possible, but if they are to be placed in confined situations, such as beneath buildings, an assessment of their volumetric instability should be made. (Richards et al, 1993)

Try to conserve or leave the material on the surface where vegetation already exists, since this might be an indication of surface materials which possess greater water holding capacity and fertility. Existing vegetation may also provide some guidance as to the species of plants that can be successfully established on other areas of the site.

Collecting and Analysis of Samples

A final part of site investigation is collection and analysis of surface materials. Sampling and analysis of surface samples is necessary to determine the nature and extent of contaminants that may be present and whether any potential exposure to animals and/or humans will be a problem after remediation. Chemically characterizing surface materials is also important for determining what amendments will be necessary to establish vegetation on the site and make the remediated site environmentally safe.

Sampling Strategy

Obtaining representative samples is often difficult since the slag site may contain different types of slags, as well as other waste materials such as refractory linings and flue dusts (Richards et al, 1993). Due to this heterogeneity, the site will have to be inspected to determine the number and location of the samples necessary to characterize the surface materials. Standard soil sampling procedures used for undisturbed and agricultural soil will usually not work in most cases (Sopper, 1994).

A degree of uncertainty will always be associated with investigations of potentially contaminated sites. The degree of uncertainty can be decreased, however, by basing sampling strategies on information obtained during the desk study and visual site inspection. Three basic sampling approaches can be used, regarding the pattern of locations where samples can be collected (Richards et al, 1993):

1) Judgmental - - samples are deliberately taken at certain locations that are selected on the basis of prior knowledge about contaminant distribution. Such sampling is very unlikely to produce samples which are representative of the site as a whole, but it is an efficient way of obtaining information on the concentration of contaminants in an area known to be heavily contaminated or the extent to which contaminants have migrated from a known source.

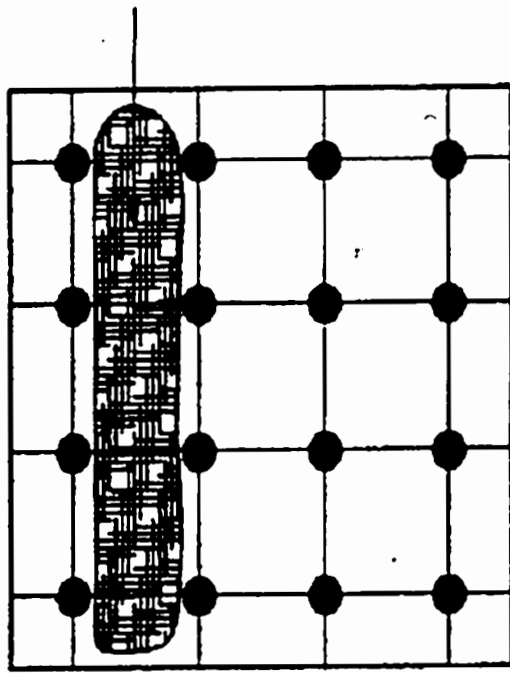
2) Systematic - - Sampling locations are defined by a grid system, as shown in Figure 5 (a). This is easy to set out on site and is generally the method chosen where there is little prior information on the location of contaminations or is where no visually detectable differences are

found during site inspection. However, if the pattern of contamination happens to coincide with the pattern of the grid, samples obtained may not be representative of the site as a whole. For example, elongated “hot spots” of contamination which are parallel to the grid lines and fall between them will be missed altogether. The risk of this can be considerably reduced by using a herringbone rather than a simple square grid pattern, as shown in Figure 5 (b).

3) Random - - While mathematically-determined random sampling may allow for statistical analysis of results, variation in the analytical data is often so large that meaningful statistical interpretation is impossible. In its simplest form, random sampling is inefficient. Unless a very large number of samples are taken, substantial areas may occur where no samples are taken at all, as shown in Figure 5 (c). More sampling locations are thus required to give the same probability of locating a “hot spot” of contamination than with systematic sampling. By dividing the site into a number of areas (e.g., equal-sized squares) and placing sampling locations randomly within each area, less sampling points are needed than for simple random sampling. This stratified random sampling is shown in Figure 5 (d). An element of judgmental sampling may be introduced by varying the relative sizes of the areas according to prior knowledge of the distribution of contaminants across a given site. (Richards et al, 1993)

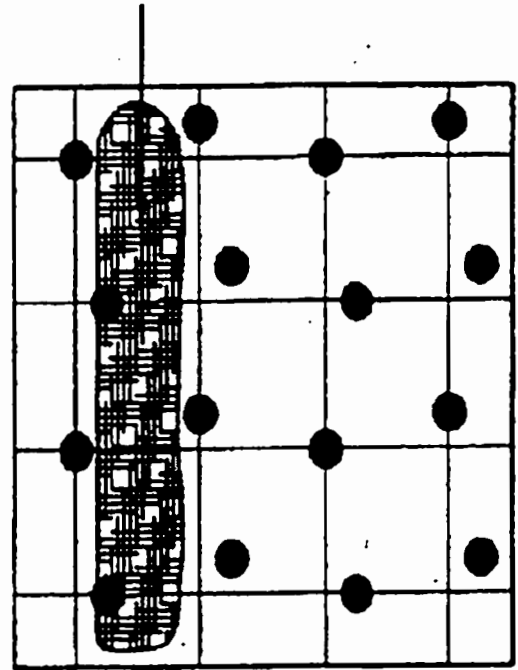
Figure 5

Hot spot of contamination

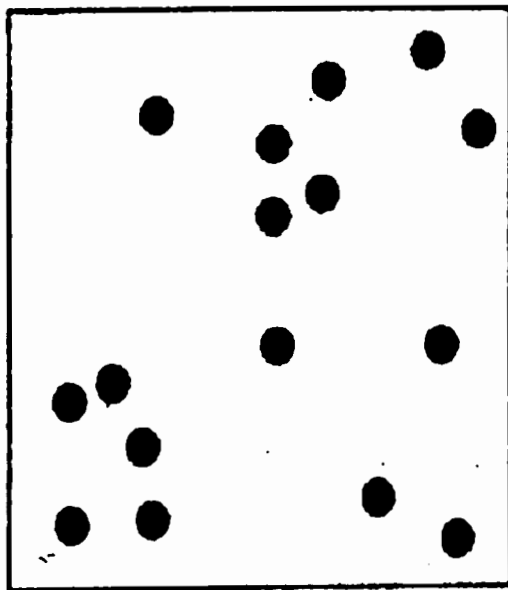


(a) Regular (square) grid pattern

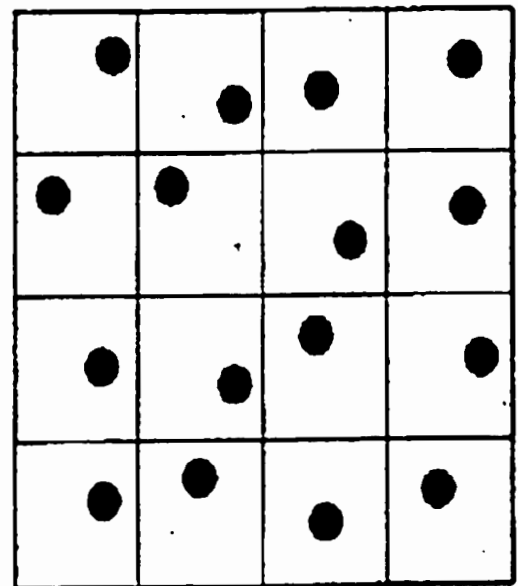
Hot spot of contamination



(b) Herringbone pattern



(c) Simple random pattern



(d) Stratified random pattern

For many types of sampling, obtaining representative samples is done by compositing multiple sub-samples, mixing these sub-samples to get a homogeneous mixture, and then taking a portion of this sub-sample mixture for analyses. This approach should not be used where sampling is designed to help locate areas of contamination or to help delineate areas of surface materials which may differ significantly in their chemical, physical, or biological characteristics.

Samples collected for chemical analysis should be put into containers that will not react with, or contaminate, the sample placed into it. Plastic containers are generally used for samples analyzed for metals and other inorganic elements, while glass containers with aluminum-lined caps are preferred when organic chemicals or solvents are to be determined. Containers with large openings facilitate easy filling, and air-tight closures may be critical when testing for volatile chemicals. Standard or official sampling procedures may need to be followed for particular types of compounds when testing for environmentally-regulated chemicals (ex., using the standard SW 846, Method 5035, for sampling volatile chemicals in soils). Proper labeling of samples and accurate recording of sample locations, sampling methods used, etc. are critical to achieving meaningful interpretation of analysis results.

Sample Analyses

Analysis of samples can often be the most expensive part of site investigation. A wide range of inorganic and organic analyses can be done, so careful thought should be given to what constituents need to be determined. Since sample collection by comparison is a lower cost, a good approach can be to collect more samples than may be necessary to characterize the site and begin by selecting a portion of these for chemical and/or physical analyses. Then additional samples can be analyzed at a later time, as needed, based on initial sample analysis results.

Richards et al (1993) suggests that the suite of chemical constituents to be tested be selected on the basis of (1) the substances which are thought likely to be present, based on past uses of the site as indicated by the desk study, and (2) the substances which are thought likely to cause a hazard, given the proposed use of the site. Generally, errors introduced by the sampling process, in terms of the samples being representative of surface materials in question, are much

greater than those at the analytical stage. Therefore, it is often better to analyze a large number of samples by a reasonably accurate method, than to analyze a small number by a very accurate and costly method. Analysis should be subject to rigorous quality control procedures to ensure that samples are not lost, correct analytical procedures are carried out, and results are reported correctly. (Richards et al, 1993)

Screening analyses, which indicate the presence of a group of substances but not the concentrations of individual compounds, can be used to gain maximum information for minimal analysis expenditure. When further analysis is required to identify and measure the concentration of particular substances present, this can then be done only on samples that the screening analysis showed to contain high concentrations of the group of compounds in question. For example, analysis of total S can be followed by analysis of total sulfate, sulfide and elemental S, and then subsequently water soluble sulfate, if total sulfate concentrations are unusually high. Similarly, analysis of total cyanides can be followed by analysis of free cyanide and thiocyanate. (Richards et al, 1993)

Measurement of pH, a basic parameter in soil and water conditions, should be carried out in nearly all site and soil investigations (Richards et al, 1993). Soil pH is important when establishing vegetation during reclamation, since it is important for assessing and modifying plant nutrient availability in the surface materials, as well as helping to decide what plant species to establish. Most grasses and legumes along with many shrubs and deciduous trees, grow best in soil with a pH range of 5.5 to 7.5. When applying municipal biosolids to land, several states have adopted regulations which require the surface soil pH to be 6.0 or greater during the first year of plant growth. (Sopper, 1994)

Essential plant nutrients needed in plentiful supply include N, P, K, Ca, Mg and S. Many of these may be deficient in the surface materials present on old iron/steelmaking slag sites. Therefore, another important test for selected samples will be a soil fertility test, which can help serve as a guide for additional nutrients needed from fertilizers, municipal biosolids, and other sources of plant nutrients to support the vegetation planned for the site. Measurement of

electrical conductivity is an indication of soluble salts present, which can be a problem for establishing and maintaining plant growth, if salt levels are excessive.

Trace metal analysis may be necessary depending on the history of the site. Trace metals of concern could be Cd, Cr, Cu, Fe, Pb, Hg, Ni and Zn. These elements might be found in concentrations toxic to plants, microorganisms, animals, and humans. As discussed earlier, analysis of vanadium may be warranted if any wildlife or animals will come in direct contact with slag materials that could be high in vanadium content. In addition, Federal 503 regulations (to be discussed more later) for municipal biosolids require testing for several pollutants, so it may be necessary to document the trace element content of surface materials before any reclamation efforts have begun.

Analysis of organic compounds is particularly complex and can be very expensive. An initial screen by solvent extraction and gas chromatograph/mass spectrometer determination is often carried out, but extraction methods do not generally measure volatile compounds. Analysis of the head space (i.e., the space at the top of the sample container) for volatile compounds is a more appropriate technique for these organics, and standard sampling methods and analysis procedures should be followed. Techniques such as thin layer chromatography can be used to separate organic compounds into different types of compounds, but the identification of specific compounds requires techniques such as gas chromatography or high performance liquid chromatography and mass spectrometry. (Richards et al, 1993)

Characterizing the biological properties of surface materials is probably not too essential. Buczek and Czerwinska (1974) found that conditions in BF slag fills were favorable for the development of various soil microorganisms and at least some species of higher plants. Where conditions were less favorable for the development of nitrifying bacteria, this situation could be attributed to the presence of excess amounts of available microelements like Fe, Ni and Cr. Their experiments indicated that the main factors limiting plant growth and development on BF slag were too high alkaline pH, lack of available N, excess of Fe, Ni and Cr, and the dry dust layer forming on the slag surface which cannot provide adequate water for plant growth.

Major Challenges for Establishing Vegetation on Slag Sites

Gemmel (1975) identified three major problems that must be overcome if grassland is to be successfully established on BF slag:

- 1) reduction of the high pH from about 10.5 to around 8.0;
- 2) correction of phosphate deficiency; and
- 3) provision for and maintenance of adequate plant-available N (PAN).

Street and Goodman (1967) indicated that, regarding the chemical composition of the rooting medium, two aspects are of importance to plant growth. One is the capacity of this media to supply adequate quantities of essential plant nutrients in a soluble form. Gemmel (1975) was referring to this aspect relevant to having adequate availability of P and N, two primary plant nutrients. The second relates to soluble elements occurring at toxic concentrations. For example, at low concentrations, certain elements (e.g., B, Cu, Fe, Mn, Mo, Zn) are essential for plant growth, but at high concentrations, these same micronutrients can be poisonous to plants, i.e., phytotoxic.

Richards et al (1993) expanded the potential problems to consider for revegetation efforts, by listing several principal characteristics (physical and chemical) which have major implications for establishing plant growth. These included:

- 1) extremes of pH (i.e., growing media is either too alkaline or too acidic);
- 2) lack of essential plant nutrients;
- 3) low organic matter content;
- 4) coarse-grained material having low water-holding capacity;
- 5) phytotoxicity; and
- 6) compaction or consolidation of surface materials.

Munshower (1994) identified three additional soil parameters that are important for successful revegetation – electrical conductivity (salinity), sodium concentrations, and cation exchange capacity (CEC). These and other potential limitations are discussed in the following subsections.

pH of the Surface Materials to be Vegetated

Substrate pH influences plant growth mainly through its effect on the solubility of chemical elements, including those which are directly toxic to plants and those which are required as nutrients. Most productive agriculture requires a soil pH between 5.5 and 7.5 for satisfactory crop growth. At this range, nutrient availability to plants is at a maximum and toxicity at a minimum. (Richards et al, 1993; Sopper, 1994)

Gemmell (1974) reported on the revegetation of BF slag in Lancashire, Great Britain. The exposure of BF slag to the weather for 12 months caused a reduction in pH from 10.5 to 8.1 and 9.0 at the surface 0 and 2.5 cm depths, respectively, due to leaching of hydroxides. However, the underlying material remained highly alkaline which limits or prevents plant growth. Consequently, plant growth was restricted on this BF slag by the limited depth of the hydroxide-free rooting substratum.

Gemmell (1975) found correction of high pH to be impossible to achieve by artificial means. Chemical acidifiers were unsuccessful because of solubility factors and the presence of free calcium carbonate in the waste. The only practical method available was to allow natural leaching to occur after the completion of any earthworks. Therefore, Gemmell (1975) suggested that reclamation should allow for a period of exposure to rainfall percolation, between final surface grading operations and planting, for the high pH to decrease.

Weathered slag has a pH of 7.5 to 8.5, which is similar to that of calcareous soils and some strip mine spoils where applications of sewage sludge have helped to decrease pH. Addition of sewage sludge at a rate of 90 metric tons/hectare (mt/ha) to a semiarid, calcareous soil resulted in a decrease in the pH from 7.8 to 7.4 in the first two growing seasons (Fresquez et al, 1990a) and to 7.2 and 7.0 in the third and fourth growing seasons, respectively (Fresquez et al, 1990b). This decrease was attributed to the leachates from the slightly acidic sludge applied and to acid-producing microbial reactions, e.g., nitrification in the soil. Incorporation of sewage sludge into the top 15-18 cm of a calcareous, strip-mined spoil decreased the surface pH from 7.5

to 7.0, 6.3, and 6.0 with the additions of 224, 448, and 896 mt/ha of sludge solids, respectively (Hinesly et al, 1982).

Lack of Plant Nutrients

The capacity of slags to supply essential plant nutrients like N, P, K and Ca can be assessed in three different ways: (1) from chemical analysis of the slag itself; (2) by studying the release of elements into solution from the slag material; and (3) by chemical analysis of the plants growing in the slag (Street and Goodman, 1967). Extreme lack of nutrients was reported in BF heaps in Styria, Austria (Punz, 1989). As noted earlier, N and P are plant nutrients that are often present at extremely low concentrations in most slags (Richards et al, 1993).

Blast furnace slag material in the Lower Swansea Valley was highly porous, so soluble nutrients (particularly N) were quickly lost. In addition to potential N deficiencies (Gemmell, 1974), P deficiencies can be expected due to the high pH of the waste and the associated immobilization of phosphates (Gemmell, 1975).

Steel tips⁸ in the Lower Swansea Valley were more or less clearly deficient in N, K and P. In glasshouse studies, Street and Goodman (1967) found that steel tip material was acceptable for emergence and establishment of seedlings of White Mustard (*Sinapis alba*), but the plants eventually showed chlorosis and grew very poorly compared to the growth that occurred in a good rooting medium. Using three test plants, White Mustard, Red Clover (*Trifolium pratense*) and Oats (*Avena Sativa*) in a glasshouse experiment, Street and Goodman (1967) showed that the growth of plants in the steel tip material was markedly improved by the addition of general inorganic fertilizer. Furthermore, the growth could be improved more by mixing a compost material into the tip material before planting.

⁸ Steel tips refers to steel works slag and other wastes that were dumped (tipped) onto the land surface as a means of disposal.

Low Organic Matter Content

Wastes from iron or steel production are usually devoid of organic matter, whereas a typical arable soil contains 0.5 to 2.5% organic matter. Soil organic matter and the associated microbial activity are key factors influencing productivity, playing major roles in the chemical, physical and biological aspects of soil (Brady and Weil, 1996; NRC, 1981). Organic matter contributes to the availability and reserves of N and other nutrients for plants, increases CEC, and improves the available water-holding capacity of slags which weather very slowly and remain coarse-grained with large pore space. Therefore, addition of organic materials to slag deposits will have a beneficial effect for revegetation. (Coppin and Bradshaw, 1982; Munshower, 1994; Richards et al, 1993).

Low Water-Holding Capacity

Coarse-grained slags have very few pores of the size needed to hold water against drainage due to gravity (Richards et al, 1993). Low available water for plants can cause stress and limit growth. Although steel tips in the Lower Swansea Valley were found to be inferior to soils in water retention, maintaining a high watering regime in glasshouse studies did not significantly elevate the unfavorable effects of the material on plant growth, since low nutrient availability was more limiting (Street and Goodman, 1967). While BF slags in Styria, Austria also had very low water retention capacity, the moss layer that covered the heaps improved conditions for seed germination and soil development (Punz, 1989).

Trace Metal Concentration

As noted earlier in the discussion of pH, potential for plant toxicity due to trace metals is minimal due to their low solubility at high pH's. Street and Goodman (1967) found that potential plant toxicity was low for steel slags compared to Cu or Zn slag deposits. In the Lower Swansea Valley study, steel slag tips had low water-soluble concentrations of Cu and Zn (compared to their solubility in Cu and Zn slags), even though the total concentrations of these metals in slag can be relatively higher when compared to their abundance in normal soils. For example, concentrations of copper and zinc were higher in EAF slags than in soils, while concentrations in BOF slags were comparable to soils and in BF slags were lower than in soils (see Table 4).

Compaction or Consolidation of Surface Materials

Barnhisel and Hower (1997) noted that soil compaction is an increase in bulk density⁹ of soil, or surface material, resulting from applied pressure. This pressure could be exerted by natural sources such as rain, but more commonly, and of greater significance, are manmade forces such as traffic from heavy equipment. The consequence of compaction or consolidation is lack of a continuous macropore network to facilitate water movement, aeration and root system extension. Coppin and Bradshaw (1982) described the symptoms of compaction as ailing trees that never grow and eventually die, a poor grass cover with many bare patches, and poor surface drainage, evident by standing puddles of water following winter snow melts or periods of rainfall. These authors also suggested that many reclamation failures are due to not correcting compaction problems during the reclamation process.

As compaction increases, less of the soil or surface material volume is occupied by pore space, so the bulk density will increase. Brady and Weil (1996) stated that root growth is greatly impaired at bulk densities of 1.6 g/cm³ or above, and Coppin and Bradshaw (1982) indicated that materials having a bulk density >1.4 g/cm³ will benefit greatly from cultivation. Therefore when present, surface and deeper tillage can be employed to enable the penetration of plant roots and water into the compacted zone. Sopper (1994) recommended contour chisel plowing to alleviate poor soil physical conditions, and Richards et al (1993) suggested that deep cultivation must extend through the layer of impeded drainage to create drainage pathways through the substrate.

Electrical Conductivity

Munshower (1994) defined salinity as a soil property referring to the amount of soluble salts in the soil or surface material acting as a media for plant growth and is commonly measured as EC (electrical conductivity). Salinity is generally a problem in arid or semiarid climates but can be a problem in more humid regions with non-weathered waste residuals containing soluble salts. High concentrations of salts around plant roots exert an osmotic effect, preventing them

⁹ Bulk density is defined as the mass (weight) per unit volume of dry soil or surface material, often expressed in g/cm³. The volume includes the solids (or particles) and the pore spaces, which will be partially occupied by air and partially occupied by water under natural conditions.

from absorbing water and nutrients. The most critical stage for the plant is during emergence and establishment of the seedling, but problems can also occur at any stage (Coppin and Bradshaw, 1982).

Soil EC values are most commonly determined using the saturation paste extract method¹⁰ and soils or surface materials with an EC greater than 4 dS/m are considered saline. Munshower (1994) used the following soil salinity guide:

<u>EC Value (dS/m)</u>	<u>Salinity Status</u>
<4	Nonsaline
4 - 8	Slightly saline
8 - 16	Moderately saline
>16	Saline

Salt-sensitive plants may be affected at EC's <4 dS/m, and salt-tolerant species may not be impacted unless the EC's are >8 dS/m. Therefore, the EC provides a guide as to when soluble salts are high enough that salt tolerance of plants should be considered to ensure successful revegetation.

Sodium Concentrations in Soil

High Na concentrations in soil, or the growing media, contributes to alkalinity rather than to salinity, which is caused by any other types of salts. The Na status can be characterized by two different measures, ESP and SAR. The exchangeable sodium percentage (ESP) identifies the degree to which the exchange complex is saturated with Na as follows (all concentrations are in meq/100 g of soil, as determined in an ammonium acetate extract):

$$\text{ESP} = \frac{\text{exchangeable sodium (meq/100 g)}}{\text{cation exchange capacity (meq/100 g)}} \times 100$$

¹⁰ The soil sample is saturated with distilled water to a paste consistency, allowed to stand overnight to dissolve the salts, and the electrical conductivity of the water extracted from the paste is measured and expressed as decisiemens per meter (dS/m). The unit of EC formerly used was millimhos per centimeter (mmho/cm), so 1 dS/m = 1 mmho/cm (Brady and Weil, 1996).

The sodium adsorption ratio (SAR) is the proportion of Na ions compared to the concentration of Ca plus Mg ions in the saturation paste extract as follows (concentrations of Na, Ca and Mg are in meq/L):

$$\text{SAR} = \frac{\text{Na}}{\sqrt{(\text{Ca} + \text{Mg}) / 2}}$$

A high ESP (>15%) or SAR (>12-15) indicates that Na concentrations in the soil or surface material are too high. These salt-affected soils are classified as sodic, or alkaline, and will typically have pH values that exceed 8.5, sometimes rising to 10 or higher. (Brady and Weil, 1996; Munshower, 1994)

Cation Exchange Capacity (CEC)

The CEC is simply defined as the sum total of exchangeable cations that a soil can adsorb. Cations, or positively-charged ions (e.g., H^+ , K^+ , Na^+ , Mg^{2+} , Ca^{2+}), are attracted to and adsorbed on negatively-charged sites located on soil colloids. The CEC of a given soil, or surface material, is determined by the relative amounts of different colloids in that soil and by the CEC of each type of colloid, i.e., the collective or total capacity of all these negatively-charged sites to adsorb cations. (Brady and Weil, 1996; Munshower, 1994)

Because cation exchange sites are located on clay and organic matter (humus) particles, the CEC of a soil generally depends on the amount of organic matter and the amount and type of clay in a soil. The cation exchange in soils, or surface materials, is involved with acidity (i.e., the greater the proportion of exchange sites occupied by H^+ ions, the greater the acidity and lower the pH), alkalinity (i.e., how much of the CEC is occupied by Na, like when the ESP is >15%), and supply or availability of cationic nutrients (i.e., Ca^{2+} , Mg^{2+} , K^+). Therefore, the CEC provides for a storehouse of several essential plant nutrients that can make the soil or surface material more fertile for supporting plant growth. Many disturbed lands, spoils, slags, etc. may lack adequate CEC to retain these nutrients for plant growth, unless amendments to increase the CEC are added (Coppin and Bradshaw, 1982; Munshower, 1994).

Temperature

Dark-colored slag can contribute to extreme temperatures occurring in slag deposits during the summer. For example, the temperature fluctuations were considerably less in steel slag (gray in color) compared to the darker-colored Zn and Cu slag tips (Street and Goodman, 1967). Microclimate (i.e., the climate at and near the soil surface in which plants grow) has an important effect on the reclamation process. The temperatures near the surface will be influenced by the color of the surface, the aspect of the surface relative to the sun, the soil moisture content, and the shading provided by any existing plants. During the summer, relatively dark, dry, bare, newly reclaimed soils with a southern exposure will experience extremely high midday temperatures, which can kill young seedlings on a revegetated area, even when the air temperature above the surface is within a normal range (NRC, 1981).

Invasive and Persistent Weeds

Many slag disposal sites can contain stands of weeds which, if spread during reclamation works, will become extensive, detrimental to the desired land use, and very expensive to control (Richards et al, 1993). Therefore, assessment of sites in order to identify the presence of invasive weeds prior to reclamation will enable a weed control strategy to be developed.

Reclamation Techniques

Richards et al (1993) used a figure to summarize 1) a number of common problems associated with the revegetation of different types of disturbed lands and 2) various techniques which are applicable to the treatment of these problems (see Figure 6). Problems usually present with iron and steelmaking slags include instability/erosion, water shortage, coarse texture, nutrient deficiency, alkalinity, and plant toxicity, as was discussed in the preceding subsection. Figure 6 also shows that addition of organic material (such as municipal biosolids or compost) has the best potential to help correct most of the common problems listed. Several techniques or practices often used for reclamation, including organic matter amendments, are discussed in more detail in the following subsections.

Use of Inorganic Fertilizers

Since BF slags are highly porous, leaching of N in the form of nitrates can be a problem. Gemmell (1974) investigated the use of S-coated urea to supply N slowly throughout the growing season to revegetate alkaline BF slags in Lancashire, Great Britain. Best revegetation occurred with the slow-release N fertilizer versus the soluble N fertilizer that was more subject to loss by leaching on the BF slag. Phosphorus fertilizers were also applied to correct the severe P deficiency problems.

Additional experiments were conducted in order to solve the problems of initial planting and early plant growth on a leveled heap of BF slag (Gemmell, 1975). Phosphate was found to be the principal growth limiting factor and additions of 100 kg/ha of P_2O_5 increased growth tremendously. Nitrogen fertilization alone had no effect on growth response, unless P fertilizers were also applied.

Use of Organic Materials

Organic matter (materials) is an excellent amendment for site reclamation because it 1) contains nutrients, 2) improves the water-holding capacity and CEC of sandy or stony soils or other surface materials, and 3) improves aeration and drainage in heavy soils or fine-textured surface materials. Organic residuals or byproducts from a wide variety of sources are suitable, and selection will usually depend on what may be available in sufficient quantities nearby and at a low cost. Coppin and Bradshaw (1982) listed a number of organic materials that can be used, as shown in Table 7.

Derelict land categories	Problems	Instability/erosion	Water shortage	Water-excess	Texture-coarse	Texture-fine	Compaction	Nutrient deficiency	Low ion exchange capacity	Alkalinity	Acidity-actual	Acidity-potential	Toxic-metals	Toxic-other	Salinity
Colliery spoil: opencast		●	⊗	○	○		⊗	●	○		○	○			○
deep mine		●	●	○	○		○	●	○		○	○			○
washeries		●	⊗	○	○	●		●	○						
Iron and steel: disused plant				●	○		⊗					○			
slog and spoil		●	●		●	○	○	●		●		○	○	●	
Coal carbonisation sites		○					○			○	○	○	⊗		
Railway land					●	●	○	●				○	○		
Demolition rubble				○	●		●	●				○	○		
Treatment															
Weathering					◆		◆	◆		◆	◆		◆	◆	◆
Grading		◆	◆	◆											
Ripping		◆	◆	◆		◆	◆								
Compacting		◆	◆	◆	◆	◆									
Liming								◆		◆	◆	◆	◆	◆	
Fertilising								◆					◆	◆	◆
Fine inorganic material			◆	◆	◆	◆			◆						
Coarse inorganic material		◆	◆	◆	◆	◆									
Bulky organic material		◆	◆		◆	◆	◆	◆	◆	◆			◆	◆	◆
Drainage		◆		◆											
Irrigation			◆				◆						◆	◆	◆
Establish vegetation		◆		◆			◆	◆	◆						

○ : Present in some cases ⊗ : Serious problem in most cases ◆ : Beneficial
 ● : Present in most cases ✱ : In some cases ◇ : Harmful

Figure 6. Common problems usually encountered on different types of disturbed lands and various treatments that can be helpful for revegetation (p. 494, Richards et al, 1993).

Figure 6

Table 7. Organic materials useful as slag amendments (p. 53, Coppin and Bradshaw, 1982).

Material	<u>Usual composition (% of dry solids)</u>			O.M ¹	Usual application rates (dry mt/ha)	Special problems or advantages
	N	P	K			
Farmyard manure	0.6-2.50	0.1	0.5	24-50	5-40	Variable
Pig slurry	0.2-4.0	0.1	0.2	3	5-20	High water content, possibly high Cu
Poultry manure, broiler	2.5-4.0	0.9-2.5	1.6-2.5	60-80	2-10	High levels of ammonia
Poultry manure, battery	1.5	0.5	0.6	35	2-10	High levels of ammonia
Sewage sludge, digested	2.0-4.0	0.3-1.5	0.2	45	5-50	Possibly toxic metals and pathogens
Sewage sludge, raw	2.4	1.3	0.2	50	5-50	Possibly toxic metals and pathogens
Mushroom compost	2.8	0.2	0.9	95	5-20	High lime content
Domestic refuse, composted	0.5	0.2	0.3	65	20-70	Contains miscellaneous objects
Brewery sludge, digested	1.5	0.9	0.3		5-20	Uncommon, low in nutrients
Peat	0.1	0.005	0.002	50	5-10	Variable, high C/N ²
Straw	0.5	0.1	0.8	95	5-20	High C/N
Sawdust	0.2	0.02	0.15	90	10-30 or 3-9 cm	High C/N
Woodchips	0.2	0.02	0.1	90	10-30 or 3-9 cm	High C/N
Bark	0.3	0.09	0.7	90	10-30 or 3-9 cm	High C/N
Lignite, ground	1	0	0	0		High C/N, high CEC ³

¹ O.M. = organic matter.² C/N = carbon:nitrogen ratio.³ CEC = cation exchange capacity.

In the Lower Swansea Valley study, Street and Goodman (1967) conducted *in situ* experiments to revegetate steel tips in 1963 and 1964. Treatments involved various combinations of NPK fertilizer and two sources of organic matter (either sewage sludge or a 3-year-old, screened domestic refuse) at different rates of application. By the second year of this study, the best growth of plant covers was obtained for plots receiving 4 or 6 in of sewage sludge with or without fertilizer. The ability of organic materials to provide nutrients over a longer time period than inorganic fertilizer salts, particularly for N, was noted by Richards et al (1993): "The application of organic nutrient sources can ensure a more consistent supply of available nitrogen than inorganic fertilisers."

To assess the long term benefits from applying fertilizer or organic amendments as a one time application at the start of the reclamation process, large scale seed trials were set up in 1965 in the Lower Swansea Valley in Wales (Street and Goodman, 1967; Gemmell, 1976). Organic treatments (sewage sludge and domestic refuse) were compared to inorganic fertilizer treatments where complete NPK fertilizer was added. The growth and dry matter production of different grass species were followed from 1966 to 1969 with the following conclusions by Gemmell (1976):

- 1) additions of sewage sludge, and to a lesser extent domestic refuse, improved initial establishment of a grass cover but had less effect over the long-term as nutrient availability from these amendments decreased; and

- 2) annual applications of fertilizers were essential to provide adequate availability of major plant nutrients and ensure long-term success of the grasses.

Sopper (1993) reviewed several references on the effects of municipal biosolids on physical properties of amended mine spoil material. He concluded that "Because sludge has a high organic matter content it increases the water holding capacity of the spoil, increases water infiltration capacity, decreases bulk density, increases saturation water percentages, and tends to reduce spoil surface temperatures and the number of water stable aggregates." Similar

improvements in soil physical properties have been observed in soils amended with biosolids (Clapp et al, 1986; Epstein, 1973; Lindsay and Logan, 1998).

Use of Legumes

Legumes such as clover (*Trifolium* spp.) can fix 100 kg or more of N per hectare per year, if provided with sufficient P, moisture and temperature for optimum growth. Legumes used in colliery spoil reclamation in England include perennial shrubs, such as lupin (*Lupinus arboreus*), gorse (*Ulex europaeus*, *U. gallii*), and broom (*Cytissus scoparius*), and trees such as black locust (*Robinia pseudoacacia*). Alder (*Alnus glutinosa*, *A. incana*, *A. cordata*), although not a legume, also fixes N and perhaps is the most important tree used in land reclamation in Britain (Richards et al, 1993).

Coppin and Bradshaw (1982) concluded that N accumulation and the build up of a N cycle is the most important factor in soil and vegetation development. If fertilizer is not added to help with this accumulation, the main source of N must be from biological fixation, i.e., legumes or other species which have N-fixing organisms (*Rhizobium* bacteria) on their roots. Once adequate N has been accumulated in the soil or surface materials by legumes and/or fertilizer, the N cycle becomes independent of external sources and mineralization of humus will supply sufficient N for continued plant growth. Therefore, legumes are included in almost every seed mix, and use of legumes in conjunction with grass seed mixtures of 2:1 to 4:1 (grass:legume) will provide N fixation and soil-building aspects necessary for more successful reclamation (Coppin and Bradshaw, 1982; Munshower, 1994).

Direct Tree Planting

Young trees (1-3 years old) are generally able to withstand the stress of replanting better than older, larger trees, and young trees are more adaptable to the harsh substrate or climate conditions of newly reclaimed sites. For this reason, transplanting 1-3 year-old trees that are approximately 1-3 feet tall is the best method for establishing trees at reclamation sites. (Richards et al, 1993). In addition, Coppin and Bradshaw (1982) indicated that bare-rooted

plants are most successful when transplanted during their dormant period, i.e., either in late autumn or early spring.

In some situations, tree plantings have been more successful than more traditional revegetation with grass covers. Cherfas (1992) evaluated reclaimed areas of Blaenavon, South Wales where coal mining was practiced, and the reclamation had been done by trucking in top soil that was mixed with the mine spoils. Although the grass bloomed quickly into a lush green cover, the reclamation had failed due to massive soil erosion which carried away the expensive imported topsoil.

Using reclamation techniques developed in Bulgaria, Cherfas (1992) started the Welsh project in 1990 by planting trees in an effort to improve the conditions of the spoil material. Slopes were planted with a variety of tree species, including the Locust tree, *Robinia pseudoacacia*, which is an early colonizing plant, probably because the Locust is a legume capable of N fixation. Later on the growth of the Locust declines and the birch, ash and pine species take over. Cherfas (1992) stated the Bulgarian approach had shown that roots of trees are strong and penetrating, erosion is prevented, and a favorable microhabitat is created where bacteria, fungi and earthworms thrive in the root zone.

Direct Seeding

Luke and Macpherson (1983) found that direct tree and shrub seeding on land reclamation sites can be considerably cheaper than planting and is well suited to "difficult" sites. Conventional reclamation methods where spoil materials are graded to a slope of 1:5 or less, covered with top soil, and then sown to grassland, has proven to be expensive. Broadcast seeding was tested as a method of sowing and found to work well. Seeds of several different shrubs and trees were spread by hand and then the seeds covered by a light tractor-drawn harrow or by hand raking, or alternatively, seeds were covered with a mulch of straw and bitumen. Spot seeding was also tested where seeds were covered by shale or a mulch of pulverized bark. Investigations in Scotland demonstrated that a wide variety of trees and shrubs could be

successfully established using direct seeding, and the growth of nitrogen-fixing shrubs was excellent on oil shale deposits.

Introduction of Native Plant Species

Industrial waste heaps in north-west England have become colonized by an interesting flora, however, the range of species was restricted and the vegetation had remained sparse, even after 100 years. Ash et al (1994) concluded this was due not only to the chemical and physical characteristics of the site which limited plant growth, but also to the difficulties of appropriate species immigrating into these sites from other locations. They hypothesized that introduction of native plant species could be the most effective improvement in the flora of these waste heaps. Therefore, experiments were undertaken to introduce a range of herbaceous species on four different sites with and without fertilizer.

All plant species introduced into the BF slag waste site (see Table 8) germinated, and all 21 out of the 41 species which established successfully, were species commonly found in calcareous grassland. *Gentianella amarella*, *Blackstonia perfoliata* and *Rhinanthus minor* (yellow rattle) proved particularly successful. Ash et al (1994) found that the plant species most likely to establish on a particular type of waste are those from communities of natural habitats with similar soil conditions, e.g., calcareous grassland species are likely to succeed on alkaline BF slag materials. In addition, a low rate of fertilizer was found to be beneficial for the growth and appearance of some species, and seed was the most successful introduction technique, having the advantages of easy handling and ready availability.

Table 8. Fate of introduced native plant species after 6 years on blast furnace slags
(Ash et al., 1994).

	Soil preferences ¹	Introduction method ²	Year of first flowering ³	Area (m ²) and mode of spread
Species spreading beyond original plots				
<i>Anthyllis vulneraria</i>	L C	PT	1	25
<i>Blackstonia perfoliata</i>	L C	S	3	>100 (seed)
<i>Briza media</i>	L C	T	3	0-1 (vegetative)
<i>Euphrasia nemorosa</i>	L C	T	1	4 (seed)
<i>Gentianella amarella</i>	L C	S	3	10 (seed)
<i>Leucanthemum vulgare</i>	L C	P	3	4 (seed)
<i>Linum catharticum</i>	L C	T	2	10 (seed)
<i>Rhinanthus minor</i>	L C	S	1	>100 (seed)
<i>Sanguisorba minor</i>	L C	PT	2	2 (seed)
Species growing, but not yet spreading				
<i>Carex flacca</i>	L C	T	3	
<i>C. nigra</i>	L C	T	4	
<i>Festuca ovina</i>	L CN	T	7	
<i>Festuca rubra</i> Dawson ⁴	M N	S	--	
<i>Festuca rubra</i> Ruby ⁴	M N	S	--	
<i>Filipendula vulgaris</i>	M N	T	--	
<i>Fragaria vesca</i>	M CN	P	3	
<i>Galium verum</i>	L C	T	--	
<i>Helianthemum nummularium</i>	L C	T	4	
<i>Koeleria macrantha</i>	L CN	T	4	
<i>Lotus corniculatus</i>	M CN	S	7	
<i>Primula veris</i>	M C	S	--f	
<i>Prunella vulgaris</i>	L CN	S	4	
<i>Sanguisorba officinalis</i>	M C	S	5	
<i>Ulex europaeus</i>	L CNA	T	--	
Species which died				
<i>Agrostemma githago</i>	M N	S	2	
<i>Agrostis stolonifera</i> Emerald ⁴	M N	S	3	
<i>Bellis perennis</i>	M N	T	1	
<i>Bromus sterilis</i>	M N	S	3	
<i>Hieracium pilosella</i>	M CN	T	2	
<i>Hordeum murinum</i>	M CN	S	2	
<i>Leontodon hispidus</i>	M N	T	3	
<i>Lotus corniculatus</i> ⁴	M CN	T	3	
<i>Papaver dubium</i>	M CN	S	1	
<i>Poa pratensis</i> Aquila ⁴	M CN	S	3	
<i>Ranunculus bulbosus</i>	M N	T	2	
<i>Sedum acre</i>	L N	T	2	
<i>Silene gallica</i>	L N	S	2	
<i>Taraxacum officinale</i>	M N	T	1	
<i>Thymus praecox</i>	L C	T	3	
<i>Torilis japonica</i>	M N	S	3	
<i>Trifolium repens</i> S100 ⁴	M N	S	4	

¹ Fertility: L=low; M=medium, H=high; then pH: C=calcareous, N=neutral, A=acidic.

² P=transplants, S=seed, T=as a turf; where two methods are indicated, both were successful.

³ Fertilizer had no significant effect, except where marked f, in which case the species died without fertilizer.

⁴ Commercial cultivar.

Vegetation Selection and Management

The preceding subsection discussed the importance of selecting plant species for a reclamation site that do well in natural habitats that have similar growing conditions as the site to be reclaimed. Vegetation selection should also be based on other factors such as future land use, climate and possible sequencing of plant types to accomplish the type of final vegetation that is desired.

The most successful revegetation schemes are those where the establishment of vegetation matches the needs of the intended land use, so a clear definition of that land use will enable the appropriate vegetation to be selected, established and maintained. Figure 7, taken from Richards et al (1993), summarizes vegetation types that are essential or possible for new uses of reclaimed lands.

Coppin and Bradshaw (1982) summarized several species selection criteria, as shown in Table 9, and listed the trees, shrubs, grasses and legumes most widely used for reclamation. The tolerance of each species to climate and substrate, and the growth habits exhibited by different ecotypes, varieties, and cultivars within one species, can be sufficient to govern the success or failure of revegetation. Munshower (1994) also suggested that "seed mixes should be tailored to the soils, climate, environmental setting, proposed land use, and plant community desired on the site". He listed the genus and species of plants commonly used in rehabilitation programs in several appendix tables for several geographic areas, i.e., Eastern, Midwestern, Northern Great Plains, and Southwestern. The species of grasses, forbs (legumes and other non-grass plants), shrubs, and trees used in Midwestern revegetation programs that were listed by Munshower (1994) are shown in Table 10.

The most commonly used procedure for revegetation of disturbed land has been to establish the vegetation immediately after earthworks have been completed which can entail considerable efforts to modify the substrates to suit the vegetation. In contrast, a pioneer crop of short duration could be established as part of a soil improvement program before the final long-term vegetation is established. For example, Luke and Macpherson (1983) used a wide range of trees and shrubs for direct sowing to reclaim coal and oil shale tips in Scotland. The seed mixture formulated was comprised of several components which included shrubs, "pioneer" trees

New use	Vegetation type	Individual trees	Forest tree species	Native tree species	Mixed woodland	Shrubs	Pasture grasses	Mown grass	Rough grass	Wildflower mixture	Wetland species	Aquatic species
Productive grazing							☒					
Marginal grazing							○		○			
Commercial forestry			☒									
Marginal forestry			○	○	○							
Sport								☒	○			
Caravan and campsites		○		○	○	○			○			
Car parks		○				○			○			
Picnic sites		○		○	○	○		○	○	○		
Walking		○	○	○	○	○	○	○	○	○		
Ball games								○	○			
Childrens play		○			○	○		○	○			
Wildlife		○	○	○	○	○	○	○	○	○	○	○
Landscape improvement		○			○	○				○		



: Essential



: Possible

Figure 7. Vegetation types for new uses of reclaimed lands (p. 478, Richards et al, 1993).

Figure 7

Table 9. Summary of species selection criteria¹ (p. 66, Coppin and Bradshaw, 1982).

Criteria		Ground Cover				Trees and Shrubs				
		Agricultural	Sports & Amenity	Wild	Under Trees	Erosion Control	Forestry	Amenity	Woodland (wild)	Screening
Climate:	Drought resistance		X	X	X		X		X	
	Frost hardness		X	X	X		X	X	X	X
	Exposure (esp. coastal)						X		X	
	Cold (short growing season)	X	X	X	X		X		X	
Land Use:	Wildlife value			X	X			X	X	
	Nativeness			X					X	
	Palatability	X								
	Productivity, high or low	X	X	X	X		X			
	Screening value							X	X	X
	Timber quality								(X)	
Soil:	pH	X	X	X	X	X	X	X	X	X
	Fertility	X	X	X	X	(X)	X	X	X	X
	Texture (water holding capacity)	X	X	X	X		X	X	X	X
	Soil depth						X	X	X	X
	Moisture availability	X	X	X	X	X	X	X	X	X
	Flooding tolerance							(X)	(X)	
	Pollution tolerance							X		X
Role:	Pioneer/Nurse				X	X	X		X	X
	Climax			X					X	
	Soil builder (N-fixation)	X	X	X	X	X	X	X	X	
	Quick establishment		X		X	X				X
Ecotypes:	Cultivar	X	X	X	X					
	Provenance						X	X	X	
Plant Habit:	Height			X	X			X		X
	Growth rate	X	X	X	X	X	X			X
	Rhizomes/stolons		X	X	X	X				
	Suckering								X	X
	Habit		X	X	X			X	X	X
	Rooting depth					X		X		
	Competitiveness			X	X				X	
	Disease resistance	X	X				X	X		

¹ X in the columns means the particular criteria is an important factor and (X) indicates the criteria is important in some cases.

Table 10. Plant species used in Midwestern revegetation programs (p. 217, Munshower, 1994).

Scientific Name	Common Name	Scientific Name	Common Name	Scientific Name	Common Name
<u>Grasses¹</u>		<u>Forbs¹ (legumes and other non-grass plants)</u>		<u>Trees¹ (continued)</u>	
<i>Agrostis alba</i> L.	Redtop	<i>Amorpha canescens</i> Pursh	Leadplant	<i>Ainus glutinosa</i> (L.) Gaertn.	European black alder
<i>Andropogon gerardi</i> Vitman	Big bluestem	<i>Astragalus cicer</i> L. ⁴	Cicer milkvetch	<i>Betula nigra</i> L.	River birch
<i>Bromus inermis</i> Leyss.	Smooth brome grass	<i>Coronilla varia</i> L.	Crownvetch	<i>Carya</i> spp. Nutt.	Hickory
<i>Cynodon dactylon</i> (L.) Pers.	Bermudagrass	<i>Helianthus annuus</i> L.	Annual sunflower	<i>C. illinoensis</i> (Wang.) Koch	Pecan
<i>Dactylis glomerata</i> L.	Orchardgrass	<i>H. maximiliani</i> Schrad.	Maximilian sunflower	<i>Celtis occidentalis</i> L.	Hackberry
<i>Deschampsia caespitosa</i> (L.) Beauv.	Tufted hairgrass	<i>Lespedeza cuneata</i> (Dum.Cours.) G. Don	Sericea lespedeza	<i>Cornus florida</i> L.	Flowering dogwood
<i>Echinochloa crusgalli</i> (L.) Beauv.	Barnyard grass	<i>L. stipulacea</i> Maxim? ²	Korean lespedeza	<i>Elaeagnus angustifolia</i> L.	Russian olive
<i>E. crusgalli</i> var. <i>frumentacea</i> (Link) W.F. Wright	Japanese millet	<i>L. striata</i> (Thunb.) Hook. & Arn. ²	Common & Kobe lespedeza	<i>Fraxinus americana</i> L.	White ash
<i>Eragrostis curvula</i> (Schrad.) Nees	Weeping lovegrass	<i>Lotus corniculatus</i> L.	Birdsfoot trefoil	<i>F. pennsylvanica</i> Marsh.	Green ash
<i>E. trichodes</i> (Nutt.) Wood	Sand lovegrass	<i>Medicago sativa</i> L.	Alfalfa	<i>Juglans nigra</i> L.	Black walnut
<i>Festuca arundinacea</i> Schreb.	Kentucky 31 Tall fescue	<i>Melilotus alba</i> Medic.	White sweetclover	<i>Juniperus virginiana</i> L.	Eastern red cedar
<i>F. rubra</i> L.	Red fescue	<i>M. officinalis</i> (L.) Lam.	Yellow sweetclover	<i>Liquidambar styraciflua</i> L.	Sweetgum
<i>Lolium multiflorum</i> Lam.	Italian ryegrass	<i>Onobrychis viciaefolia</i> Scop.	Sainfoin	<i>Liriodendron tulipifera</i> L.	Yellow poplar
<i>L. perenne</i> L.	Perennial ryegrass	<i>Trifolium hybridum</i> L.	Alsike clover	<i>Maclura pomifera</i> (Raf.) Schneid.	Osage-orange
<i>Panicum clandestinum</i> L.	Deertongue	<i>T. pratense</i> L.	Red clover	<i>Pinus banksiana</i> Lamb.	Jack pine
<i>P. virgatum</i> L.	Switchgrass	<i>T. repens</i> L.	Ladino or white clover	<i>P. echinata</i> Mill.	Shortleaf pine
<i>Pennisetum americanum</i> (L.) K. Schum? ²	Pearl millet	<i>Vicia villosa</i> Roth	Hairy vetch	<i>P. nigra</i> Arnold	Austrian pine
<i>Phalaris arundinacea</i> L.	Reed canarygrass			<i>P. resinosa</i> Ait.	Red pine
<i>Phleum pratense</i> L.	Timothy	<u>Shrubs¹</u>		<i>P. rigida</i> Mill.	Pitch pine
<i>Poa compressa</i> L.	Canada bluegrass	<i>Caragana arborescens</i> Lam.	Siberian peashrub	<i>P. sirobus</i> L.	Eastern white pine
<i>P. pratensis</i> L.	Kentucky bluegrass	<i>Cornus amomum</i> Mill	Silky dogwood	<i>P. sylvestris</i> L.	Scotch pine
<i>Schizachyrium scoparium</i> (Michx.) Nash ² (<i>Andropogon scoparius</i> Michx. of Hitchcock 1950)	Little bluestem	<i>C. racemosa</i> Lam.	Gray dogwood	<i>P. taeda</i> L.	Loblolly pine
<i>Setaria italica</i> (L.) Beauv.	Foxtail millet	<i>C. stolonifera</i> Michx.	Red-osier dogwood	<i>P. virginiana</i> Mill. ²	Virginia pine
<i>Sorghastrum nutans</i> (L.) Nash	Indiangrass	<i>Crataegus</i> spp. L.	Hawthorn	<i>Platanus occidentalis</i> L.	American sycamore
<i>Sorghum sudanense</i> (Piper) Stapf.	Sudangrass	<i>Elaeagnus umbellata</i> Thunb.	Autumn olive	<i>Populus deltoides</i> Marsh.	Eastern cottonwood
<i>S. vulgar</i> Pers. including <i>S. bicolor</i> (L.) Moech.	Sorghum	<i>Lespedeza bicolor</i> Turcz.	Shrub lespedeza	<i>Prunus serotina</i> Ehrh.	Black cherry
		<i>Rhus copallina</i> L.	Shining sumac	<i>Quercus acutissima</i> Carruth. ²	Sawtooth oak
		<i>Robinia hispida</i> L.	Bristly locust	<i>Q. alba</i> L.	White oak
		<u>Trees¹</u>		<i>Q. imbricaria</i> Michx.	Shingle oak
		<i>Acer rubrum</i> L.	Red maple	<i>Q. macrocarpa</i> Michx.	Bur Oak
		<i>A. saccharinum</i> L.	Silver maple	<i>Q. pallustris</i> Muenchh.	Pin oak
		<i>A. saccharum</i> Marsh.	Sugar maple	<i>Q. prinus</i> L.	Chestnut oak
		<i>Ailanthus altissima</i> (Mill.) Swingle	Tree-of-heaven	<i>Q. rubra</i> L.	Northern red oak
				<i>Robinia pseudoacacia</i> L.	Black locust
				<i>Taxodium distichum</i> (L.) Rich.	Bald cypress

¹ Nomenclature from Hitchcock, 1950 except as noted.

² Nomenclature from Bailey and Bailey, 1976.

³ Nomenclature from Mohlenbrock, 1986 except as noted.⁴ Nomenclature from Hitchcock and Cronquist, 1973.

and slow growing trees, and each component was designed to be a different phase for the sequential development of vegetation.

The first phase was dominated by shrubs like fast-growing nitrogen fixers such as broom (*Cytissus scoparius* L. Link), gorse (*Ulex europaeus* L.), and lupins (*Lupinus* spp.) and slower growing shrubs, like blackthorn (*Prunus spinosa*) and wild roses (*Rosa* spp), that contributed to the cover in the third and fourth years. As the shrub cover developed, the second phase commences with the emergence of pioneer trees, such as alders (*Alnus* spp) and birch (*Betula* spp.). The third phase will be initiated as the slower growing trees, like ash (*Fraxinus excelsior*) and Oak (*Quercus robur* L. and *Q. petraea*), emerge between the pioneer trees.

When the objective of the reclamation is to create naturalistic habitats or to conserve wildlife, using only local ecotypes can be particularly important. Where natural colonization of spoil material has already occurred, the existing plants may be better adapted to the site conditions than other commercially available plant materials. For example, Bush (1999) and Bush and Koch (2000) found that continued succession of native warm season grasses established on a slag refuse area in the IIUIA enhanced wildlife habitats and improved the grass cover and aesthetic value of the site. Therefore, the propagation of colonizing plants (either by seed or vegetative means) should be considered. (Richards et al, 1993)

Finally, as a general rule plants which can tolerate poor site conditions do not produce rapid growth or high crop yields. The use of tolerant species is likely to restrict the range of vegetation functions available, since species which possess tolerance of extreme conditions are generally specialized in their adaptation. However, this approach will be more suitable for revegetation schemes intended to improve the landscape and to provide wildlife habitats or low-key informal recreation facilities, rather than for schemes intended to provide highly productive agriculture or forestry uses of the site. (Richards et al, 1993)

Summary

Now that iron and steel slag site conditions that must be considered for reclamation have been identified, and various reclamation techniques that can be used have been discussed, we are ready to focus more specifically on how municipal biosolids might be used for reclamation in the IIUIA. Because the literature contains very few articles and studies specifically on using biosolids for slag disposal site reclamation, the next section discusses experiences and knowledge gained from a wide variety of reclamation projects where biosolids have been used for other disturbed lands.

Section IV. Reclamation of Disturbed or Contaminated Lands and Slag Disposal Sites Utilizing Municipal Biosolids

Introduction

This section will cover the use of municipal biosolids (i.e., sewage sludge) for reclamation of mine spoils, acid mine lands, alkaline soils, and other disturbed lands. The approaches and methods of reclamation used in these various disturbed land areas can be easily adapted to alkaline slag disposal site conditions, especially when using municipal biosolids and compost as surface amendments for reclamation. At the end of this section is a discussion of how biosolids might be used in the IIUIA for reclamation of slag disposal sites.

Use of Municipal Biosolids (Sewage Sludge) for Reclamation of Acidic Mine Lands, Mine Spoils, Alkaline Soils, and Metal-Contaminated Sites

While many references were found regarding the use of biosolids on different types of disturbed land, particularly on coal mine lands, no references were found that specifically reported on utilizing biosolids to amend iron and steelmaking slags. Bastian et al (1982) talked in general about various disturbed land areas where biosolids might be utilized that included: surface mines, mine tailings, borrow pits, and quarries; clear-cut, burned and low production forest lands; and dredge spoils, fly ash, highway corridors, rights-of-way, construction sites, and other disturbed lands.

Coppin and Bradshaw (1982) discussed the establishment of vegetation in quarries and open pit non-metal mines, and Munshower (1994) addressed revegetation on disturbed lands commonly found in the Western United States that included western coal mining, metal mine wastes, western phosphate mining, western bentonite mining, sand and gravel pits, highway shoulders, ash disposal ponds, drill pads, and abandoned mine lands. Proceedings of a symposium held in 1976 at Wooster, OH (Schaller and Sutton, 1978) contains chapters that discuss drastically disturbed lands, including mostly mine lands and wastes, but also metal mine wastes, mine tailings, phosphate mines, oil shale, stone quarries, sand and gravel pits, borrow pits, highway corridors, and dredged materials. Proceedings of another symposium held in 1980 at Pittsburgh, PA (Sopper et al, 1982) again mostly focused on coal mining land reclamation with

municipal wastewater and sludge, but several chapters discussed gravel spoils, zinc smelter polluted soils, iron ore overburden, iron ore tailings, taconite tailings, and pyrite mine spoils.

Probably the most comprehensive listing of land reclamation projects utilizing municipal biosolids was done by Sopper (1993), which updated his initial effort to list such projects (Sopper and Seaker, 1983). The different types of disturbed land for which he cited references are shown in Table 11. The reader will not find slag sites among the various types of disturbed lands listed where biosolids have been used.

Table 11. Types of disturbed land reclamation projects utilizing municipal biosolids (from p. 14-21, Sopper, 1993).

Acid strip mine spoil	Calcareous strip mine spoil	Abandoned pyrite mine
Deep mine anthracite refuse	Coal refuse	Sandstone/siltstone mine soil
Zinc smelter site	Reconstructed prime farmland	Non acid-forming overburden
Coal mine spoil	Acidic coal refuse	Overburden mine soil
Copper mine spoil	Canal dredge material	Iron ore tailings
Borrow pit	Gravel spoils	Taconite tailings
Kaolin spoil	Degraded, semiarid grassland	Colliery coal mine waste
Marginal land	Zinc smelter surroundings	Opencast coal mine site
Strip mine spoil	Lignite overburden	

While specific studies could not be found on amending slag deposits with biosolids, the authors are confident that biosolids and other organic materials can modify the alkaline pH of slags, provide essential plant nutrients, particularly N, and improve the physical conditions of slag deposits to make them a better growing media for successful revegetation. Various individual studies reported below provide evidence that high rates of municipal biosolids can be effective in correcting the major problems or limitations associated with disturbed lands, particularly in alkaline soils and other alkaline spoil materials like BF slags.

Acidic Strip Mine Spoils on the Palzo Tract (Illinois)

Stucky et al (1980) conducted a study to investigate several critical factors necessary to develop guidelines for applying large quantities of sewage sludge to acidic strip-mine spoils. The Palzo tract, 78 ha of land devoid of vegetation and located in the Shawnee National Forest in

Southern Illinois was acquired by the United States Department of Agriculture Forest Service. This site contained mine spoils from strip-mining operations with a pH of approximately 3.0. Sixteen combinations of different forages were planted on seven field sites following applications of 448 to 997 dry mt/acre of a liquid, anaerobically-digested sewage sludge from the Metropolitan Sanitary District of Greater Chicago (the District's name is now the Metropolitan Water Reclamation District of Greater Chicago, or MWRDGC).

Sludge applications increased the mean pH of approximately 3.0 to 4.4 - 5.5, and a high correlation was observed between this pH increase and an associated increase in the growth and percent cover of grasses. After three growing seasons, the authors concluded that reed canarygrass (*Phalaris arundinacea* L.) and switchgrass (*Panicum vergatum* L.) were the most successful perennial grasses, while orchardgrass (*Dactylis glomerata* L.) ranked second and tall fescue (*Festuca arundinacea* Schreb.) ranked third. Although these grasses were established in the presence of potentially toxic quantities of Cd, Cu, Mn, Ni, Pb, and Zn, accumulation of all elements in plant tops, after three growing seasons, were within ranges considered not to be harmful or phytotoxic. The decrease in uptake of these metals from year one to the third growing season could also be attributed to the increase in soil pH caused by the sewage sludge applications.

Coal Refuse Studies at Fulton County (Illinois)

Sewage sludge has also been used as an amendment to reclaim coal refuse material (which tends to be acid-forming) on a site in Fulton County, IL owned by the MWRDGC (Pietz et al, 1989a,b). Sludge was applied at a rate of 542 dry mt/ha over three years with either lime or gypsum or both. The rate of gypsum was 112 mt/ha and for lime was 89.6 mt/ha on a dry weight basis.

The sewage sludge applied with lime was more effective for maintaining the refuse pH and reducing water-soluble Al and Fe and total acidity, when both materials were used together than when lime or sludge was used separately. Profile sampling at 0 to 100 cm at the beginning of the experiment in 1976, and at the end of the experiment in 1981, showed a decline in pH and an increase in the water soluble Al and Fe and total acidity from the sewage sludge plus gypsum and the gypsum alone treatments compared to untreated coal refuse (Pietz et al, 1989a).

However, the final pH's in 1981 for lime (2.9), sludge (3.3) and sludge+lime (4.9) treatments were still higher than in the untreated coal refuse (2.6), so the effectiveness of these treatments in reducing total acidity was sludge+lime > sludge > lime.

Pietz et al (1989b) seeded plots with a mixture of bromegrass (*Bromus inermis* Leyss.), tall fescue (*Festuca arundinacea* L.), and alfalfa (*Medicago sativa* L.). The percent plant cover and dry matter yields of this forage mixture increased each year from 1978 to 1980 in treatments receiving lime, sewage sludge, or both amendments. The better survival of bromegrass and tall fescue, as compared to alfalfa, and the increased crop yields generally were associated with the observed increase in the pH of the strongly-acid coal refuse. Grasses usually will tolerate acidic pH's (<6.0) better than legumes, like alfalfa.

Long-Term Reclamation of Pyritic Mine Spoils

Abandoned mine lands containing pyritic spoil may become toxic due to production of sulfuric acid and subsequent high levels of heavy metals. A field study in Ohio compared the long-term effectiveness of municipal biosolids (224 dry mt/ha), power plant fly ash (448 mt/ha), papermill sludge composted with wood bark (67,90 and 112 dry mt/ha), and limed topsoil in maintaining a grass-legume vegetation (Pichtel et al, 1994). Amendments were incorporated into the top four inches of spoil (initially pH 3.4) whereas eight inches of topsoil were placed on top of the spoil.

The limed topsoil and biosolids maintained the overall highest yields and greatest percent vegetative cover. The pH and plant-available nutrients increased over the 10-year time period and were higher than in the control (unamended spoil) but did not reach the same levels observed in the limed topsoil, as shown below.

	Changes from 1979 - 1989				
	pH	Bray P1	K	Ca	Mg
			mg/kg		
Control	3.4 → 3.8	19 → 22	53 → 51	868 → 566	108 → 184
Biosolids	5.4 → 6.4	48 → 63	53 → 75	2680 → 3140	146 → 298
Topsoil	7.3 → 7.0	14 → 11	151 → 144	4000 → 3930	379 → 365

The authors concluded that the biosolids amendment as a topsoil substitute was roughly equivalent to limed topsoil for successful long-term reclamation of toxic mine spoil for pasture or forage crops.

Acidic Bituminous and Anthracite Spoil Sites (Pennsylvania)

Sopper and Kerr (1982) treated several plot areas at a bituminous strip mine site (having a pH of 3.8) and an anthracite refuse bank (having a pH of 3.6) with several types of municipal sludge: 1) liquid digested (applied at rates of 7 and 11 dry mt/ha); 2) dewatered by centrifuge (applied at rates of 90 and 184 dry mt/ha), vacuum filter (applied at rates of 80 and 108 dry mt/ha), and sand-bed drying (applied at 90 and 184 dry mt/ha); 3) heat-dried (applied at 0, 40, 76, and 148 dry mt/ha); 4) dewatered that was composted with wood chips (applied at 202 dry mt/ha); and 5) a compost-sludge cake mix (applied at 134 dry mt/ha). Some of the plot areas received lime prior to sludge application, and then all plot areas were broadcast seeded with a mixture of grasses and legumes.

The highest dewatered sludge application of 184 mt/ha in combination with lime continually increased the spoil pH at the 0 to 15 cm depth during the 2½ year period following sludge application, from pH 6.2 at the end of the first growing season to pH 7.3 at the end of the third growing season. Data collected during the 3-year period showed that sludge applications ameliorated the harsh site conditions and resulted in a quick vegetative cover that completely stabilized the demonstration sites. Although sludge applications increased some trace metal concentrations in the vegetation, all of the concentrations were below plant tolerance levels and no phytotoxicity was observed. A groundwater monitoring system installed at each demonstration site showed that sludge applications had no significant adverse effect on the chemical and bacteriological quality of groundwater and soil percolate water.

Acidic Brown Coal Spoils (Denmark)

Olesen et al (1984) applied sewage sludge (0, 40, and 120 mt/ha dry matter) and lime (4 mt/ha) to an acid and nutrient deficient soil of a brown coal pit in Denmark with the goal of establishing vegetation. Pine (*Pinus silvestris*) trees were planted and a mixture of mainly fescue grasses was sown. The pH increased from 3.3 to 4.1 after six years due to the application of the sewage sludge at 120 mt/ha, and to a higher pH of 5.1 when 4 mt/ha lime were also applied. The

120 mt/ha sludge treatment caused one-half of the trees to die, whereas only liming of the control plots allowed all trees to survive. The detrimental effect of the sludge on tree growth was thought to be due to the high Zn additions resulting from the high Zn concentration (9,600 mg/kg) present in the sludge. This added Zn would be highly bioavailable under the strongly-acid pH conditions in the sludge-amended spoil, so the increase in pH caused by liming, reduced the negative effect of the Zn added by sludge treatments. However, sludge additions had a positive effect on grass growth due to improved N release from sludge mineralization, the improved plant-available P status, and probably a greater tolerance of fescue grasses to high plant-available Zn concentrations compared to pine seedlings.

Reclamation of Mine Spoils in the Central Appalachians

Municipal biosolids were utilized for field-oriented research and demonstration at the Powell River Project Research Area in Wise County, VA (Daniels and Haering, 1994). Overburden and mine soils in this area generally nonacidic. Experiments began with biosolids as a mine spoil amendment to reconstruct topsoil substitutes from hard rock overburden. Later a “mine mix” of biosolids and composted wood chips were used to reclaim a recently regraded surface mine. The objective of this experiment was to monitor the effect of biosolids on forage quality, soil properties and long-term surface and groundwater quality.

In the early study (Moss et al, 1989), lime-treated biosolids at rates of 22, 56, 112 and 224 dry mt/ha were compared to fertilizer and fertilizer+sawdust versus a limed and fertilized topsoil. The fertilizer+sawdust and the 22 & 56 mt/ha biosolids treatments increased the stem volumes of 3-year pine seedlings by five times and three times, respectively, compared to the topsoil. At the 112 and 224 mt/ha biosolids treatments, increased seedling mortality and decreased growth were observed due to Mn deficiency and probably high soluble salts.

In the later study (Daniels and Haering, 1994), rates of 92, 184, 368 and 552 dry mt/ha mine mix (equivalent to 25, 50, 100 and 150 dry mt/ha biosolids cake) were used and a mixed grass-legume pasture was seeded. The mine mix increased average pH from 5.6 to 6.5 and increased soil nutrient (P, K, Ca, Mg) levels, carbon (organic matter) content, CEC & exchangeable bases, and extractable Zn but not extractable Mn. Forage yields for biosolids treatments started out comparable to the fertilized control but after four years, biosolids-treated

plots supported a much more vigorous and diverse vegetative stand. Plant tissue had increased Zn and Cu concentrations with increasing biosolids rates (though well below phytotoxic levels), while Cd, Cr, Fe, Pb, Mn, and Ni levels showed no consistent effect due to biosolids treatments. Nitrate N, Cd, Cu, Cr, Pb and Ni levels in sediment ponds and groundwater from discharge points showed no evidence of being influenced by the mine mix applications.

Biosolids vs. Fertilizer Rates on Coal Mine Spoil (Colorado)

Topper and Sabey (1986) evaluated the use of a liquid, aerobically-digested municipal sewage sludge as an amendment for revegetation of a Colorado coal mine spoil as a function of application rate. Plant growth responses to sewage sludge additions were compared to inorganic N and P fertilizer treatments on a grass pasture mixture. Sewage sludge was applied at 0, 14, 28, 55, and 83 dry mt/ha to compare against inorganic N fertilizer applied at 0, 40, 80, 120, and 160 kg N/ha (plus 160 kg P/ha applied at each rate) and to also compare against inorganic P fertilizer applied at 0, 40, 80, 120, and 160 kg P/ha (plus 160 kg N/ha applied at each rate).

Sewage sludge rates less than 83 mt/ha yielded greater plant growth than any of the inorganic N and P fertilizer treatments for two growing seasons. However, 14 mt/ha added adequate plant-available N and P to obtain total N and P concentrations in seeded grass tissue that were equivalent to those from the highest inorganic fertilizer treatments. The highest sewage sludge rate (83 mt/ha) yielded less than the lower sludge rates in the second growing season, probably due to increased soluble salt concentrations. Sludge-amended spoil pH's decreased from 7.1 to 6.2 and organic carbon increased from 5.7% to 9.4%, as sludge rates increased from 0 to 83 mt/ha.

Reclaimed Pasture Study on Colliery Spoil (United Kingdom)

Michael et al (1991) conducted a 2-year field experiment to assess the effectiveness of fertilizer and surface applied or injected liquid digested sewage sludge for increasing yields of a reclaimed pasture located on colliery spoil¹¹ having a pH of 7.5. The most effective treatments for grass production in both the first and second years were large amounts of fertilizer N (300 kg/ha) with 75-150 kg/ha fertilizer P, or the surface application of sewage sludge at a rate of 11 mt/ha dry solids with 75 kg/ha fertilizer K. Surface applications of sewage sludge were found to

¹¹ Colliery spoil is waste material produced during coal mining (Richards et al, 1993).

be an excellent method of maintaining the yields of grass swards established on reclaimed land. These researchers concluded that application to the surface was preferable to injecting sewage sludge into the soil, because injection placed sludge nutrients too deep to be available for shallow-rooted grasses.

Calcareous Strip Mine Spoils in Fulton County (Illinois)

Peterson et al (1982) reported that in 1968, the MWRDGC purchased 6289 hectares of calcareous, strip mine spoils in Fulton County, IL for the purpose of land reclamation. Digested sewage sludge was applied from 1972 through 1979 to fields situated on non-mined and mine-spoil areas at total accumulative rates of 217 to 362 dry mt/ha and 235 to 453 dry mt/ha, respectively. Crops grown included corn, soybeans and wheat.

Sewage sludge application resulted in a decrease in soil pH and an increase in soil organic C content, available mineral N, available P, and exchangeable K in the mine spoils. On the calcareous mine spoil fields, the pH dropped from an initial range of 6.8 - 8.1 to a range of 5.9 - 6.8 after 6 years of sludge application. The yields of crops were variable and largely depended on availability of moisture and essential plant nutrients, especially when crops were grown immediately after land leveling. In general, the Fulton County calcareous, strip mine spoils were improved substantially by the addition of liquid digested sewage sludge, based on the positive changes in the soil fertility status. (Peterson et al, 1982)

A one-time, relatively high, sludge loading rate study was also established on calcareous, strip-mined spoil banks in Fulton County, IL (Hinesly et al, 1982). Application rates of digested sewage sludge were 0, 224, 448, and 896 mt/ha of dry sludge solids. Conclusions from this study (see Table 12 for summarized data) were:

- 1) sludge treatments decreased soil pH from 7.5 to 6.0 and increased organic carbon from 2.4% to 6.9%, as sludge rates increased;
- 2) the percent of water stable aggregates greater than 0.25 mm in diameter and the percent water retained at 15 bar matrix tension (indicative of available water-holding capacity) increased as sludge rates increased;

Table 12. Changes in soil properties and grain yields for sludge-amended mine spoils (data summarized from Hinesly et al, 1982).

Soil Property or Grain Yield	Sludge Application Rate (mt/ha)			
	0	224	448	896
Soil pH	7.5	7.0	6.3	6.0
Organic carbon (%)	2.4	2.8	4.7	6.9
Water-stable aggregates (%)	12	23	34.3	42
Water retained at 15 bar (%)	13	15	17	22
Conductivity (mmho/cm)	2.2	3.5	5.5	6.6
Corn grain yields (mt/ha)	3.0	6.8	6.2	3.7
Rye grain yields (mt/ha)	2.5	2.4	2.4	2.3

3) the electrical conductivity increased from 2.2 to 6.6 mmho/cm for the highest sludge rate, indicating that soluble salt levels were high enough to cause a 25 to 50% reduction in corn yields; therefore, soluble salts appeared to be the major factor causing the decrease in corn grain yields on sludge-amended mine spoils at loading rates which exceeded 224 mt/ha; and

4) significantly higher concentrations of N, P, Ca, Mg, Mn, Zn, Cd, and Ni were found in plant leaves, and significantly higher N, P, Mg, Fe, Mn, Zn, Cd, and Ni in corn grain, when comparing crops grown on untreated mine spoil versus crops grown on sludge-amended mine spoils.

Selenium Bioavailability in Alkaline Mine Spoil (Wyoming)

Johnson et al (1994) conducted a greenhouse pot study to determine if sewage sludge would enhance or decrease Se uptake by sweet clover (*Melilotus officinalis*) and thick spike wheatgrass (*Agropyron dasystachyum*) grown on alkaline coal mine backfill material (i.e., overburden material that has been displaced). The addition of sewage sludge at rates of 25, 50 and 100 dry mt/ha significantly decreased plant Se levels, even though total Se analyses showed that sewage sludge applications increased Se levels in the soil. Therefore, the sludge Se was not found to be in a plant-available form. This conclusion was supported by the fact that AB-DTPA

extractable¹² Se concentrations decreased with increasing sludge applications. Higher sludge applications also influenced Se bioavailability in soils by causing soil pH's to decrease, which results in Se being less available for plant uptake.

Use of Sewage Sludge to Reclaim Alkaline Soils

Fresquez et al (1990a,b) applied dried, anaerobically-digested sewage sludge on a degraded, semiarid grassland in New Mexico that was classified as a snakeweed/blue grama-galleta (*Gutierrezia sarothrae/Bouteloua gracilis-Hilaria jamesii*) plant community and having a Little silty clay loam (fine-silty, mixed mesic Ustollic Camborthid) soil. The application of the sewage sludge significantly increased soil organic matter and plant-available N, P and K, as well as other essential plant nutrients.

After four growing seasons, the levels of DTPA-extractable¹² micronutrients (i.e., Cu, Fe, Mn and Zn) increased linearly with the application of 22.5, 45 and 90 dry mt/ha sludge. The higher micronutrient levels were probably due to the additions of these micronutrients present in the sludge and also to the significant decrease in soil pH from 7.9 to 7.0, which is a more favorable soil pH for increased solubility and bioavailability of these elements. Although plant density, species richness, and diversity decreased with increasing sludge rates, total plant foliar cover and herbaceous yields generally increased, especially for the blue grama. (Fresquez et al, 1990a,b)

Reclamation of Metal Contaminated Sites

Dried biosolids were applied to severely eroded hilltop sites in the Tennessee Copper Basin that were devoid of vegetation (Berry, 1982). The Tennessee Copper Basin is an area where all natural vegetation was killed by air pollution from primitive Cu ore processing methods in the mid-to-late-1800's. Obstacles to reforestation of the area are lack of soil nutrients and organic matter, lack of soil moisture during dry periods and dessication of trees by wind.

After leveling the eroded areas, broadcasted applications of 34 dry mt/ha or 896 kg/ha (800 lb/ac) of 10-10-10 fertilizer plus 1420 kg/ha lime were incorporated into the top 10 cm by

¹² The AB-DTPA and DTPA extractants are soil tests used to estimate plant nutrient availability in soils for crop uptake.

double disking. After four years, growth of loblolly pine, shortleaf pine and Virginia pine was significantly increased by biosolids compared to the fertilized treatment. Followup evaluation a few years later (McNab and Berry, 1985) showed that estimated aboveground biomass in these three pine species was more than three times greater on sludge plots than on fertilizer plots. This increase was attributed to the higher fertility and sustained nutrient availability of the biosolids treatment.

In Poland, toxic Zn and Pb smelter wastes were stabilized with calcium carbonate (CaCO_3), calcium oxide (CaO) and 0, 150 and 300 mt/ha biosolids (Daniels et al, 1998). Amendments were incorporated with a chisel plow to a depth of 15 cm. Higher amounts of CaO were used for the Doerschel smelter wastes due to its acidity (pH 3.6) than for the Welz smelter wastes which had a pH of 6.9. Lime was added to reduce water soluble metals in these wastes, even though the Welz waste was near neutral pH. The chemical properties of the two wastes before (1994) and after (1995) amendment with biosolids plus lime were as follows:

Smelter Waste		Water-Soluble Concentrations			pH	EC
		Zn	Cd	Pb		
		mg/kg				-- dS/m --
Welz	Before	343	17.6	1.8	7.0	7.3
	After	279	17.7	1.1	7.2	3.5
Doerschel	Before	1,670	108	5.4	5.8	16
	After	983	57.4	2.9	6.0	9.0

Vegetation (metal and salt tolerant grasses) was successfully established on 85% of the Welz material. Vegetation failed on the Doerschel material, so this area was retreated with a 15 cm cap of waste lime ($\text{CaO} + \text{CaCO}_3$) plus 300 mt/ha biosolids. This second treatment resulted in 75 - 80% ground cover. Soluble Zn and Cd and high salinity were considered the most limiting factors controlling the effectiveness of revegetation on both areas. This biosolids and heavy liming combination was an effective restoration option to establish vegetative cover on toxic smelter wastes and a much cheaper alternative to using a thick topsoil layer.

Using Biosolids, Composts and Tailor-Made Biosolids Mixtures for Remediation

Brown and Chaney (2000) and Chaney et al (2001) recently summarized how biosolids and other by-products can be combined to make "tailor-made" biosolids mixtures for reclaiming

disturbed lands, metal-contaminated soils and urban and brownfield sites. This remediation will involve an alteration of soil chemistry and often re-establishment of the microbial community in these surface materials. Some examples of different reclamation projects follow.

Mine Tailings

By-product tailings from Arizona Cu mining operations are not metal toxic unless pyrite oxidation occurs but low soil pH, severe infertility and poor physical properties prevent a self-sustaining vegetative cover from developing on these tailings piles. While application of lime and inorganic fertilizers had limited success, biosolids amendment showed excellent growth response.

Attempts to revegetate Pb and Zn tailings rich in dolomite in Missouri using fertilizers had limited success. These tailings had very low P content, and high Pb plus high pH from the dolomite further reduced P availability for plants. A high Fe, high lime biosolids compost was able to provide sufficient P to sustain plant growth.

Tailings from a mining and smelting operation in British Columbia had low soil P, Ca and N plus elevated concentrations of Zn, Pb and Cd. Mixing papermill sludge with the tailings in a 40:60 ratio (tailings:paper sludge) corrected the P deficiency, allowed the establishment of legumes (that could fix N), improved water holding capacity (which reduces droughty conditions), and increased soil pH for more favorable plant nutrient availability.

Acid Coal Mine Spoils

Severe acidity, low nutrient status and poor physical properties limit plant growth on acid mine spoils. Biosolids in combination with lime can successfully revegetate these materials. Flue gas desulfurization (FGD) by-products have a high Ca content and may also have a high calcium carbonate equivalent (CCE) that can substitute for aglime for combining with organic amendments to improve vegetative cover in acid mine spoils. These co-utilized materials also increased soil pH and exchangeable Ca and Mg and decreased soluble Al and Fe.

Metal Contaminated Soils

Landscapes surrounding mining and smelting operations are often polluted with particulate deposition that causes soil pH to decrease and metals to become increasingly plant available, killing existing vegetation. Loss of vegetation can then lead to erosion, leaving soils that have potential phytotoxicity, acidic soil pH's, poor physical properties and low nutrient status. A mixture of biosolids with a high CCE by-product successfully established vegetation.

In these applications, biosolids were found to be effective in adsorbing heavy metals and reducing their phytoavailability, likely due to the high-surface area of Al, Fe and Mn oxide minerals present in the biosolids. In addition, the organic matter addition provides a substrate for soil microbes, which contributes to establishing nutrient cycling for plant growth.

Summary of Individual Studies on Use of Biosolids for Reclamation

The above summarized individual studies provide evidence that municipal biosolids can be useful for reclaiming a large number of different types of spoils, deposits, disturbed lands, and contaminated soils. More specifically, these studies demonstrated that:

1) biosolids can increase the very acid pH's of acidic mine spoil and coal refuse closer to a more neutral pH (7.0), making the amended surface material more favorable for plant growth;

2) by increasing the pH these acidic conditions, water soluble concentrations of metals can be reduced, thereby eliminating phytotoxic conditions of metal uptake by plants, particularly when liming (acid-neutralizing) materials are added along with the biosolids;

3) biosolids can improve overall growth of plants by moderating very strong acidic or alkaline pH conditions;

4) can help improve the quality of groundwater and surface water drainage coming from acidic mine spoil conditions;

5) when added to calcareous mine spoil, or other alkaline surface materials, either as a one-time or repeated applications, biosolids can decrease an alkaline pH to a more optimum level for better plant growth response and nutrient availability; and

6) biosolids can increase plant-available nutrient supplies, CEC, and exchangeable bases that are essential plant nutrients, thereby increasing the fertility of the amended surface materials; organic matter content and water-holding capacity will also be increased, altering soil properties to make growing conditions more optimum.

In addition to demonstrating the many benefits that biosolids can provide, these studies additionally showed that other factors need to be considered or properly managed when utilizing biosolids for reclamation:

1) good quality biosolids should be used, so high loadings of metals will not be introduced and cause undesirable uptake into plants, or be phytotoxic;

2) although biosolids may add elements that are non-essential for plant growth, overall plant uptake of potentially toxic elements may be less where biosolids are applied than from surface materials that are not amended with biosolids;

3) very high biosolids applications can cause decreased plant growth due to high soluble salts;

4) low to medium application rates of biosolids can provide as much available N and P for plant growth as high agronomic applications of fertilizers and will usually sustain sufficient levels of nutrients for longer times than commercial fertilizers;

5) for shallow rooted crops like grasses, better plant growth will occur if biosolids are surface applied or mixed with the top few inches of soil or surface material, rather than injecting biosolids nutrients below the rooting zone; and

6) biosolids used in combination with other by-products for “tailor-made biosolids mixtures” can enhance the benefits provided by biosolids to better correct unfavorable growing conditions that are present at a reclamation site.

In summary, biosolids can overcome essentially all of the potential problems frequently encountered with slag sites (which were discussed in Section III), i.e., extremes of soil pH, lack of essential plant nutrients, low organic matter, low water-holding capacity, phytotoxicity, compaction or consolidation, and low CEC. The other two soil parameters identified as important for successful revegetation, i.e., soluble salts or salinity and high Na concentrations, will need to be appropriately addressed. Biosolids can add soluble salts to surface materials being amended that may negatively affect plant growth when high application rates are used. This may be managed by using lower rates, selecting plant species more tolerant to soluble salts, or correcting the high salinity by using irrigation and normal precipitation to leach these salts below the rooting zone. Due to the nature of the treatment processes that generate biosolids, Na concentrations are low and will not contribute or cause high Na problems.

By-products used in combination with biosolids as tailor-made mixtures may contain soluble and/or Na salts. Therefore, depending on the concentrations present in these by-products and the rates applied, these potential constituents must be considered and managed appropriately to accomplish a successful reclamation. As was suggested in the discussion on tailor-made biosolids mixtures, the soil chemical conditions of the surface materials to be reclaimed must be considered relative to the amendments selected to use, so the desired remediation goal can be achieved.

Methods of Applying Municipal Biosolids

Halderson and Zenz (1978) discussed different methods that can be used to apply municipal biosolids to reclamation sites, and Rimkus and Sernel (1980) discussed application methods used at the Fulton County Land Reclamation site in Illinois, where sewage sludge was applied to strip mine spoils. Techniques used for liquid biosolids include (1) gated pipe that release liquid slurries to flow down surfaces that have been carefully graded to maintain constant slopes; (2) spray application using large-sized traveler or center-pivot sprinklers; (3) injection by liquid tank pull trailers or truck-mounted tank injectors; or (4) incorporation equipment (e.g., injectors, disk, plow) connected to a dragline. While some of the equipment used to incorporate liquid biosolids might be useful for incorporation of dried biosolids, use of liquid biosolids for reclamation of slag sites in the IUUA is not being recommended.

Halderson and Zenz (1978) had a good discussion of options available for dry biosolids, typically having a solids content of 30% or greater. Depending on how dry the biosolids may be, dust problems during handling and application may or may not be an issue. Application equipment can vary depending on the size of the area to be amended. Brown and Hallman (1986) showed and discussed a wide range of equipment that has been used for seedbed preparation and application of biosolids or other soil amendments. Forste (1996) indicated that land application of biosolids generally entails (1) transportation from the treatment or storage facility to application sites, (2) temporary on-site storage, as needed, and (3) application to agricultural, reclamation or other sites. She discussed options for applying dewatered biosolids which varied from a box or V-shaped spreader drawn by a tractor to more sophisticated and high-volume commercial machinery having high flotation tires which minimize soil compaction during application.

Sopper (1994) suggested that dewatered biosolids can be spread by tractors and farm manure spreaders, commercial box spreaders, bulldozers, loaders, pans and graders. The biosolids should then be incorporated with up to six inches of spoil or other surface material with a heavy mining disk or chisel plow. Halderson and Zenz (1978) cautioned that considerable care should be used in evaluating costs for alternate transportation and application systems and selecting a system that will be cost-effective.

Use of Biosolids to Reclaim Iron and Steel Slag Disposal Sites in the IIUIA

Biosolids are derived from the organic and inorganic matter removed from sewage at wastewater treatment plants (WWTP), or publicly-owned treatment works (POTW). The chemical, physical and biological nature of biosolids are determined by the type of treatment employed at the WWTP, and by the quality of the influent sewage. Generally the more industrialized a community, the higher will be the concentrations of various constituents present in the influent sewage. However, pretreatment programs have reduced the levels of these constituents and significantly improved the quality of resulting biosolids that are generated. The type of treatment employed by the WWTP will also influence the constituents present in biosolids.

Biosolids contain nutrients and organic matter which can be beneficially utilized for plant growth. Municipal biosolids can supply appreciable amounts of N and P but only small quantities of K, the other major plant nutrient, as well as all the other essential plant nutrients. While the amount of organic matter added by an agronomic¹³ application is small compared to that already present in an agricultural soil, higher rates of biosolids used on slag deposits could be expected to significantly increase organic matter levels in the amended slag. Biosolids can also significantly improve other properties of slag deposits as a media for plant growth, as previously discussed in this report.

Problems which must be addressed for biosolids applications to slag or other disturbed land areas in the IIUIA include obtaining public acceptance, odors and aesthetics, potential

¹³ "Agronomic" refers to the use of biosolids in a soil-plant system at a rate to provide adequate nutrients for crop growth but not an excessive amount of nutrients which might cause pollution.

pathogens in biosolids, and biosolids quality with respect to toxic organic chemicals, salts, heavy metals, and other inorganic pollutants.

Federal Biosolids Regulations, Part 503

The U.S. Environmental Protection Agency (USEPA) has provided guidance and rules for the safe use of biosolids in its current rule for the final use or disposal of sewage sludge, Part 503 of 40 CFR (Code of Federal Regulations). USEPA began developing this new and comprehensive, risk-based rule in 1984 by considering over 50 pollutants (USEPA, 1994). After careful screening and analysis, this initial list of pollutants was reduced to 10 inorganic elements and 15 organic chemicals. Risk of exposure to these 25 pollutants was evaluated by using 14 different pathways of exposure to the public and to the environment (see Table 13).

Considering analytical results from the USEPA National Sewage Sludge Survey (NSSS), the 15 organic chemical pollutants were deleted from the Part 503 standard and are not regulated because of one or more of the following reasons (USEPA, 1994):

- 1) the pollutant was not present in analyzed NSSS biosolids;
- 2) the pollutant was only present in NSSS biosolids at levels about 10 to 100 times below the pollutant limits calculated by risk assessment for biosolids to be protective of human health and the environment; or
- 3) the pollutant has been banned by USEPA and is no longer being used or manufactured in the United States.

Part 503 established Pollutant Concentration Limits (PCL) and Ceiling Concentration Limits (CCL) for the 10 inorganic elements when the regulation was published in the Federal Register on February 19, 1993 (USEPA, 1993). Subsequent amendments on February 25, 1994 and October 25, 1995 deleted the CCL and PCL for Cr, deleted the PCL for Mo, and increased the PCL for Se to 100 mg/kg, the same as the CCL for Se. The CCL's and PCL's are shown in Table 14 compared to the median concentrations for each pollutant found in NSSS biosolids in 1988 (USEPA, 1990b), in AMSA (Association of Metropolitan Sewerage Agencies) biosolids in 1996 (Pietz et al, 1998), and in Michigan biosolids sampled and analyzed about 1980 (Jacobs et al, 1981).

Table 13. Part 503 pathways of exposure from land application of biosolids (USEPA, 1994).

Pathway	Description
1. Biosolids → Soil → Plant → Human	Consumers in regions heavily affected by landspreading of biosolids
2. Biosolids → Soil → Plant → Human	Farmland converted to residential home garden five years after reaching maximum biosolids application
3. Biosolids → Soil → Child	Farmland converted to residential use five years after reaching maximum biosolids application with children ingesting biosolids-amended soil
4. Biosolids → Soil → Plant → Animal → Human	Households producing a major portion of their dietary consumption of animal products on biosolids-amended soil
5. Biosolids → Soil → Animal → Human	Households consuming livestock that ingest biosolids-amended soil while grazing
6. Biosolids → Soil → Plant → Animal	Livestock ingesting food or feed crop grown in biosolids-amended soil
7. Biosolids → Soil → Animal	Grazing livestock ingesting biosolids/soil
8. Biosolids → Soil → Plant	Crops grown on biosolids-amended soil
9. Biosolids → Soil → Soil Biota	Soil biota living in biosolids-amended soil
10. Biosolids → Soil → Soil Biota → Soil Biota Predator	Animals eating soil biota living in biosolids-amended soil
11. Biosolids → Soil → Airborne Dust → Human	Tractor operator exposed to dust from biosolids-amended soil
12. Biosolids → Soil → Surface Runoff → Fish & Human	Humans eating fish and drinking water from watersheds draining biosolids-amended soils
13. Biosolids → Soil → Air → Human	Humans breathing fumes from any volatile pollutants in biosolids
14. Biosolids → Soil → Groundwater → Human	Humans drinking water from wells surrounded by biosolids-amended soils

Table 14. Biosolids trace element concentrations from the NSSS (USEPA, 1990b), AMSA (Pietz et al, 1998), and Michigan biosolids (Jacobs et al, 1981) compared to Part 503 concentration limits of pollutants (USEPA, 1993)¹

Trace Element (Pollutant)	Michigan Median (1980)	NSSS Mean (1988)	AMSA Median (1996)	Pollutant Concentration Limits	Ceiling Concentration Limits
----- mg/kg (d.w. basis) -----					
Arsenic (As)	8	9.9	5.4	41	75
Cadmium (Cd)	11	6.9	4.4	39	85
Chromium (Cr) ²	130	119	62.0	1200	3000
Copper (Cu)	580	741	416	1500	4300
Lead (Pb)	270	134	75.7	300	840
Mercury (Hg)	2	5.2	1.8	17	57
Molybdenum (Mo) ³	32	9.2	12.0	18	75
Nickel (Ni)	49	42.7	35.0	420	420
Selenium (Se) ²	32	5.2	4.1	36 100	100
Zinc (Zn)	1200	1200	744	2800	7500

¹ MI biosolids sampled from >200 WWTPs in 1980; NSSS = National Sewage Sludge Survey samples taken in 1988; AMSA = Association of Metropolitan Sewerage Agencies samples taken in 1996; Ceiling Concentration Limits taken from Table 1 and Pollutant Concentration Limits taken from Table 3 of Part 503.13 amendments to Title 40 CFR (Code of Federal Regulations), February 19, 1993.

² The Ceiling Concentration Limit and Pollutant Concentration Limit for chromium were deleted from Tables 1 and 3 of Part 503.13, and the Pollution Concentration Limit for selenium was increased to 100 mg/kg in Table 3 of Part 503.13, by amendments to Title 40 CFR, October 25, 1995 (effective October 25, 1995).

³ The Pollutant Concentration Limit for molybdenum was deleted from Table 3 of Part 503.13 by amendments to Title 40 CFR, February 25, 1994 (effective February 19, 1994), pending EPA's reconsideration of an appropriate molybdenum pollutant limit.

For a biosolids to be land applied, the concentrations of the nine regulated pollutants cannot exceed the CCL's. The PCL's provide a benchmark of quality for biosolids. If the concentrations of all regulated pollutants (except Mo) in a biosolids are less than all the PCL's, then the biosolids can be judged exceptional quality (EQ), if further 503 requirements for highly reduced pathogen levels (Class A) and vector attractiveness are also met (USEPA, 1995). The reader can see that the national median concentrations 11 years ago (NSSS values in Table 14) and five years ago (AMSA values in Table 14) and the Michigan median concentrations 20 years ago (MI values in Table 14) would easily qualify for EQ biosolids, relative to their PCL's. Therefore, biosolids quality in the U.S. today can be expected to be of high quality, given the continued effort of water quality protection regulations. In addition, these data suggest that biosolids quality has continued to improve during the past 20 years.

Subpart D of the Part 503 rule describes the pathogen and vector attraction reduction requirements that must be met for land application of biosolids, to protect public health and the environment. Pathogen requirements are divided into two categories -- Class A and Class B (USEPA, 1995). Class A biosolids can be land applied without any pathogen-related restrictions on the site and can be met by six alternative treatment processes that accomplish the Class A pathogen standard. Biosolids that are sold or given away in a bag or other container for application to land and bulk biosolids that are applied to a lawn or home garden must meet Class A pathogen requirements.

Bulk biosolids that are applied to agricultural land, forests, public contact sites, or reclamation sites must meet the Class B pathogen requirements. For vector attraction reduction, two general approaches are used for controlling the spread of disease via vectors (such as insects, rodents, and birds) (USEPA, 1995):

- 1) reducing the attractiveness of the biosolids to vectors (Options 1 to 8) and
- 2) preventing vectors from coming into contact with the biosolids (Options 9 & 10).

Therefore, the Part 503 rule essentially addresses some of the potential problems noted earlier when land applying biosolids, i.e., biosolids quality and concerns about pathogens and vector attractiveness. The latter is particularly important for land uses of reclaimed slag disposal sites where public contact or exposure is expected. The 503 risk assessment process and the

pathways that were evaluated (see Table 13) have also addressed the exposure of biosolids-treated soil to some wildlife and soil biota. While the literature again has limited studies specifically addressing this topic, the following two papers provide some information and conclusions regarding wildlife exposed to biosolids-treated areas.

Alberici et al (1989) evaluated trace element concentrations in meadow voles in mine land reclamation where 134 dry mt/ha of a 1:1 mix of composted biosolids and dewatered biosolids cake was applied. The amended site was seeded with tall fescue, orchardgrass, birdsfoot trefoil and mixed clovers. Concentrations of Cd, Co, Cu, Ni and Zn were not significantly different between voles collected from biosolids-treated areas versus voles from unamended control areas. Concentrations of Cr in kidney and bone tissues and Pb in liver and bone tissues were higher in voles from control areas than from biosolids-treated areas.

Haufler and West (1986) reported on several studies on wildlife exposed to forests where biosolids were applied. The studies cited by these authors included black tailed deer, voles, unspecified wildlife and earthworms. Their review of the literature at that time indicated that direct effects of wildlife populations coming into contact with biosolids appear to be minimal. No toxicity problems to wildlife were observed when good quality biosolids were used. Because biosolids application adds nutrients into the forest ecosystem, increased vegetative productivity results which in turn caused the populations of many wildlife species to also increase. The authors concluded that biosolids application can offer valuable benefits to wildlife.

Application of Biosolids to Sites in the IIUIA

This literature review is not intended to be a "how to" manual outlining procedures that should be followed to accomplish slag site remediation with biosolids. Guidance on these practices can be found in several of the references cited throughout this review, such as Chapter 9 in USEPA (1995) on "Process Design for Land Application at Reclamation Sites", the manual for revegetation of mine lands by Sopper (1994), the handbook on disturbed land revegetation by Munshower (1994), the manual on quarry reclamation by Coppin and Bradshaw (1982), the book on reclamation of former coal mines and steelworks by Richards et al (1993), and the chapter by Halderson and Zenz (1978).

The use of biosolids for reclamation of sites containing iron and steelmaking slags and other steel industry wastes is a good choice. The reader of this literature review at this point should recognize that biosolids are a versatile material providing benefits in the past for many different types of reclamation. In addition, more recently biosolids have been combined with other by-products to produce “tailor-made biosolids mixtures” that can further enhance their ability to change the properties and conditions of various deposits, disturbed lands and contaminated soils to make them more suitable for vegetation and other land uses. While the literature is lacking in studies specifically on utilizing biosolids for reclaiming iron and steel slag disposal sites, the authors are confident that this is a viable option for the IIUIA.

Organic materials like biosolids offer many advantages as amendments to slag deposits for significantly improving them as a media for vegetation establishment. Other organic materials such as composted and screened yard wastes would also be good materials to use in conjunction with biosolids to manage high total N loadings that can be a source of nitrate-N leaching, if high rates of biosolids are used. When high rates of biosolids are utilized to rebuild topsoil on disturbed land surfaces, total plant-available N may exceed the amounts that plants can use. The excess quantity of nitrate-N added may be at risk of being lost by leaching before vegetation can use it. Therefore, adding high C:N ratio materials like woody yard wastes, sawdust, etc. along with the biosolids, can capture this excess nitrate-N by immobilization due to the high N demand of these high C materials.

Two general approaches could be used for reclamation of iron and steel slag disposal sites. One approach would be to place a layer of biosolids or a biosolids mixture on the surface of these disposal sites, after general land leveling, or incorporation of desired topographical relief, has been accomplished. This is commonly done at mine land sites to provide an adequate plant rooting depth, or layer, on top of the surface materials that are not suitable for vegetation. This allows the focus of the reclamation to be on the materials or mixtures that would make up this layer rather than on how to moderate the negative properties of the original surface materials. This requires a much greater volume of amendments across the site due to the depth of this layer which may need to be 12 inches or more.

The second approach is to use smaller quantities of amendments by incorporating the biosolids or biosolids mixtures into the upper 6-8 inches of surface materials. For this option, the focus must be on using rates and mixtures that will adequately remediate the negative properties of the disposal sites.

Our recommendation is for those interested in site remediation in the IIUIA to engage the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) in cooperative agreements to utilize their biosolids. Two of their water reclamation plants (WRP) are located in close proximity to the IIUIA -- the Calumet WRP and the Stickney WRP. These two MWRDGC plants produce close to 31,000 and 150,000 dry tons of biosolids, respectively. The quality of these biosolids are also very good, as shown in Table 15 compared to the Part 503 PCL's, and portions of these biosolids are Class A, eliminating any pathogen concerns relative to public contact.

Table 15. Mean trace element concentrations in 1999 biosolids from the MWRDGC Calumet and Stickney water reclamation plants (WRP) compared to Part 503 Pollutant Concentration Limits, originally proposed in 1993 regulations (Granato et al, 2001).

Trace Element (Pollutant)	Calumet WRP (1999)	Stickney WRP (1999)	Pollutant Concentration Limit
- - - - - mg/kg (d.w. basis) - - - - -			
Arsenic (As)	10	5	41
Cadmium (Cd)	6	15	39
Chromium (Cr) ¹	135	448	±200
Copper (Cu)	434	504	1500
Lead (Pb)	171	216	300
Mercury (Hg)	0.7	1.5	17
Molybdenum (Mo) ¹	15	12	±8
Nickel (Ni)	44	74	420
Selenium (Se) ¹	8	2	100
Zinc (Zn)	1,595	1,225	2800

¹ Subsequently, the PCL for Cr and Mo were dropped and the PCL for Se was changed from 35 to 100 mg/kg.

In 1997, the MWRDGC recently utilized about 60,000 dry tons from each of these two WRP's for construction of the Water's Edge Golf Course in Worth, Illinois. The soil on this site consisted largely of compacted material excavated from the Cal-Sag channel during its construction, was clay textured and unsuitable for use in establishing golf course turf. The biosolids were applied to about 95 acres to enhance the fertility and physical properties of these soils. In 2000, MWRDGC biosolids were used on five acres at the J. Sterling Morton West High School for the establishment of a soccer field. The area consisted of a shallow, slightly alkaline (pH 7.5), infertile, low organic matter and rocky clay loam. Approximately 640 dry tons of biosolids were used as a soil substitute and nutrient-rich seedbed for establishing a healthy turf at a cost savings in excess of \$30,000, if a layer of topsoil had been used instead of incorporated biosolids. (personal communication, Thomas Granato, MWRDGC)

Biosolids from the District has also been used to produce final vegetative covers at local landfills. The largest such use was for the 103rd Street and Doty Avenue Municipal Solid Waste Landfill for its final cover. Subsequently, this 225 acre landfill was combined with an adjacent area directly to the south (that was owned by the Illinois International Port District) for the development of a public golf course. District biosolids were applied to this entire area (totaling 456 acres) as fill to provide topographic relief for the links style courses and as the final protective vegetative layer to provide a root zone that was seeded with turfgrass. This reclaimed area became the Harborside International Golf Center in 1995 and includes two 18-hole golf courses and an associated 58 acre golf academy. A total of approximately 500,000 tons of biosolids from the District's Calumet and Stickney plants were utilized for these combined projects from 1989-1994. (personal communication, Richard Pietz and Thomas Granato, MWRDGC)

The District has conducted a large number of projects in the metropolitan area that include final landfill covers, athletic fields, highway medians & parkways, golf courses and public parks (Granato, 2001). But more specifically, the MWRDGC has recently initiated a research and demonstration project at a USX site, a 570 acre brownfield located at 87th Street and Lake Michigan. The objective is to determine whether biosolids can be beneficially utilized for site reclamation. Biosolids, soil and soil+biosolids mixtures (50:50 and 75:25) will be placed on top of the slag site surface, either with or without a six inch layer of a silty clay loam soil

between the amendment and the slag surface. The purpose of the silty clay loam layer is to evaluate the potential for nutrient leaching from the nutrient-rich biosolids. Experiences learned from this project should provide direction as to the best reclamation approach to use for reclamation of iron and steel slag disposal sites in the IIUIA.

Final Report Summary

The MWRDGC has had many years experience of using biosolids in reclamation projects, such as the examples discussed above within the metropolitan area and at the long-time project at Fulton County, the latter project discussed earlier in this literature review. And now more recently with the USX research and demonstration project, the District is gaining knowledge and on-hands' experience with slag site reclamation. With their large annual production of high quality biosolids, their close proximity to the IIUIA that would minimize transportation costs, and their previous visibility in utilizing biosolids at public sites, MWRDGC would be an excellent partner to accomplish beneficial reuse of biosolids and to reclaim slag disposal sites in the IIUIA for new, innovative land uses.

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