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EMISSIONS FROM IRON ORE MINING, BENEFICIATION AND PELLETIZATION

by

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PREFACE

The iron ore industry in the U.S. has experienced radical reshaping and growth over the past 25 years. Originally, the industry mined mainly high-grade direct-shipping ores from mine pockets for use in iron making. However, with the depletion of these ores, lower grade ores had to be mined and beneficiated to a higher iron content with relatively simple separation techniques. Soon even the reserves of these ores were not sufficient to meet the demand, and it became necessary to augment natural and beneficiated iron ore concentrates with pellets produced from low-grade taconite ores. As a result, the taconite industry, which produces the pellets, has increased in size over the past 10 to 15 years until it now accounts for more than 75 percent of the total iron ore concentrates produced in the U.S. for iron making. The extensive mining and processing activities associated with this industry are sources of both point source and fugitive emissions.

This report presents the findings of a preliminary study of the iron ore industry to identify, quantify and rank emissions sources. It also presents recommendations for future research and development aimed at filling emissions information gaps and at reducing emissions from this industry. Based upon available emissions data, it is estimated that ten major point sources from beneficiating and pelletizing of taconite ores in the U.S. emit

on the order of 100,000 metric tons of particulates each year. Many of the point sources contributing to these emissions are already being controlled with devices that average nearly 99 percent efficiency by mass. Open pit mines, talilings basins, haul roads, and loading and unloading of crude ores, overburden and surface materials were identified as potentially significant fugitive emissions sources. Data for quantifying these sources are unfortunately not available, even though these sources could possibly be more significant emissions sources than the point sources associated with beneficiation and pelletizing.

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INTRODUCTION

Background

The iron ore industry in the United States has experienced a radical change in the past 25 years. Although iron ore beneficiation has been going on for more than twice that long in the production of gravity concentrates, many natural ores were still shipped in the 1950's. In recent years most of the higher grade ores have been mined and the vast reserves of lower grade ores (taconites) are now being used. These taconite ores are concentrated (usually about 2.5 or 3 to 1 in terms of iron content) and pelletized before being shipped to the steel mills. The importance of beneficiation can be illustrated by looking at Minnesota's 1973 shipments (more than 2/3 of U.S. production). These shipments consisted of 3 percent direct shipping ores, 27 percent gravity concentrates, and 70 percent taconite concentrate pellets.

The emissions sources associated with beneficiation and pellet production are confined sources that lend themselves to standard control technology. Most of the emissions from mining and from tailings disposal are fugitive emissions, and, as such, do not lend themselves to control by conventional means other than through changing the mining or handling procedures or the use of dust suppressants.

The atmospheric emission data from the iron ore industry are very limited. Some previous EPA contracts (PH22-68-65; 68-02-1321, Task Order No. 5; and 68-02-1323, Task Order No. 15) have provided some emission factors that were obtained through literature review and personal contacts with other people in the industry. These contracts pointed out the need for obtaining reliable emission data for the industry; these data would have to be obtained by emission source testing when they are not available from industry.

Program Objectives

The objectives of this program were to identify the emission sources in the iron ore mining, beneficiation and pelletizing industry; to quantify those emissions; to rank the emissions based on their environmental impact; and to make recommendations for future research, development and/or demonstration projects to reduce emissions from the most critical sources. The data required to achieve these objectives were obtained from the EPA and state regulatory agencies, from literature surveys, discussions with people in the industry and through field testing.

DESCRIPTION OF THE INDUSTRY

General

Iron ore is a massive mining and processing industry that shipped approximately 80 million metric tons* of product (pellets, concentrates and direct shipping ores) in 1976 in the United States. This is down from nearly 88 million tons in 1973. However, pellet production alone is expected to increase to 90 million tons per year by 1980. To deliver 90 million tons of pellets to the steel mills, the industry has to mine about 230 million tons of crude ore and handle an equivalent amount of waste--i.e., overburden from the mine area and gangue from the beneficiation. The U.S. production is approximately 10 percent of world production. Iron ore resources in the U.S. are approximately 100 billion metric tons.

Most of the naturally occuring iron ores mined in the U.S. today are unsuitable for feeding directly into iron making processes without beneficiation of some sort. Less than 5 percent of production consists of direct shipping ore and more than 2/3 now consists of taconite concentrate pellets; the remainder is made up of gravity concentrates and washed ores and a very small amount of sinter. The pellets are produced in very large plants having capacities from 1 to 18 million tons of pellets per year. Essentially all of the new beneficiation capacity coming on line is in pelletizing plants.

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*The gross ton (2240 lb) is the conventional unit used in the U.S. and the metric ton (2205 lb) is used elsewhere. The difference is so small that for purposes of this study the two will be used interchangeably and referred to as metric tons or only as tons.

Technical

The iron ore mining, beneficiating and pelletizing industry consists of removing overburden (except for the few underground mines), mining the crude ore, crushing and grinding it, concentrating the ore by separating the iron-containing particles from the gangue, pelletizing the iron ore concentrate and indurating the pellets with heat.

Raw Materials

The raw materials for this industry are a wide variety of ores containing high iron content minerals. The desirable iron minerals present in the crude ores are usually some form of iron oxide. The most common forms are hematite, α-Fe_2O_3, and magnetite, Fe_3O_4. Hydrous iron oxide, goethite or limonite, $Fe_2O_3.nH_2O$, and the metastable maghemite, γ-Fe_2O_3, are the recoverable iron minerals occurring in some ore bodies. Siderite, $FeCo_3$, is a less desirable but recoverable iron mineral in special cases. Iron sulfides are usually not considered as primary sources of iron except as an iron oxide by-product from sulfide roasting operations. Iron that occurs in chemical combination in silicate minerals is not usually recoverable. The largest iron ore reserves occur near the surface in deposits that are 15 to 300 meters thick and are interlayered with waste materials.

In additon to the crude ore, other resources that go into the production of pellets are water, bentonite and energy. Although these plants use large quantities of water in the grinding and concentration processes, most of the water is recycled. Typical plants processing magnetite recycle more

than 95 percent of the 35,000 to 75,000 liters (9,000 to 20,000) gallons) that are used for processing each ton of pellets. Plants processing hematite typically recycle less water, but still more than 90 percent. Thus, rasonable estimate of makeup water usage would be 5 percent of 55,000 liters, or 2,750 liters (725 gallons), per ton of pellets.

Bentonite is mixed with the iron ore concentrate to bind the pellets together. Between 4.5 and 9 kilograms (10 to 20 pounds) are added to each ton of concentrate (i.e., 1 percent or less by weight).

According to the Process Evaluation Group of the U.S. Bureau of Mines, the energy consumed at a typical magnetic-separation taconite plant amounts to 1 million Btu's per ton of pellets. In the early 1970's, that energy consumption was distributed as 39 percent electrical and 61 percent natural gas; a small amount of fuel oil also continues to be consumed at some plants. The current energy situation has produced a great deal of interest in finding a fuel substitute for natural gas. This is exemplified by the fact that a new pellet production facility, which recently started operation, was designed to use coal with oil as a standby fuel; that other new facilities, which are either under construction or being planned, are also designed to ultimately use coal; and that most existing facilities are making the necessary conversion in storage and firing equipment to convert from natural gas to coal firing. Pilot studies are also underway at one plant to gasify coal for use in a shaft pelletizing furnace.

Mining

Today's mining of iron ore is done almost entirely in open pit mines. After the overburden has been removed, the ore is mined along different levels, called benches. The operations that take place are drilling, blasting, loading and hauling.

Blastholes of 30 to 46 cm (12 to 18 inches) in diameter are drilled to a depth that is typically 10 to 15 meters (35 to 50 feet), about 1.5 meters (5 feet) more than the bench height. Jet piercing and rotary drills are water cooled and the steam that is generated when the water contacts the hot taconite expands and flushes the spalled chips from the hole. The rotary drills use water flushing for dust suppression and cooling.

The blastholes are loaded with explosives that are detonated to break loose up to 2 million metric tons of ore at one time. Blasting is intermittent, occurring from once every several days to once per week. Meteorological conditions are monitored to find the best times for blasting to minimize dust transport and lessen the impact of noise and vibration.

Large electric shovels--9 to 11 cubic meters (12 to 14 cubic yards)--pick up the broken ore and dump it into trucks or rail cars. In most mines this takes place at several sites, 24 hours per day. Trucks or trains

haul the ore to the first stage in the processing plant; in a few mines trucks haul to a common point for transfer to trains.

Processing

Iron ore processing consists of a combination of unit operations specifically adapted to the characteristics of the crude material and of the final product specifications which are designed to satisfy constraints of iron-making technology, economics, energy consumption, and environmental impacts. The basic processes are beneficiation and agglomeration. Beneficiation of an iron ore involves, to varying degrees, liberation of iron ore minerals and concentration of the iron-bearing particles; agglomeration is a size enlargement process to produce pellets from the concentrate of a size and character required for iron making (this is usually accomplished by a process referred to as pelletization). Associated with beneficiation is the generation of waste materials (gangue) that must be disposed of in an acceptable manner. Approximately 40 percent of the crude iron ore as mined in the U.S. becomes shippable product for iron making after beneficiation. Thus, the beneficiation process liberates approximately 400 kilograms (900 pounds) of iron mineral grains from each metric ton of crude ore and generates approximately 600 kilograms (1,305 pounds) of gangue that has to be disposed of.

Liberation. The liberation of the iron mineral grains from the gangue is accomplished by crushing and grinding the ore to a particle size sufficiently close to the grain size of the iron-bearing mineral to allow for a high degree of mineral liberation. This requires a balance between completeness of mineral liberation and the comminution energy expended. Some ores are sufficiently liberated after only moderate size reduction but most of the low grade iron ores (taconites) being used today are very fine-grained and therefore require very fine grinding for adequate liberation.

The comminution of crude iron ores is normally performed in three successive stages of dry crushing in gyratory and cone crushers with intermediate screens for closed circuit operation of the fine crushers. These are followed by wet grinding in rod mills and ball mills, also in closed circuits with classification systems (e.g., cyclones). Alternatively, some coarse ores may be fed directly to wet or dry semi-autogenous or autogenous grinding mills in which the larger ore lumps and, in the case of semi-autogenous mills, some steel balls as well serve to crush smaller ones. These are also followed by pebble or ball mills. Ideally, the liberated particles of iron minerals and barren gangue should be removed from the comminution circuits by mineral separation techniques as soon as they are formed, while returning residual middling particles for further grinding. The process flow used for liberation, therefore, usually consists of interspersed grinding, size classification, and mineral separation operations with appropriate recycling for optimum results. There are many variations in the way these basic steps

are arranged in different plants, but the overall process is basically the same. A flowsheet of a typical taconite beneficiation process with magnetic separation is shown in Figure 1. Each box in the figure represents a basic operation and those with a short upward-pointing arrow indicate operations that are emission sources.

A relatively small percentage of the total U.S. crude iron ore is beneficiated by a flotation process; flotation processes are used for ores where the iron bearing particles are largely non-magnetic (e.g., hematite ores). Ores containing large fractions of both magnetic and non-magnetic iron ore are beneficiated by flotation as well as the normal processes used for mainly magnetic ores.

Concentration. The concentration of iron ores is accomplished by using the differences in certain characteristics between the various mineral particles in the ground-up ore. Applicable separation schemes in common use today are based on particle size, mineral density, magnetic susceptibility, surface activity, or electrical properties; magnetic susceptibility and surface activity (i.e., flotation) are used almost exclusively for separation of ground taconite ores.

Some classes of crude iron ore, usually ores of higher grade than taconite but lower than direct shipping ores, are amendable to simple gravity separation systems including tables, jigs, Humphrey spirals, elutriation devices or the use of heavy media, often in conjunction with size classification by

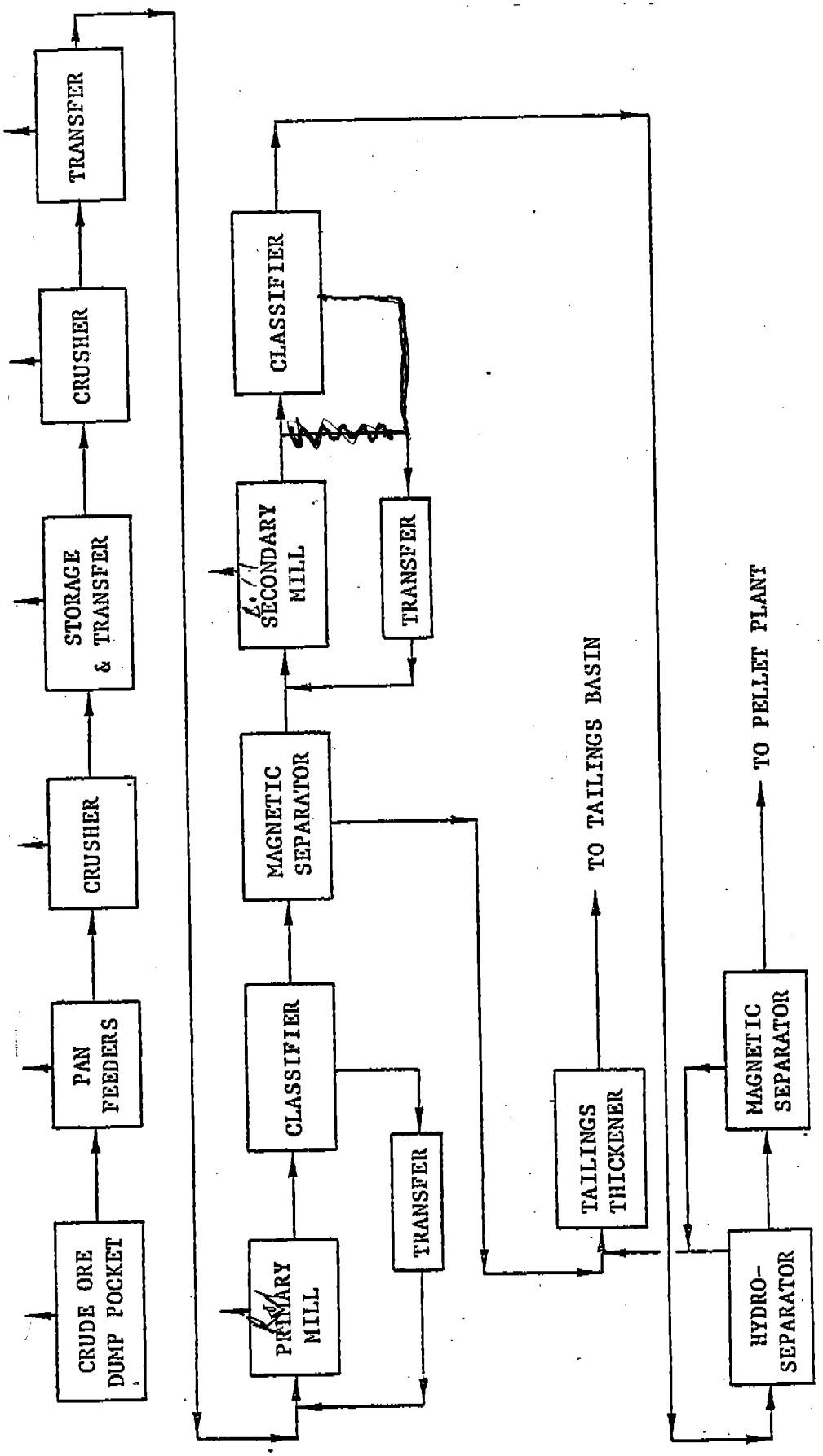

Figure 1. Ore Beneficiation Flowchart

screens. Moderate crushing or coarse grinding of these ores yields ore particles that vary widely in iron content regardless of the particle size; this rules out separation techniques based on particle size alone. There is, however, a direct relationship between iron ore grade (i.e., iron content) and mean specific gravity of the individual particles because densities of the iron minerals are nearly twice those of any gangue minerals likely to be present. Gravity separation techniques, based upon density difference, use the net buoyancy of a heavy medium to separate gangue from iron-bearing minerals. The density of the heavy media is adjusted to a value where most gangue readily floats and most iron minerals remain in suspension or settle out. Heavy media separation is often interdispersed between stages of grinding so as to optimize the effectiveness of the separation process. As a result, gangue (or rejects) of coarse and fines are produced. A heavy media is a dense suspension of very fine mineral particles in water; finely ground magnetite or ferrosilicon or a specially prepared fine spheroidal ferrosilicon are the mineral particles ordinarily used to form the heavy media because they can be recovered for recycling by magnetic separation. Although many gravity concentrates are coarse enough to be marketable, others may need some size enlargement by agglomeration.

Crude ores in which most of the recoverable iron occurs as magnetite (or, in rare cases maghemite) are normally concentrated by magnetic separation. The crude ore is a very fine-grained hard rock containing 30 to 35 percent total iron by assay but only about three-quarters of this, or 22 to 25 percent iron, corresponds to the theoretically recoverable magnetite. The rest of

the iron is present mostly as complex iron silicates and becomes part of the gangue. The liberation size for taconite is much too small for gravity methods of separation; in fact, it is often barely large enough for efficient magnetic separation. This is because the net attractive force exerted by a magnetic field on a particle containing magnetite is directly related to its iron content and as the size decreases and thus the iron content, so does the attractive force.

Nonmagnetic low-grade iron ores that are too fine-grained for gravity separation methods, such as those that exist in Upper Michigan, are concentrated by use of the particle surface activities in froth flotation or a combination of selective flocculation and flotation. In this case, the particle characteristic responsible for separation is the relative exposures of iron oxide and gangue minerals at the surfaces of the individual particles. However, because the surface exposure of a mineral may or may not be proportional to the bulk proportions of that mineral in a given particle, or because the ore particles may also become coated indiscriminately by extremely fine particles of interfering minerals, sharp separation is often difficult. Overcoming such difficulties is a part of the flotation art.

Various combinations of two or more basic separation methods (e.g., magnetic and flotation) may be applied to crude ores containing various iron minerals (e.g., magnetite and hematite) or wide ranges of mineral grain sizes. Flotation is also often used as a final polishing operation on magnetic concentrates to remove residual middling particles in which magnetite grains are enclosed by, or attached to, quartz or silicate grains. This produces a higher quality concentrate with a lower silica content.

Size Enlargement. Most of the iron ore currently being produced is destined for smelting in blast furnaces and must, therefore, meet certain specifications concerning chemical and physical qualities. Iron ore concentrates, as a result of beneficiation, meet the requirements for chemical composition, but only those coarser than about 10 mesh are physically acceptable as blast furnace feed without further treatment. The finer concentrates must therefore be enlarged in size to make them usable.

Most taconite concentrates are fine enough to agglomerate into small "green" pellets. The agglomeration is accomplished by tumbling moistened concentrate either in a balling drum or on a balling disc. A binder additive is frequently added to the balling feed depending on the particulate properties of the concentrate and on the subsequent hardening process. Powdered bentonite, the most common binder used, may be lightly mixed with the carefully moistened feed at 4.5 to 9 kilograms (10 to 20 lb) per metric ton of concentrate to improve ball formation and the physical qualities of the "green" balls, in both the wet and dry states, prior to being hardened by induration.

The usual pellet hardening process consists of drying and heating the green balls in an oxidizing atmosphere at incipient fusion temperatures [1290 to 1400°C (2350-2550°F) depending on the composition of the balls] for several minutes and then cooling. All of this is done at conditions conducive to producing the desired qualities of the finished pellets. Three general types of indurating apparatus are used--the vertical shaft furnace, the straight grate, and the grate-kiln.

In the vertical shaft furnace, the wet, green balls are distributed evenly over the top of the slowly descending bed of pellets; countercurrent to the descending bed of pellets is a rising stream of gas of controlled temperature and composition. The residence time in the hottest zone, which is very near the top of the column, and the temperatures throughout the shaft are controlled by the relative material flow rates and by auxiliary fuel combustion chambers that supply hot gases midway between top and bottom of the shaft furnace. The straight grate type of apparatus simply carries a continuous bed of agglomerated green pellets through various up and down cross-flows of gases at controlled temperatues. The pellets are first dried, then preheated and finally fired as the grate travels. The grate-kiln apparatus consists of a continuous traveling grate followed by a rotary kiln. After drying and preheating on the grate, the balls are discharged into the kiln for the actual induration which, in this case, is augmented by the kneading action of the tumbling mass that tends to compact the pellet surfaces. Straight grate indurated pellets are cooled either on an extension of the grate or in a separate cooler, whereas the grate-kiln product has to be cooled in a separate cooler, usually an annular cooler with countercurrent airflow. A typical pelletizing flowsheet is shown in Figure 2.

Products

The products of this industry include a small amount of natural ore and beneficiated iron ore concentrates for iron making. More than 75 percent of the concentrates are taconite pellets and that percentage is increasing

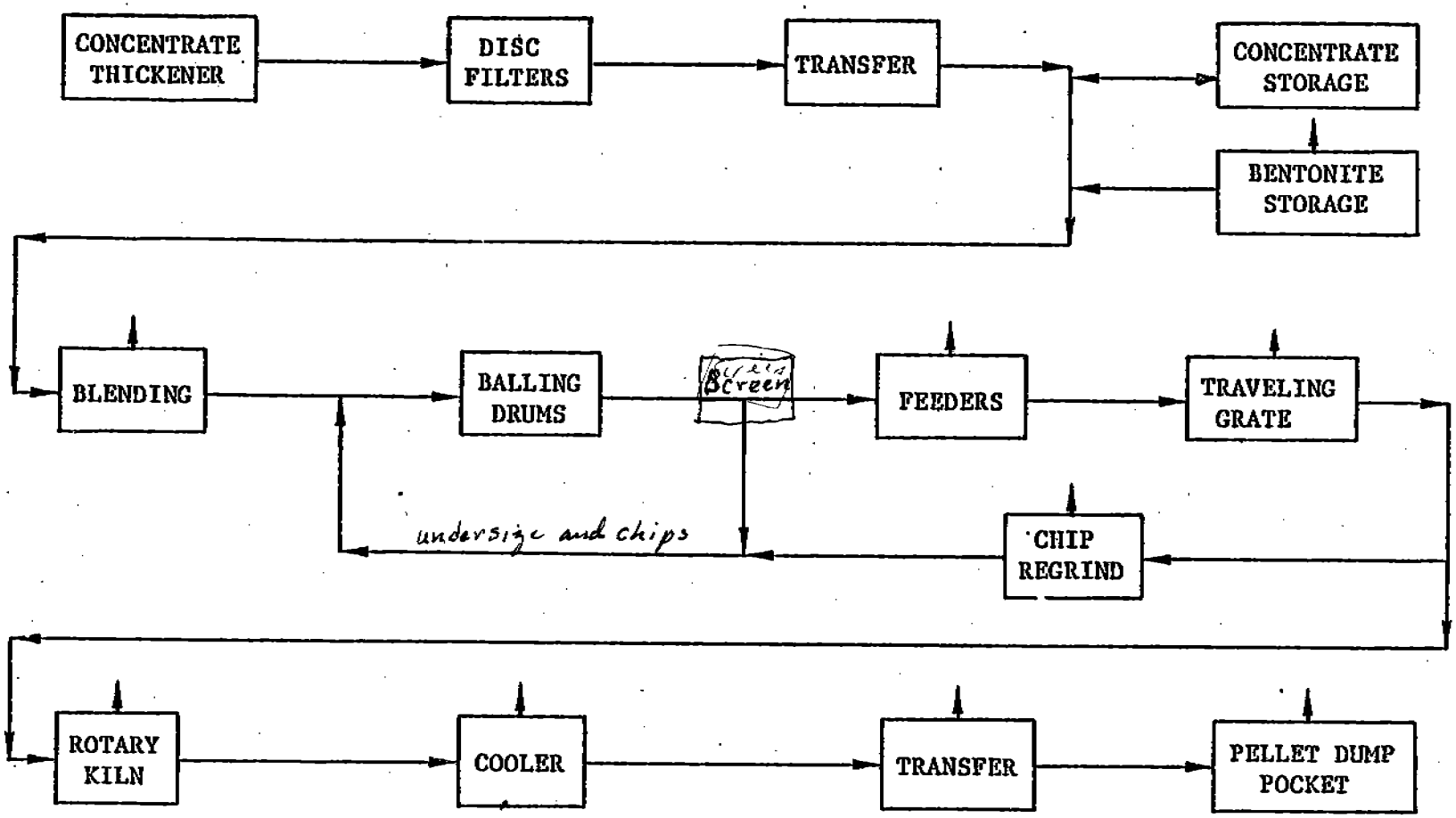

Figure 2. Pelletizer Flowchart

with time; gravity concentrates make up most of the rest of the concentrate tonnage. Direct shipping ore has almost disappeared from the scene, being less than 5 percent of total shipments. The pellets of commerce are commonly 1/2-inch nominal diameter spheres and contain at least 65 percent total iron in the fully oxidized (hematite) state and less than 7 percent SiO_2. They must also meet certain standardized specifications of physical strength and durability as well as behavior in simulated blast furnace tests. Demand for partially pre-reduced or metallized pellets for special purposes is just beginning although it is not significant in the total production of the industry.

POTENTIAL POLLUTANTS

The principal emphasis of this study was on air emissions in iron mining, beneficiation and pelletization. A study of the existing data on pollution control also revealed information on water pollution and solid waste generation. It must also be remembered that when air emissions are controlled, the material removed becomes part of a wastewater or solid waste stream if the material is not recycled. Thus, information available regarding water pollution and solid waste was analyzed for this report. Energy use information was also obtained.

Air

The amount of particulate air emissions from the iron ore mining, beneficiating and pelletizing industry within the U.S. is unknown but some reasonably good estimates can be made, at least for some of the operations. Total emissions from beneficiating and pelletizing were estimated by using two methods. In the first method, the median value for ten controlled sources was used as a minimum. Then, applying the median values for the ten point sources to the total U.S. production (80 metric tons per year) resulted in an industry particulate emission estimate of 57,000 tons per year from beneficiation and pelletization. This estimate does not account for any emission sources other than the ten identified in Table 4; other sources within the benefication and pelletizing processes exist, but they are believed to be less significant. In addition, it does not account for the fact that sources at some operations are uncontrolled. In the second method,

the total U.S. emissions from pellet plants are estimated by adding the known emissions from four plants that account for 25 percent of the U.S. production, and multiplying that sum by four. These plants use technology that is typical of that used for most of U.S. production. Using this method gives a sum of 112,000 tons of emissions per year for beneficiation and pelletization.

Most of the data used for these calculations are from 1974 and there have been additions to emission controls in old plants that would reduce those numbers. However, some new plant capacity has also been added so it appears safe to conclude that the emissions from the beneficiation and pelletization of iron ore is of the order of 100,000 TPY.

Fugitive emissions from tailings basins is an emission source resulting from land disposal of gangue generated during beneficiation. The only emission data available are from measurements made by MRI at one taconite plant tailings basin.(1) Modeling of the emissions for such a basin has been based on that sampling and a climatological dispersion model. The model predicts an expected fugitive emission rate due to wind erosion and truck traffic to and from the site of 14.5 metric tons per day from a tailings disposal basin of 11.3 square kilometers (4.4 square miles) located on the eastern half of the Minnesota Mesabi Iron Range. This is approximately equal to 1 kg of emissions per metric ton of production, which would total 70,000 metric tons per year. It should be pointed out, however, that this result is based on very limited test data and should be supported by other

measurements before it is accepted as realistic. It is also unrealistic to apply this result to all tailings basins because of the variations in design, size, remaining capacity, and prevailing meteorological conditions. Some tailings basins are very shallow and have large surface areas, while others are deep with steep walls, resulting in much smaller surface areas that are directly exposed to winds. Also, water cover prevents emissions and the percent of area that is water-covered varies greatly from one basin to another.

Emission rates from the mines and associated roads are unknown, but based on the surface area and the activities that take place within them, emissions could possibly be as great or greater than from tailings basins. Thus, total air emissions for the industry in the contiguous United States are probably greater than 300,000 metric tons per year.

Emissions Sources

Air emissions sources in iron ore mining, beneficiating and pelletizing are found in the mines, the processing plants and the tailings basins. Roads on the mining properties are also a major source of fugitive emissions.

Mine Sources. Drilling of blastholes causes some air pollution but the overall impact of this source is believed to be relatively insignificant. When jet piercing drills are used, the spalled chips are removed from the hole by the rapid flow of steam that is genrated by bringing water into contact with the burners for cooling purposes. In rotary drilling, water is

used for dust suppression and cooling. With this use of water, particulate emissions released by the drilling process appear to be quite low.

Blasting produces particulate emissions, but it is probably not an important source relative to other sources. Much of the material thrown into the air is so large that it settles to the surface rapidly. Also, blasting is intermittent, occurring only from once every several days to once a week. Meteorological conditions are monitored to find the best times for blasting to minimize dust transport and lessen the impact of noise and vibration. The pollutants from this source cannot be controlled using conventional entrapment technology.

Ore loading is a process that appears to contribute significantly to airborne pollutants. Large electric shovels (often 9 to 11 cubic meters) pick up the broken ore and dump it into trucks or rail cars. In most mines this is taking place at several sites throughout the mine, 24 hours per day, and hence could be the largest source of airborne particulates resulting from ongoing mining activities. In fact, it was obvious from observation at several sites that dumping ore from a shovel generates more emissions than does loading of the shovel, and that removing glacial surface and waste rock or overburden did not generate significant amounts of dust. For these reasons, this source was field sampled as part of this study and the results are presented elsewhere in this report. Controlling emissions from dumping is possible through the use of entrapment technology and by modifying the loading procedures to minimize the tumbling action as the ore is dumped.

Hauling the ore to the primary crusher is obviously a major source of fugitive emissions when trucks are used. When temperatures are above freezing, the mine roads are normally wetted down by water sprinkler trucks to suppress dusting; this helps but does not eliminate dusting. Control of road dust may be extremely difficult unless the roads are paved, sealed, treated, particularly for roads within the mine area which are continuously being built and abandoned. Treating of roads with dust suppressants have been tried at a few locations with good visual results but its effectiveness has not been verified by field testing. Furthermore, the pratice is not widespread enough to have a major impact. Finally, there is the dust that is raised on windy days from the barren surface of the mine (typically 2.5 to 25 square km). This is another source that appears difficult to control except through early revegetation of areas that have been mined out. This source is believed to be a less significant one than truck haul roads.

In summary, the amounts of particulate emissions in an open pit iron ore mine are not known and are generally difficult to control. A network of fugitive emissions sampling stations up- and down-wind from a mine would be beneficial for acquiring data on the quantity and characteristics of pollutants that are carried outside of the mine. When carried out with selective use of control technologies, this would provide added insignt as to the sources within a mine that should be controlled.

Processing Sources. The air emissions sources in the processing plants are depicted by the upward pointing arrows in the previously presented Figures 1 and 2. In the beneficiation plant, ore is handled in the dry state through

the crushing stages and all crushers, size classification screens and conveyor transfer points are major point sources of particulate emissions. Except in a few plants that use dry autogenous or semi-autogenous grinding, grinding of crushed ore is done wet with rod- and ball-mills. The ore remains wet through the rest of the beneficiation process so air emissions after crushing are insignificant.

The first sources of air emissions in the pelletizing process are associated with the handling of bentonite. It can become airborne when it is loaded into bins, unloaded, blended with the ore concentrate, or transferred. In iron ore plants each of these sources is controlled. In many cases, such as at transfer and blending points, the control consists of entrapment followed by a control unit that serves other sources as well. The ore concentrate (with bentonite added) is usually too wet to cause appreciable dusting as it moves to and through the balling process and into the induration furnace. Most of the large plants and new plants use a grate-kiln system; dusting begins in the drying zone (the first zone) and becomes the most intense in the indurating kiln where the pellets are tumbled. A large volume of gas moving countercurrently through the grate-kiln system entrains particulates as it goes and becomes heavily loaded before exiting--at this point these gases are referred to as the main waste-gas stream.

Fired pellets emerging from a kiln are cooled before they are stockpiled or shipped. This is commonly accomplished by dumping the pellets onto an

annular cooler with upward flow of cooling air. Dumping pellets onto the annular cooler produces abrasion, thus generating emissions that are picked up by the cooling air. At a number of plants the cooling air from the front portion of the annualr cooler is ducted into the kiln so that common emission controls can be used; cooling air from the latter portion of the annular cooler is directly exhausted through a separate (annular cooler) stack. Because the average size of the particulates elutriated by cooling air could be small and thereby pose a significant health hazard, an annular cooler was selected as a source for field sampling in this program. The results of these tests are presented in the field sampling section of this report.

Plants that use vertical shaft furnaces or straight grate furnaces rather than rotary kilns for induration, or grate type coolers instead of annular coolers, are expected to produce fewer emissions because there is less tumbling action of the pellets. This is true so long as the pellets are of high quality; poor quality pellets appear to produce significantly greater emissions.

Pellets emerging from the cooler are transported to a pellet loadout point where they are either stockpiled or directly loaded into rail cars. Loadout would be expected to produce some emissions from the action of a stream of pellets falling down on the storage pile or in loading a rail car. Observations at several operations revealed obvious dusting while loading rail cars; one operation shrouded the car loading area as a method of entrapping the emissions for subsequent control. Storage pellet piles

are a possible source for fugitive emissions although the significance of this source would vary greatly among plants. This is because some plants accumulate pellets in storage piles for several months while others maintain a nominal supply.

In addition to the emissions from the fixed sources, many plants have significant in-plant "fugitive" emissions. Some of the sources of these emissions are the return side of conveyors and scavenger-type controls rendered ineffective by pressure gradients throughout buildings. Although there is no way to estimate the amount of these emissions, they will vary greatly from plant to plant.

Tailings Basin. Tailings basins (frequently many square kilometers in area) often have large dry areas, especially along the beaches, and these can become large sources of fugitive emissions on windy days. Much of the solid gangue contained in these basins has been reduced to a very small particle size in the grinding process; it can become and remain airborne quite easily. At a majority of the plants, dry coarse tailings are delivered to the disposal site for use in constructing roads and dikes; dumping and truck traffic over roads covered with them cause emissions. These emissions most likely are not as significant as those resulting from the large dry areas of the basin. Attempts to quantify these emissions should be made because control strategies for them are possible.

Roadways. Unpaved roadways exist in and around mines, tailings basins, and processing areas; paved roads exist between outside highways and corporate

offices and major processing areas. The paved roads primarily carry all small vehicle traffic (i.e., employees and construction workers traveling to and from work) and do not appear to be a significant source of fugitive emissions. Many of the unpaved roads are used as haul roads for moving ore, overburden, and tailings. Much of the travel on haul roads is by very heavy trucks (70 to 140 ton); most of the travel occurs within the mines and as an emission source was previously discussed along with other mine sources. Heavily traveled haul roads often extend outside the mine area, especially if the primary crusher does not immediately adjoin the mine. Additionally, haul roads exist between mine areas and dump sites for oxidized waste rock and overburden. Other unpaved haul roads are used to carry coarse tailings by truck to tailings basins. Roads in and around the tailings basins are also traveled by heavy equipment (e.g., bulldozers, graders and scrapers) used in the construction of the basins. All of these unpaved roads are significant sources of fugitive emissions except when they are covered by snow. During dry periods, water trucks wet the roads to reduce emissions; however, the roads dry so rapidly that wetting down of roads is at best a partial solution. As previously mentioned, dust suppressants would probably aid in reducing fugitive emissions from unpaved roads. This option, however, has not been fully explored technically and economically.

Analysis of Existing Data

The "existing emission data" used in this study included materials from EPA studies, industry "114" responses to request for information from EPA,

and data on file at the Minnesota Pollution Control Agency and at the Air Pollution Control Division of the Michigan Department of Natural Resources. Applicable data from the NEDS (National Emissions Data System) data bank and data avialable in numerous published reports and articles were also used although data from these sources were very limited.

Sources. A listing of all possible sources of emissions from United States iron ore operations[2]--both natural ore and taconite operations--is presented in Table 1. The only available data on emissions, however, were limited to taconite operations. Furthermore, all emissions data represented only in-plant process sources; emissions data from roadways, tailings basins, etc. were not contained in the available data sources used. Emissions from natural ore operations are believed to be insignificant compared to those from taconite operations based upon site surveys at a number of natural ore operations. The main reasons for concluding this are that natural ore operations are seasonal and relatively small, that handling and processing of natural ores do not produce as much dusting as occurs with crude taconite, and that the natural ore tailings disposal basins are more amenable to revegetation.

Available data were analyzed by first compiling it into tabular form by emissions source. From this a simplified process flow scheme for a taconite operation was developed consisting of ten in-plant emissions sources. Although actual processes may vary somewhat from plant to plant, these emission sources are representative of what would be found at essentially all of these operations. The emission sources in the order they occur in this process flowsheet are as follows:

Table 1. United States Iron Ore Operations

Name of Operation/Location	Start Up	Mine	Drills	Haulage (ore)	Ore & Waste (mtpd)	Ore Grade (ave. %)	Conc. Output (mtpd)	Conc. Grade (%)	Conc. Methods (nat. ore)	Conc. Methods (pellet plants)	Agglomeration	Pellet Firing	Pellets (mtpd)	1973 Production (mtpy)	1974 Production (mtpy)	% Grade Final Product	Employees Waged	Employees Salaried	Expansions Under Way? Completed?
Atlantic City mine Atlantic City, Wyoming	1962	op		truck						mag. sep.	pz	sg			1,500,000				
Arcturus mine Marble, Minnesota	na	op	rotary	truck, conv	na	na	--	--	h-m	--	--	--	--	na	na	na	na	na	no; no
Butler Taconite Nashwauk, Minnesota	1967	op	rotary	truck	38,000	21.8	7,100	68	--	mag. sep.	pz	g-k	8,000	2,511,000	2,626,000	66.1	435	85	no; yes
Canisteo mine Coleraine, Minnesota	1933	op	rotary	truck	na	38.10	8,100	56	wash, h-m	--	--	--	--	1,092,897	1,200,000	56	204	24	no; no
Cedar City mine Cedar City, Utah	1946	op	rotary	truck	8,900	39.8	3,600	58	h-m, mag. sep.	--	--	--	--	na	na	na	na	na	na
Comstock mine Cedar City, Utah	1953	op	rotary	truck, conv	15,600	51.92	--	--	--	--	--	--	--	922,982	950,000	51.92	na	na	no; no
Coons Pacific[1] Eveleth, Minnesota	1950	--	--	--	--	--	9,500	56-62	wash, jig. h-m, spir	--	--	--	--	na	na	--	55	2	no; no
Eagle Mountain mine Eagle Mountain, Calif.	1948	op	rotary down-h	truck	170,000	34	18,000	60	--	wash, jig h-m mag. sep.	pz	sg	6,500	3,902,800	3,791,000	61	1,375	125	no; no
Empire Iron Mining Co. Ishpeming, Michigan	1964	op	rotary	truck	86,000	33	16,920	66.5	--	mag. sep. flot. siphon.	pz	g-k	10,085	3,540,472	4,060,000	64.65	726	101	no; yes
Erie Mining Co. Hoyt Lakes, Minnesota	1957	op	rotary jet	truck, rail	145,000	32	29,600	62.5	--	mag. sep.	pz	vsf	29,100	11,657,600	10,600,000	62.5	2,126	642	no; no
Eveleth Expansion Co. Eveleth, Minnesota	1976	op	rotary jet	truck	na	na	na	na	na	mag. sep.	pz	g-k	na	na	na	na	na	na	yes; no
Eveleth Taconite Co. Eveleth, Minnesota	1965	op	jet. rotary	truck, rail	24,000	23.5	5,567	67.12	--	mag. sep.	pz	g-k	5,700	2,065,000	2,300,000	64.4	385	87	no; no
Grace mine Morgantown, Pennsylvania	1958	ug	perc. down-h	i-h-d, conv	8,500	41.75	4,900	66.35	--	mag. sep.	pz	vsf	4,900	1,110,700	1,160,700	65.4	700	115	yes; yes
Gross-Nelson mine Eveleth, Minnesota	1966	op	down-h	truck	8,000	48	3,600	54	wash, jig h-m	--	--	--	--	330,000	300,000	54	50	5	no; no
Groveland mine Randville, Michigan	1959	op	rotary	truck	31,500	35	5,850	61	--	mag. sep. flot	pz	sg	6,000	1,971,000	2,045,000	63	395	80	no; no
Hibbing Taconite Co. Hibbing, Minnesota	1976	op	rotary	truck							pz								
Hill Annex mine Calumet, Minnesota	1917	op	rotary down-h	truck conv	21,000	36.55	6,000	59.67	wash, h-m h-m, cyc, spir	--	--	--	--	970,000	940,000	58	180	20	no; no
Hull-Rust mine Hibbing, Minnesota	1965	op	down-h	truck	8,000	58	3,200	54	wash	--	--	--	--	170,000	150,000	54	45	4	no; no
Humboldt Pellet Plant Michigan											pz				900,000				
Jackson County Iron Co. Black River Falls, WI	1969	op	rotary	truck	21,000	36	2,700	67.75	--	mag. sep.	pz	sg	na	955,504	920,000	64.91	210	32	no; no
Lind-Greenway mine Grand Rapids, Minnesota	1953	op	rotary down-h	truck	20,500	30	5,800	58.70	wash, jig h-m	--	--	--	--	1,007,281	918,000	58.70	150	20	no; no
Lone Star Steel Co. Lone Star, Texas	1947	op	rotary	truck	na	26.68	3,821	42.10	wash	--	sn	rotary kilns	--	na	na	52.60	108	24	no; no

Table 1. United States Iron Ore Operations (Continued)

Name of Operation/Location	Start Up	Mine	Drills	Haulage (ore)	Ore & Waste (mtpd)	Ore Grade (ave. %)	Conc. Output (mtpd)	Conc. Grade (%)	Conc. Methods (nat. ore)	Conc. Methods (pellet plants)	Agglomeration	Pellet Firing	Pellets (mtpd)	1973 Production (mtpy)	1974 Production (mtpy)	% Grade Final Product	Employees Waged	Employees Salaried	Expansions Under Way? Completed?
Buck Mining Co Silver City, New Mexico	1938	op	rotary	truck	730	43	none	--	--	--	--	--	--	28,600	40,000	43	9	2	no; no
MacIntyre Development Tahawus, New York	1942	op	rotary	truck	21,600	28	1,000	62-64	mag. sep.	--	--	--	--	316,226	261,000	62-64	140	46	no; no
Father mine Ishpeming, Michigan	1943	ug	perc, auger	rail, hoist	na	54.69	--	--	--	--	--	--	--	1,958,657	1,954,000	60.22	526	49	no; no
McKinley mine McKinley, Minnesota	1968	op	rotary down-h	truck	30,000	56.5	12,000	60	wash	--	--	--	--	2,260,000	2,240,000	60	215	30	no; no
Meramec Mining Co. Sullivan, Missouri	1961	ug	rotary perc. down-h	truck rail conv.	na	45	5,500	69	--	mag. sep. flot. fine scr	pz	vsf	4,800	1,629,593	na	67	na	na	no; no
Minntac Plant Mt. Iron, Minnesota	1967	op	rotary	truck, rail	175,000	22	35,000	65	--	mag. sep.	pz	g-k	35,000	12,312,000	12,500,000	65.3	2,600	340	yes; no
National Steel Pellet Plt. Keewatin, Minnesota	1967	op	rotary	truck conv.	40,800	31	7,200	67.2	--	mag. sep.	pz	g-k	7,740	2,560,747	2,600,000	65.7	470	99	yes; no
Nevada-Barth Corp. Carlin, Nevada	1960	op	perc	truck	1,200	60	none	none	--	--	--	--	--	101,000	105,000	60	14	6	no; no
Neville mine Chisholm, Minnesota	1974	op	rotary	truck	na	na	na	na	wash	--	--	--	--	--	200,000	na	200(2)	26(2)	no; no
New York Division Star Lake, New York	1944	op	rotary	truck	15,600	23.2	2,730	66.3	--	mag. sep. spir	sn	--	--	854,019	943,000	65.2	440	69	no; no
Pilot Knob Pellet Co. Ironton, Missouri	1968	ug	perc	conv. i-h-d	6,294	34.6	5,616	65	--	mag. sep. flot	pz	sg	4,080	949,723	950,000	63.46	360	75	yes; no
Pioneer Pellet Plant Ishpeming, Michigan	1965	--	--	--	--	--	4,800	60.75	h-m	none	pz	g-k	4,616	1,577,611	1,550,000	61.5	97	16	no; no
Plummer mine Coleraine, Minnesota	na	op	rotary	truck conv.	na	na	na	na	wash h-m	--	--	--	--	na	na	59.9	na	na	no; no
Rana mine Kinney, Minnesota	1974	op	down-h	truck	7,000	58	2,400	52	wash	--	--	--	--	--	100,000	52	27	2	no; no
Republic mine Ishpeming, Michigan	1956	op	rotary, jet	truck	57,200	36	10,400	65.37	--	flot, elut	pz	g-k	na	2,674,639	2,610,000	65.2	740	91	no; no
Reserve Mining Company Silver Bay, Minnesota	1955	op	jet	truck	130,000	24	28,500	64.6	--	mag. sep.	pz	sg	29,500	10,422,648	10,491,583	60.76	2,200	650	no; yes
Rouchleau group Virginia, Minnesota	1943	op	rotary	truck rail	na	na	na	na	crush scr, h-m	--	--	--	--	na	na	58.17	na	na	no; no
Sherman mine Chisholm, Minnesota	1948	op	rotary	truck rail	na	na	na	na	wet scr, h-m	--	--	--	--	na	na	59.18	na	na	no; no
Sherwood mine Iron River, Michigan	1940	ug	perc	rail, conv, hoist	1,600	54.7	na	na	--	--	--	--	--	381,865	385,000	55	100	9	no; no
Stephens mine Aurora, Minnesota	1957	op	rotary	truck	na	na	na	na	crush scr	--	--	--	--	na	na	58.18	na	na	no; no
Sunrise mine Sunrise, Wyoming	1900	ug	perc	rail,conv, hoist	3,600	na	2,400	48.99	jig, h-m	--	--	--	--	450,347	500,000	48.99	200	25	no; no
Tilden Mining Company Ishpeming, Michigan	1974	op	rotary	truck	46,800	36	12,300	65.61	--	flot, selective floc	pz	g-k	11,000	none	none	65.90	528	90	no; no
U.S. Pipe & Foundry Co. Russellville, Alabama	1954	op	rotary	truck	1,500	48	1,000	50+	h-m, flot	--	--	--	na	na	na	na	42	4	no; no
Whitney mine Hibbing, Minnesota	1973	op	rotary	truck, conv	44,100	na	13,500	52.6	wash, h-m	--	--	--	--	none	700,000	52.6	306	31	no; no
Wyoming mine Virginia, Minnesota	1960	op	rotary	truck	na	na	na	na	h-m	--	--	--	--	175,000 (conc.)	175,000 (conc.)	na	200(2)	26(2)	no; no

Crude ore dump pockets

Coarse crushing

Ore transfer

Fine crushing/grinding

Bentonite transfer

Bentonite blending

Grate feed

Grate discharge

Waste gas

Pellet handling

Emissions control data for each of the ten sources are presented in Tables 2 through 11. These tables list the process weight, production time, air flow rate, loadings, and efficiencies as well as the type of control device. Emissions data for plants with dry autogenous grinding were included under fine grinding. The emissions data for each of these ten sources were analyzed to obtain the ranges of emissions, in kilograms per metric ton of pellets produced, for both the uncontrolled and controlled cases. The ten emission sources were then ranked according to the mass of emissions per ton of pellets produced based on three parameters: bottom of the range, top of the range, and the median value; use of any one of these parameters did not significantly change the ranking. Where the number of samples was even, the median value was obtained by averaging the two middle values.

Table 2. Crude Ore Dump Pockets Emission Control

PROCESS WEIGHT RATE (Tons/Hr)	PRODUCTION TIME (Hrs/Yr)	CONTROL DEVICE						EMISSION RATE (Lb/Hr)	BASIS
		TYPE	NO. OF UNITS	FLOW RATE (SCFM)	INPUT (gr/SCF)	OUTPUT (gr/SCF)	EFFICIENCY (%)		
824	8400	Dry Mechanical	1	60,814	0.813	0.122	85	63.6	Estimate
824	8400	Dry Mechanical	1	23,500	12.29	0.209	98.3	42.0	Estimate
3417	8400	Cyclone	1	47,000	0.327	0.049	85	19.65	Field Testing
3417	8400	Cyclone	1	47,000	0.420	0.063	85	25.3	Field Testing

Target

0.514 lb/ton

3.004

0.039

0.050

3.607 / 4 = 0.901

Table 3. Coarse Crushing Emission Control

PROCESS WEIGHT RATE (Tons/Hr)	PRODUCTION TIME (Hrs/Yr)	CONTROL DEVICE						EMISSION RATE (Lb/Hr)	BASIS	lb/ton
		TYPE	NO. OF UNITS	FLOW RATE (SCFM)	INPUT (gr/SCF)	OUTPUT (gr/SCF)	EFFICIENCY (%)			
960	8,400	Dry Mechanical	1	17,871	1.10	0.165	85	25.2	Field Sampling	.026
1022	7,920	Multiclone	1	18,000	0.389	0.031	92 @ 10μ	4.80	Field Sampling	.0047
1165	7,920	Multiclone	1	18,400	0.360	0.043	88	6.81	Field Sampling	.0058
2534	6,824	Bag Collector	2	97,200			99		Mfg. Rating	
2533	8,400	Bag Collector	2	65,000	12.0	0.012	99.9	6.67	Mfg. Rating	.0026
1267	6,824	Rotoclone	4	13,308	0.4726	0.0398	91.6	4.54	Field Sampling	.0036
1867	8,400	Scrubber	2	8,000	4.27	0.043	99.0	2.93	Mfg. Rating	.0016
383	8,424	Scrubber	10	15,000	0.237	0.012	95	1.52	Field Sampling	.0040
1034	8,736	Multiclone	1	18,000	0.419	0.034	92	5.2	Field Testing	.005
1054	8,736	Multiclone	1	18,400	0.388	0.047	88	7.3	Field Testing	.0069
4523	6,825	Bag Collector	2	97,200			99		Estimate	
4523	6,825	Scrubber	4	13,308	0.48	0.04	91.6	18.2 ?	Field Testing	.0040
2169	8,760	Bag Collector	2	65,000	11.0	0.011	99.9	6.4	Estimate	.003
1598	8,760	Bag Collector	2	8,000	4.1	0.041	99.0	2.8	Estimate	.0018
824	8,400	Cyclone	1	17,871	0.77	0.116	85	17.9	Field Testing	.0217

$\frac{.0899}{13} = .0069$

Table 4. Ore Transfer Emission Control

PROCESS WEIGHT RATE (Tons/Hr)	PRODUCTION TIME (Hrs/Yr)	CONTROL DEVICE						EMISSION RATE (Lb/Hr)	BASIS
		TYPE	NO. OF UNITS	FLOW RATE (SCFM)	INPUT (gr/SCF)	OUTPUT (gr/SCF)	EFFICIENCY (%)		
4338	8700	Scrubber	1	11,500	0.333	0.010	97	0.97	Mfg. Testing
1450	8700	Scrubber	1	20,700	0.333	0.010	97	1.74	Mfg. Testing
1450	8700	Scrubber	1	13,200	0.333	0.010	97	1.11	Mfg. Testing
1450	8700	Scrubber	1	15,800	0.333	0.010	97	1.32	Mfg. Testing
1986	8700	Scrubber	1	9,800	1.000	0.010	99	0.86	Mfg. Testing
1057	7900	Multiclone	1	10,300	--	0.032	--	2.84	Field Testing
1043	7900	Scrubber	6	10,500	9.0	0.045	99.5	24.5	Field Testing
1043	7900	Scrubber	1	31,400	9.0	0.045	99.5	12.2	Field Testing
1043	7900	Scrubber	5	25,000	9.0	0.045	99.5	48.7	Field Testing
1043	7900	Scrubber	1	16,400	11.8	0.059	99.5	8.2	Field Testing
1037	7900	Multiclone	1	10,300	--	0.037	--	3.3	Field Testing
1024	7900	Scrubber	5	10,500	13.1	0.131	99	58.9	Field Testing
1024	7900	Scrubber	1	32,000	9.8	0.049	99.5	13.47	Field Testing
1024	7900	Scrubber	4	25,000	9.8	0.049	99.5	42	Field Testing
1024	7900	Scrubber	1	16,800	--	0.053	--	7.6	Field Testing
3286	8760	Cyclone	2	29,400	0.0033	0.0005	85	0.13	Field Testing
822	8760	Rotoclone	1	11,969	3.59	0.061	98	6.3	Field Testing
822	8760	Dry Mechanical	1	3,931	0.313	0.047	85	1.58	Field Testing

Table 5 . Fine Crushing Emission Control

PROCESS WEIGHT RATE (Tons/Hr)	PRODUCTION TIME (Hrs/Yr)	CONTROL DEVICE						EMISSION RATE (Lb/Hr)	BASIS
		TYPE	NO. OF UNITS	FLOW RATE (SCFM)	INPUT (gr/SCF)	OUTPUT (gr/SCF)	EFFICIENCY (%)		
741	6,665	Rotoclone	7	29,825	4.33	0.013	99.7	3.32	Field Sampling-ASME-PTC-27
240	8,400	Rotoclone	1	24,865	2.1	0.042	98.3	8.5	Field Sampling
240	8,400	Rotoclone	1	22,647	1.35	0.027	98.3	5.3	Field Sampling
240	8,400	Rotoclone	1	19,665	1.9	0.038	98.3	6.9	Field Sampling
240	8,400	Rotoclone	1	19,222	1.2	0.024	98.3	3.9	Field Sampling
204	7,920	Scrubber	5	44,000	12.0	0.060	99.5	22.6	Field Sampling
194	7,920	Scrubber	6	44,000	14.19	0.0567	99.6	21.4	Field Sampling
633	8,400	Scrubber	4	21,500	0.267	0.008	97	1.44	Mfg. Rating
507	8,400	Scrubber	2	21,400			97		Estimate
507	8,400	Scrubber	3	20,900			97		Estimate
507	8,400	Scrubber	1	20,000			97		Estimate
507	8,400	Scrubber	1	10,500			97		Estimate
373	8,400	Scrubber	3	18,700	0.267	0.008	97	1.33	Mfg. Rating
373	8,400	Scrubber	3	19,000	0.267	0.008	97	1.38	Mfg. Rating
227	8,400	Scrubber	10	18,800			97		Estimate
227	8,400	Scrubber	1	20,200			97		Estimate

.0045
.0354
.111

Table 6. Bentonite Transfer Emission Control

PROCESS WEIGHT RATE (Tons/Hr)	PRODUCTION TIME (Hrs/Yr)	CONTROL DEVICE						EMISSION RATE (Lb/Hr)	BASIS
		TYPE	NO. OF UNITS	FLOW RATE (SCFM)	INPUT (gr/SCF)	OUTPUT (gr/SCF)	EFFICIENCY (%)		
7.99	8760	Bag Collector	1	10,000	1.00	0.01	99	0.88	Estimate
1.14	8760	Bag Collector	3	1,600	6.40	0.064	99	0.88	Estimate
4.00	8760	Bag Collector	4	10,000	1.00	0.010	99	0.88	Estimate
2.85	8760	Scrubber	1	8,860	0.20	0.004	98	0.3	Field Sampling
2.85	8760	Not Reported	1	3,780	0.10	0.001	99+	0.03	Field Sampling

Table 7. Bentonite Blending Emission Control

PROCESS WEIGHT RATE (Tons/Hr)	PRODUCTION TIME (Hrs/Yr)	CONTROL DEVICE						EMISSION RATE (Lb/Hr)	BASIS
		TYPE	NO. OF UNITS	FLOW RATE (SCFM)	INPUT (gr/SCF)	OUTPUT (gr/SCF)	EFFICIENCY (%)		
2.4	7900	Scrubber	1	3,500	1.67	0.022	98.7	0.65	Field Testing
2.4	7900	Bag Collector	1	1,500	1.10	0.011	99	0.139	Field Testing
2.66	7900	Scrubber	1	3,500	3.14	0.020	99.3	0.66	Field Testing
2.66	2800	Bag Collector	1	2,800	1.65	0.017	99	0.396	Field Testing
87.26	1400	Bag Collector	1	--	--	--	99.7	--	Field Testing

.121
.1058
.25
.15

Table 8. Grate Feed Emission Control

PROCESS WEIGHT RATE (Tons/Hr)	PRODUCTION TIME (Hrs/Yr)	CONTROL DEVICE						EMISSION RATE (lb/Hr)	BASIS	
		TYPE	NO. OF UNITS	FLOW RATE (SCFM)	INPUT (gr/SCF)	OUTPUT (gr/SCF)	EFFICIENCY (%)			
311	7,900	Scrubber	1	9,600	2.15	0.028	98.7	2.27	Field Testing	.0023
315	7,900	Scrubber	1	12,300	2.08	0.027	98.7	2.85	Field Testing	.009
261	8,760	Scrubber	3	13,600	6.2	0.062	99	7.2	Estimate	.028
342	8,760	Scrubber	2	15,000	8.4	0.084	99	10.7	Estimate	.03
274	8,760	Scrubber	1	19,406	0.15	0.003	98	0.5	Mfg. Rating	.0018

Table 9 . Grate Discharge Emission Control

PROCESS WEIGHT RATE (Tons/Hr)	PRODUCTION TIME (Hrs/Yr)	CONTROL DEVICE						EMISSION RATE (Lb/Hr)	BASIS
		TYPE	NO. OF UNITS	FLOW RATE (SCFM)	INPUT (gr/SCF)	OUTPUT (gr/SCF)	EFFICIENCY (%)		
311	7,900	Scrubber	1	11,100	4.0	0.028	99.3	2.62	Field Testing
315	7,900	Scrubber	1	14,500	3.86	0.027	99.3	3.35	Field Testing
261	8,760	Scrubber	3	13,600	6.2	0.062	99.0	7.2	Estimate
342	8,760	Scrubber	2	15,000	8.4	0.084	99.0	10.74	Estimate
274	8,760	Scrubber	1	19,206	0.15	0.003	98	0.5	Estimate

Table 10. Waste Gas Emission Control

PROCESS WEIGHT RATE (Tons/Hr)	PRODUCTION TIME (Hrs/Yr)	CONTROL DEVICE						EMISSION RATE (Lb/Hr)	BASIS
		TYPE	NO. OF UNITS	FLOW RATE (SCFM)	INPUT (gr/SCF)	OUTPUT (gr/SCF)	EFFICIENCY (%)		
274	8,760	Venturi Scrubber	1	260,000	1.6	0.024	98.5	53.5	Estimate
261	8,760	Scrubber	1	216,000	---	0.060	---	107	Mfg. Rating
31.5	8,760	1 Multiclone & 28 Cyclones	29	260,000 (combined flow)		0.097	95-98	179	Field Testing
31.1	8,760	1 Multiclone & 28 Cyclones	29	240,000 (combined flow)		0.099	95-98	205	Field Testing
182	7,488	Electrostatic Precipitator	1	241,000	4.124	0.045	98.9	93.8	Field Testing
203	7,488	Electrostatic Precipitator	1	255,000	3.053	0.034	98.9	73.4	Field Testing
213	7,488	Electrostatic	1	202,000	3.534	0.042	98.8	3.5	Field Testing

Table 11. Pellet Handling Emission Control

PROCESS WEIGHT RATE (Tons/Hr)	PRODUCTION TIME (Hrs/Yr)	CONTROL DEVICE						EMISSION RATE (Lb/Hr)	BASIS
		TYPE	NO. OF UNITS	FLOW RATE (SCFM)	INPUT (gr/SCF)	OUTPUT (gr/SCF)	EFFICIENCY (%)		
274	8760	Rotoclone	1	7,700	0.075	0.0015	98	0.1	Field Testing
351.7	7920	Scrubber	1	15,500	3.44	0.024	99.3	3.2	Field Testing
351.7	7920	Scrubber	1	10,800	6.33	0.019	99.7	1.8	Field Testing
310	7920	Scrubber	1	17,200	3.14	0.022	99.3	3.3	Field Testing
310	7920	Scrubber	1	8,500	3.9	0.039	99	2.8	Field Testing
310	7920	Scrubber	1	16,000	3.4	0.034	99	4.7	Field Testing
261	8760	Scrubber	6	13,600	6.2	0.062	99	7.2	Estimate
342	8760	Scrubber	2	30,000	6.0	0.060	99	15.3	Estimate
1698	6824	Scrubber	1	7,335	11.297	0.283	97.5	17.8	Field Testing

.00036

.028

.045

.01

The rankings by source for controlled and uncontrolled emissions based upon median values are presented in Table 12; the actual median values are also presented. Note that coarse crushing has the greatest change in rank between controlled and uncontrolled emissions. Although it ranks fifth out of the 10 sources for controlled emissions, it drops to 8th for uncontrolled emissions, indicating that controls on that particular source are probably not as effective as on some other sources. Dump pockets drop two positions in this ranking from the controlled to the uncontrolled groupings.

Table 12. Ranking of Ten Common Emissions Sources Based on Kilograms of Emissions Per Metric Ton of Pellets Produced. Number 1 is Largest Quantity.

	Emissions Sources (Median Values in Kilograms/Metric Ton)			
Rank	Controlled		Uncontrolled	
1	Waste gas	(0.44)	Fine crushing	(39.9)
2	Fine crushing	(0.18)	Waste gas	(14.6)
3	Dump pockets	(0.07)	Pellet handling	(1.7)
4	Pellet handling	(0.008)	Grate discharge	(0.66)
5	Coarse crushing	(0.006)	Dump pockets	(0.44)
6	Grate discharge	(0.005)	Grate feed	(0.32)
7	Grate feed	(0.004)	Bentonite blending	(0.11)
8	Ore transfer	(0.001)	Coarse crushing	(0.10)
9	Bentonite blending	(<0.001)	Ore transfer	(0.05)
10	Bentonite transfer	(<0.001)	Bentonite transfer	(0.02)

The data in Table 12 also show that the main waste gas stream and fine crushing are the two largest sources of particulate emissions, both uncontrolled and controlled.

The various combinations of sources and controls used in the industries are summarized in Table 13. Those that have been tested are denoted by (X) and those known to exist but for which no test data are available are denoted by (0); blanks indicate combinations not known to exist. Note that the main waste gas stream has been divided according to type of induration unit--straight grate or grate-kiln--and that some test results have been obtained for nearly all the combinations of sources and controls that exist for the four sources shown (i.e., ten of thirteen). Also note that no test results were available for scrubbers on coarse crushers but they did exist for fine crushers. Notably absent are test data on baghouses controlling the emissions from crushers. Thus, the combination of baghouse on a crusher was selected as one source to be tested on this program. These results are presented in the "Field Testing" section of this report.

Table 13. Existing Combinations of Sources and Controls That Have Been Tested (X) and Have Not Been Reported as Tested (0)

Emission Source	Control System					
	scrubber	cyclone	multiclone	rotoclone	baghouse	electrostatic precipitator
Coarse Crush	0	X	X	X	0	
Fine Crush	X			X	0	
Waste Gas (sg)*			X			X
Waste Gas (g-k)*	X		X			X

*sg - straight grate; g-k - grate-kiln.

Information about emissions from sources within the mines was not contained in the available data. As described in a previous section of this report, these sources are drilling, blasting, loading and hauling. Water is used in drilling and it suppresses particulate emissions from that source. Blasting is done only intermittently so even though a blast could possibly release large amounts of particulates, it may not be a significant source. Also, much of the material that is thrown into the air is in a size range large enough to cause it to settle out before it can leave the mining property. Shovel loading of trucks and rail cars is a continuous, 24-hour, operation that releases noticeable quantities of particulates. Road dust caused by ore hauling is also a large source of emissions, especially during dry periods which can occur during the winter months prior to the time when snow cover exists. Sprinkler trucks apply water to these roads regularly during the summer, but the roads are so porous that it is nearly impossible to keep them wet. Most of the mines are in areas with long winters preventing water use during that season. Emissions sources within the mine area need to be quantified by rather extensive field testing because of the lack of emission data.

Of the mine sources discussed above, the shovel loading appears to be the one most easily measured, a continuous source and also probably significant in quantity of emissions. Therefore, that source was chosen as one to be field tested. To avoid collecting road dust in the samples, the shovel loading site that was sampled is one using rail cars instead of trucks for hauling. The results are discussed under "Field Testing" section of this report.

Annular coolers are another source not listed among the ten shown in Table 12. The principal reason for leaving them out is that they are normally associated with grate-kiln induration systems; they are not used with straight grate or vertical shaft furnace induration systems. Annular coolers were not originally considered for field sampling because the mass loadings are small, typically less than 0.11 gram/cubic meter (0.05 gr/SCF). For that reason, most coolers do not have emission control devices. The gas flow rates, however, are so high [typically more than 2,800 cubic meters per minute (100,000 SCFM)] that the coolers generally emit 4.5 to 45 kilograms of particulates (10 to 100 pounds) per hour. Much of this material could be the result of dry autogenous grinding of the hardened pellets. Therefore, the particle size could be very small, allowing the material to remain airborne over great distances and, in that way, it could be a significant source from a health standpoint. Consequently, an annular cooler was chosen as a source for field sampling. These results are also presented under "Field Testing."

The fuel used for most pellet induration is natural gas but this will be changing in the near future. Heavy oil is currently being used in a few plants and coal handling facilities are being or have been constructed at other plants. This change from natural gas increases the importance for collecting data on main waste gas streams of oil- and coal-fired induration systems. An oil fired main waste gas stream from a vertical shaft furnace was selected for analysis on this program; a coal fired system was not yet available for sampling. These results are also found under "Field Testing."

Control Technology

A variety of emission control devices are used by the iron ore industry as previously shown in Tables 2 through 11. The use of these control devices, however, is almost exclusively limited to taconite beneficiation and pelletizing processes. An occasional exception is their use in controlling emissions from pellet load out. There is also some indication that some of these control devices might be used in the future to control dusting from drilling. Such a device was recently introduced into the market.

Emissions control of sources in the mining and tailings basin areas, which are primarily fugitive sources, are restricted to special operating procedures and techniques. These include such control methods as wetting down haul roads and revegetation of tailing basins. Although no emissions data exist on the effectiveness of these control methods, their impact on emissions appears to be minimal in most cases. There also are no data available on the magnitude of these sources.

Control devices, for the purposes of reviewing control technology, were grouped into the following eight categories: scrubbers, cyclones, multiclones, rotoclones, electrostatic precipitators, bag collectors, dry mechanical, and centrifugal. Further consolidation of categories was not possible because of insufficient information or because of the large variation in the terminology used to report each basic type of control technology. The application and effectiveness of these eight control devices in controlling emissions from iron ore beneficiation and pelletizing are discussed below. A general discussion

on the operating characteristics of dry collectors, wet collectors, and electrostatic precipitators follows.

Control of Point Sources. Application of the eight control devices for ten point sources is found in Table 14. This table shows the reported efficiencies and their basis, and the number of such applications. It should be noted that Table 14 is based entirely on combinations of devices and sources for which emissions data were available. Even so, it is believed the combinations and their relative frequency of application is fairly representative for the industry.

From Table 14, it is obvious that scrubbers are the most widely used control device for the ten point sources associated with iron ore beneficiation and pelletization. In fact, scrubbers are found to control all of the ten sources except crude ore dump pockets. Table 14 also reveals that the other control devices are restricted in their application to the various sources. For example, note that data for bag collectors were reported for only three out of the ten sources--coarse crushing and bentonite blending and transfer--and data for electrostatic precipitators were only reported for one source--waste gas. Many of these control devices could be applied effectively to other sources for which no data were reported; however, economic and technical limitations have, in some cases, restricted such applications.

Overall control efficiency of each of the ten point sources is presented in Table 15. These efficiencies, which are based upon the data of Table 14, show that the average control efficiencies of all sources except three-dump

Table 14. Control Efficiencies for Various Combinations of Control Devices and Sources* (Percent)

TYPE OF CONTROL DEVICE	CRUDE ORE DUMP POCKET	COARSE CRUSHING	ORE TRANSFER	FINE CRUSHING	BENTONITE TRANSFER	BENTONITE BLENDING	GRATE FEED	GRATE DISCHARGE	WASTE GAS	PELLET HANDLING
Scrubber		95(10)f 91.6(4)f 99(2)m	99.5(18)f 99(5)f 97(4)m 99m	99.5(5)f 99.6(6)f 97(10)m 97(19)e	98(f)	98.7f 99.3f	97.8(2)f 98m 99(5)e	99.3(2)f 99(5)e 98e	98.5e 89e	99.3(2)f 99.7f 99(2)f 97.5
Cyclone	85(2)	85	95(2)						95-98(56)f	
Multiclone		92(2)f 88(2)f							95-98(2)f	
Rotoclone		91.6(4)f	98f	99.7(7)f 98.3(4)f						98
Bag Collector		99(2)m 99.9(2)m 99(4)e 99.9(2)e			99(8)e	99(2)f 99.7f				
Electrostatic Precipitator									98.9(2)f 98.8	
Dry Mechanical	85e 98.3e	85f	85f							
Centrifugal							88f 98e 99.4e	88f 99.4e		

*Number in parentheses are the number of indicated combinations with the stated efficiency. The letters m, f, e, simply mean that the stated efficiencies were based upon manufacturer's rating (m), field testing (f), or estimated (e), respectively.

pockets, coarse crushing and waste gas--varies between 97.9 and 99.7 percent. Data from Table 12 can also be used to asses average control efficiency,although these efficiencies will differ slightly from those presented in Table 15. The reason for the differences is that the data used for Table 12 and 15 differ. All available data on loading rates were used to develop Table 12 even when loadings were only reported for one location (either before or after a collector); data used to develop Table 15 were restricted to data on reported efficiencies or where both the input and output loadings were reported.

Table 15. Control Efficiency of Common Air Pollution Sources*

Sources	Average Control Efficiency, % (Number of Observations)
Crude ore dump pockets	88.3 (4)
Coarse crushing	94.6 (36)
Ore transfer	99.7 (32)
Fine crushing	98.0 (51)
Bentonite transfer	98.9 (9)
Bentonite blending	99.1 (5)
Grate feed	97.8 (11)
Grate discharge	97.9 (10)
Waste gas	96.5 (63)
Pellet handling	98.4 (16)

*Results are based upon efficiencies reported in Table 14.

An overall control efficiency of the emissions from all of these ten point sources can be estimated in a number of ways. First, it can be estimated from the data of Table 12 by summing the median values for all ten sources for both controlled and uncontrolled emissions. This reveals that the sum for the uncontrolled sources is 80 times the corresponding value for controlled sources. This translates to an overall control efficiency of nearly 99 percent for the ten point sources. Another approach is to apply the individual average control efficiencies for each source from Table 15 to the corresponding median uncontrolled emissions from Table 12. This yields an overall efficiency of nearly 98 percent. Finally, the data of Tables 2 through 11 can be used, wherever both the input and output loadings are given, to calculate average loadings before and after controls for each source. These, when summed for uncontrolled and controlled emissions, yield an overall efficiency of nearly 99 percent. Each of these approaches yields slightly different results because some data represent average values whereas others represent median values,or because the data bases are not always identical as previously noted. However, since the results are so close for each of three approaches, it can be concluded that the overall control efficiency for the ten sources is around 98 to 99 percent.

Control efficiencies by type of control device are shown in Table 16. These efficiencies show that scrubbers, rotoclones, bag collectors and electrostatic precipitators are considerably more efficient on the average than are the others. This is understandable since the other devices--cyclone, multiclones, dry mechanical and centrifugal--all operate dry and rely solely upon inertial forces for collection. Application, therefore, of the more

Table 16. Control Efficiencies by Type of Control*

Control Device	Average Control Efficiency, % (Number of Observations)
Scrubber	97.9 (118)
Cyclone	95.6 (61)
Multiclone	95.6 (61)
Rotoclone	97.3 (17)
Bag Collector	99.2 (18)
Electrostatic Precipitator	98.9 (3)
Dry Mechanical	88.3 (4)
Centrifugal	94.0 (6)

*Results are based upon efficiencies reported in Table 14.

efficient control devices to all waste gas, fine crushing and dump pockets sources--the three largest uncontrolled point sources within the industry--would certainly improve the overall control efficiency for the point sources associated with beneficiation and pelletization. This would result in an overall control efficiency above the current estimated value of 98 to 99 percent. However, the impact that this would have in reducing the total--point and fugitive--emissions from the industry is unknown until such time that the fugitive emission sources are quantified. The possibility exists that it would be more cost-effective for the existing industry to control fugitive emission sources rather than to retrofit existing controls with more efficient ones.

The following is a general discussion on the control technology and is divided into the areas of dry collection, wet collection, and electrostatic

precipitators. Much of the information presented was extracted from References 3 and 4.

Dry Collection. Dry collectors include various inertial devices (e.g., cyclones, baghouses, and other fabric filters) and they all share the following functional characteristics:

1. Particulates are collected dry and in usable condition.
2. Exhaust gas is not cooled or saturated with moisture.
3. Subsequent solids handling units must be carefully designed to avoid secondary dust problems.
4. Unlike scrubbers, filters and dry collectors do not add moisture to the cleaned exhaust , and hence do not create a plume.

Cyclones. The basic principle of a dry cyclonic collector is simple. Dirty gas is guided into a cylindrical tube or chamber in such a way that a whirling action is set up within the chamber. This whirling action generates centrifugal forces that tend to throw suspended particles toward the outside. The forces acting on these particles vary with the square of the velocity and inversely with the radius of the cyclone. These two improtant factors influence the overall efficiency and cleansing action of any cyclonic collector. Four basic arrangements are common:

1. Tangential inlet and axial dust discharge.
2. Tangential inlet with peripheral dust discharge.
3. Axial inlet through swirl vanes with axial dust discharge.
4. Axial inlet through swirl vanes with peripheral dust discharge.

The first arrangement is the one most commonly used by the iron ore industry.

The centrifugal force in a cyclone causes the formation of a layer of dust that slowly swirls down the walls and collects in the bottom of an attached hopper. Reentrainment of the solids should not occur during discharging. A small purge (up to 10 percent of inlet airflow) at the dust outlet greatly increases the separation efficiency. Separation efficiency also increases with an increase in particle density, particle diameter, inlet velocity, cyclone body length, number of times the gas in the cyclone swirls around, ratio of cyclone body diameter to outlet diameter, amount of dust in the inlet air and the smoothness of the inner wall. If the inlet dust concentration is very high (above 50 grains/SCF) some agglomeration of collected dust is likely to occur and this increases collection efficiency.

Efficiency of separation decreases with an increase in the air viscosity, inlet duct width, inlet area, outlet diameter, cyclone diameter,and the density of the air. Collection efficiency in a cyclone is also decreased by the installation of inlet vanes or guide vanes.

High efficiency cyclones have smaller inlet widths and body diameters and hence produce greater separating forces. Cyclones with up to 9-inch body diameters are often considered to be "high-efficiency" cyclones.

A typical relationship between velocity and efficiency is shown in Figure 3. This shows that as the inlet velocity is increased, a rapid linear rise in efficiency results. The slope of the line is greater for larger

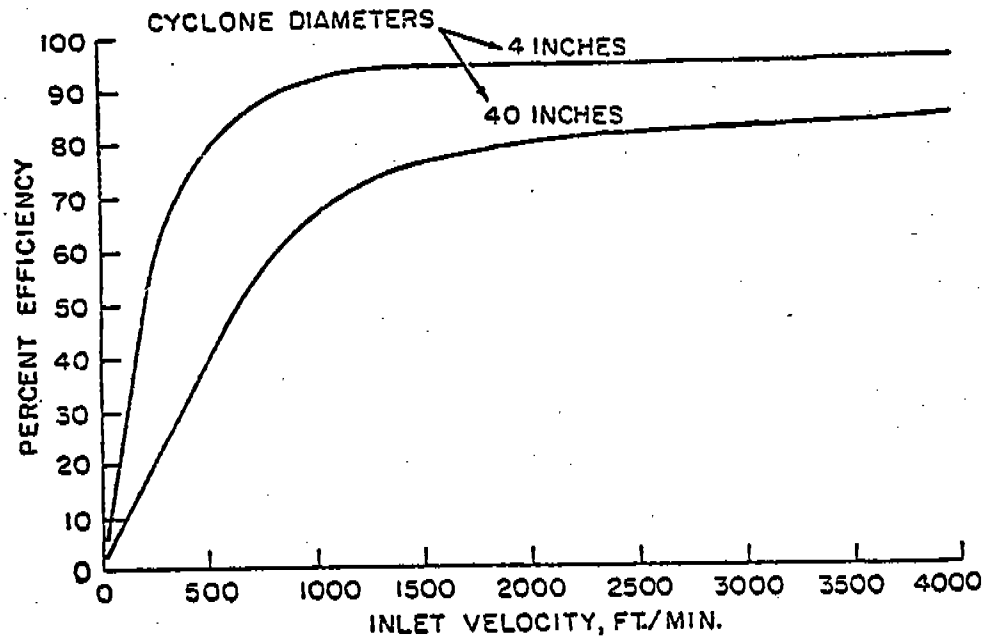

Figure 3. Influence of Inlet Velocity and Cyclone Diameter on Cyclone Efficiency

particles and for smaller cyclones. At about 70 percent efficiency, the slope decreases rapidly, and therefore, cyclones are not designed for use in this region. The inlet velocity at which the flat portion of the curve is reached, is lower for small diameter cyclones and for larger particle sizes.

Cyclone efficiency is also affected by particle size distribution, but to establish this relationship--termed fractional efficiency--requires testing. Once established, however, the overall efficiency can be calculated for a dust with a known size distribution.

Cyclones, in general, provide low collection efficiencies for particle size less than 10 μm (see Table 17) but are still used by the iron ore industry because they are the least expensive control devices to install and operate. As long as the source flow rate is not too large, cyclones are more effective for controlling iron ore emissions than for some other sources in other industries because of the relatively high particle density of iron ore emissions--particle densities of the range between 2.6 to 5.0 gm/cc. Cyclones have also been used by the industry because of their capability to operate at higher temperatures than is possible with other control devices. Furthermore, cyclones are relatively maintenance free and thus comply with the continuous operation requirement. Some problems that have been noted with the use of cyclones are due to bridging and caking of collection emissions at the cyclone-hopper junction or in an air lock used to separate a cyclone from its hopper. However, with proper engineering, these problems, which mainly arise when cyclones are used on crushing operations,

Table 17. Efficiency of Cyclones

Particle Size Range (μm)	Efficiency Range (% Collected)	
	Conventional	"High-Efficiency"
Less than 5	Less than 50	50-80
5-20	50-80	80-95
15-40	80-95	95-99
Greater than 40	95-99	95-99

have been overcome. As noted earlier, the collection efficiency of cyclones used by the industry averaged 95 percent by weight.

Small diameter cyclones can be manifolded in parallel to handle large gas volumes. If the number of parallel cyclones is large, a common inlet plenum chamber, dust storage bin and outlet plenum chamber are used. To obtain efficiencies near those of a single tube of the same size, it is necessary to equalize the gas and dust load distribution between the cyclones to prevent backflow, plugging, or reentrainment from the dust bin. Multiclones are such a control device and are often used by the iron ore industry on sources that require a fairly high level of control. Advantages of the multiclone are that they are capable of operating at relatively high temperatures (e.g., waste gas), require very little maintenance, and can be designed to handle relatively large flow rates (e.g., waste gas emissions).

A summary of the features of various cyclone designs is presented in Table 18. The costs shown are from about 1973-1974. The characteristics of some other dry collectors are shown in Table 19.

Table 18. Comparison of Various Cyclones

Collector Type	Space Requirements	Volume Range	Efficiency by Weight	Pressure Loss in Inches H_2O	Temperature Limitations (°F)	Power HP per 1,000 CFM Gas	Costs per cu ft Gas, ¢
Conventional cyclone	Large	Normal range up to 50,000 cfm	50% on 10 μm	1-3	700-1000° limited only by materials of construction	0.24 - 0.73	.03 - .10
High-efficiency cyclone	Medium	Normal range up to 12,000 cfm	80% on 10 μm	3-6	700-1000° limited only by materials of construction	0.73 - 1.2	.07 - .15
Multitube cyclones	Small	Normal range up to 100,000 cfm	90% on 5 μm	3-6	700-1000°	1.1	.09 - .15

Table 19. Dry Collector Characteristics

Types	Features				
	Space Required	Maximum Capacity ACFM	Efficiency and Micron Size to Which it Applies	Pressure Drop Inches H_2O	Temperature Limit °F	Cost
Gravity Chamber	Large	Available space is the only limit	over 50 µm	0.2 - 0.5	700 - 1000	Low
Cyclone	Large to Medium	50,000	50-80% on 10 µm	1 - 6	700 - 1000	Low
Rotary Dust Separator	Medium	18,000	90% on 2 µm	to 8	to 500	Moderate
Multiple Cyclone	Small	100,000	90% on 5 µm	3 - 6	700 - 1000	Moderate
Inertial Collectors	Small	75,000	90% on 2 µm	3 - 6	to 700	Moderate
Dynamic Precipitators	Small	25,000	90% on 2 µm	None; it is a fan	to 500	Moderate

In selecting the dry inertial type collector (e.g., cyclones) best suited for a particular application, one must consider the airflow rate; temperature; pressure; dust loading (grains/SCF); dust particle size; distribution and characteristics; legal requirements on emission concentrations; the end use of the collected dust; layout; space; maintenance; and economic factors. A partial list of suppliers of inertial collectors is presented in Appendix J.

Bag and Fabric Filters. Baghouses and fabric filters are used where efficient removal of particulates from exhaust air is required. In a bag filter, the particulates from a dust-laden gas are deposited in the voids and/or on the surface of a porous medium (paper, woven or felted fabric) as the gas passes through. As voids fill up, or the surface layer builds up, pressure drop increases until it reaches a point at which the fabric must be cleaned. Baghouses are efficient controls except for very small particles. The average efficiency reported by the iron ore industry for baghouses, for which there were field test data, was 99+ percent.

Cleaning of fabric filters can be intermittent or continuous automatic. Intermittent cleaning of baghouses occurs after the unit has ceased filtering--at the end of a work day. They cannot be cleaned while on-line, and so are limited to low dust loadings or infrequent operation. Continuous automatic baghouses, on the other hand, can operate 24 hours a day without shutdown and can handle high dust loadings. Because iron ore processing is a 24-hour operation, the iron ore industry has to use continuous automatic baghouses.

Baghouses are also characterized according to the method used to remove collected material from the bags. These methods include various techniques for shaking the bags, reversing the direction of air flow through the bags, or rapidly expanding the bags by a pulse of compressed air.

Bags in *shaker-type baghouses* are supported by a structural framework that is free to oscillate when driven by a small electric motor. When operated as an intermittent filter, the unit is shut down, filtering stopped, and the bags are shaken for a period of approximately one minute to dislodge collected dust. To operate a shaker filter as an automatic continuous unit, a damper, on a time basis, isolates one of the several compartments of the shaker baghouse so that there is no air flow in that compartment. The bags in that compartment are then shaken for approximately one minute; the collected dust cake is dislodged from the bags and falls into a hopper below for removal. The dampers then open, allowing the section to go back on-line.

Reverse flow baghouses are sectionalized as in the automatic continuous shaker-type filter, and three dampers isolate the units. At the same time an auxiliary fan damper is opened forcing air through the bags in the direction opposite to filtration. This backwash action collapses the bags and fractures the dust cake allowing it to drop into a hopper. When the bags are brought back on-line and reinflated, more of the fractured dust cake is dislodged into the hopper. This procedure may be repeated several times during the two or three minute cleaning cycle.

Reverse pulse baghouses have been used increasingly in recent years. This design utilizes a short pulse of compressed air through a venturi, directed from the top to the bottom of the cylindrical-shaped bag. This primary pulse of air aspirates secondary air as it passes through the venturi. The resulting air mass violently expands the bag as it propagates through and casts off the collected dust cake. No sectionalizing is required as the pulse of compressed air actually prevents process or dust-laden gases from flowing through the individual bag being cleaned.

Total pressure drop across fabrics is the result of the combined resistance of the clean cloth and the dust mat. At average airflow rates, resistance to the clean cloth rarely exceeds 0.1 inch H_2O.

Air-to-cloth ratio or filtering velocity is another critical factor in systems design. The value of this ratio depends on the 1) type of fabric, 2) method of cleaning, 3) properties of the particulates, and 4) gas properties. Typical air/cloth ratio values for iron ore dust for the various collector types are as follows:

Shaker collector	0.9 - 1.07 CMM/M^2 (3.0 - 3.5 CFM/ft^2)
Reverse jet	3.05 - 3.7 CMM/M^2 (10 - 12 CFM/ft^2)
Pulse jet	3.35 - 3.7 CMM/M^2 (11 - 12 CFM/ft^2)
Reverse air collapse	no data available

Tubular bag filters, a common configuration for use in baghouse, range in diameter from 15 to 30 cm (6 to 12 inches) and vary in length from 1.5

to 7.6 meters (5 to 25 feet). Length-to-diameter ratios for tubular bags are not standardized.

Gases from furnaces or other high-temperature sources must be precooled before entering a baghouse. Available cooling methods include 1) cooling by convection, radiation, or by the use of waste heat boilers, 2) tempering with ambient air, and 3) cooling by water sprays. A combination of these methods can also be employed.

The characteristics of various fabrics used in baghouses are given in Table 20. This table lists both the physical and chemical resistances for twelve fabrics. For use in the iron ore industry, the physical resistances are more critical. In fact, abrasion resistance is probably the single most important consideration for low-temperature application. Taconite ores and concentrate dusts are very abrasive and this is believed to be the major reason baghouses are not in widespread use throughout the industry. In many cases where baghouses are being used by the industry, it was necessary for them to identify the most common locations for fabric failure and to reinforce these areas. One way this was done was to attach nylon fabric to the areas subject to the greatest level of abrasion. This extends the useful lifetime of the filter considerably. Fabric filter replacement in baghouses takes place most often on a regularly scheduled basis rather than on a performance basis. Consequently, for emissions to be controlled to high level the abrasive resistance of the fabric must be excellent and a replacement schedule should be limited to the expected life of the fabric.

Table 20. Characteristics of Filter Fabrics

Fabric	Maximum Operating Temperature °F	Specific Gravity	Physical Resistance					Chemical Resistance					Relative Cost
			Dry Heat	Moist Heat	Abrasion	Shaking	Flexing	Mineral Acids	Organic Acids	Alkalies	Oxidizing Agents	Solvents	
Cotton	180	1.6	G	G	F	G	G	P	G	F	F	E	Low
Dacron	275	1.4	G	F	G	E	E	G	G	F	G	E	Moderate
Orlon	250	1.2	G	G	G	G	E	G	G	F	G	E	Moderate
Nylon	250	1.1	G	G	E	E	E	P	F	G	F	E	Moderate
Dynel	180	1.3	F	F	F	P-F	G	G	G	G	G	G	Moderate
Polypropylene	225	0.9	G	F	E	E	G	E	E	E	G	G	Low
Creslan	275	1.2	G	G	G	G	E	G	G	F	G	E	Moderate
Vycron	300	1.4	G	F	G	E	E	G	G	G	G	E	Moderate
Nomex	450	1.4	E	E	E	E	E	P-F	E	G	G	E	High
Teflon	500	2.3	E	E	P-F	G	G	E	E	E	E	E	High
Wool	200	1.3	F	F	G	F	G	F	F	P	P	F	Moderate
Glass	550	2.5	E	E	P	P	F	E	E	G	E	E	High

E-Excellent G-Good F-Fair P-Poor

Guidance for the selection and application of bag filters in processes common to the iron ore industry is provided in Table 21. The recommended selections listed in this table are in the order of preference and the numbers listed are identified by the following:

1. Woven or felted fabric filter with shaker type cleaning.
2. Felted fabric filter with pulse jet type cleaning.
3. Felted fabric filter with reverse jet cleaning for high-temperature service.

Table 21. Filter Selection Guide

Type of Application	Dust Loading (grains/SCF)	50% of the Dust Particles in the Size Range Given (μm)	Recommended[c] Selections Listed in Order of Preference
Rock Products and Mining			
Materials handling[a]	3-5 and up	2 - 15	1, 2
Crushing and Screening[a]	Over 5	7 - 15	1, 2
Dryers and Kilns[a,b]	3-5 and up	2 - 15	1, 2, 3
Coolers[a]	3-5	over 15	1, 2

[a] Wet collectors are preferred.

[b] Gas cooling may be needed for fabric filter use.

[c] See list above for description of selection as numbered.

The primary considerations relative to the dust to be collected include having information on:

1. Dust loading (usually expressed in gr/SCF).

2. Particle size (usually expressed in microns).

3. Properties including hygroscopicity, bridging, caking characteristics, and angle of slide.

4. The permissible levels of dust in the final exhaust.

In sizing a baghouse, the determining factor is the pressure drop across the filter fabric. Pressure drop increases with the time period between cloth cleanings and with filtering velocity (or air/cloth ratio). The increase in pressure drop with loading of the filter is accompanied by a reduction in flow rate.

In high-temperature applications, the cooling of the gas is vital. The trend toward fabrics that tolerate higher operating temperatures has reduced cooling requirements but increases the gas volume to be filtered. On the other hand, if the gas is at or below its dew point, baghouses are not suitable unless external heating is applied ahead of the baghouse.

The following steps should be used in selecting a baghouse system:

1. Determine the dust loading and the minimum volume to be vented.

2. Estimate the maximum desirable baghouse pressure drop (6 to 12 inches H_2O).

3. Select blower type and operating point to determine minimum operating volume at maximum resistance.

4. Estimate the minimum baghouse resistance after bags are cleaned and determine the second operating point on the blower curve.

5. Determine the required filtering area for maximum air/cloth ratio and from choice of filter fabric.

6. Size blower and determine best configuration and layout for plant.

In summary, flowrate, temperature, pressure, humidity, abrasiveness, and corrosiveness are all important design considerations. In addition, the application engineer must know if the collected dust is reused or dumped and should also be aware of the space available for the mounting of the equipment.

A partial list of suppliers of bag and fabric filters is found in Appendix J.

Settling Chambers. Settling chambers are large, rectangular expansion chambers with gas inlet at one end and outlet at the opposite end or top. Settling occurs due to the reduction in gas velocity. Because of the size, these chambers are usually field fabricated.

The gravity settling chamber is the simplest dust collection device. It lends itself to almost any type of construction, if due consideration is given to the temperature and corrosive nature of the gas. Industrial applications of settling chambers are limited because they are able to remove only the larger particles (25 to 50 μm in diameter). Below this size, the settling velocity required is very low and the volume requirements become unmanageably large. Particles that can be removed in settling chambers are seldom important pollutants, and in the iron mining, beneficiation and pelletizing industry, these particles would usually not be found beyond the property line of the plant. The only practical use for settling chambers would be as precleaners ahead of another control device. Settling chambers per se are not used in the iron ore industry but their principles are often designed into the processes.

Wet Collection. One of the principal methods for removing fine particulate matter from gas streams is by contact with a liquid in one of many types of wet scrubbers. These devices are used extensively in iron ore beneficiation and pelletizing operations and have an average field tested efficiency of 99 percent by weight.

A wet scrubber mixes the air or gas stream with a liquid medium, entrapping the material to be collected in the liquid and draining it away. The normal liquid used is water, but other liquids have been and are used in special applications. Methods of mixing the air and liquid vary from one model of scrubber to the next, but the basic operating principle is the same.

In the process of mixing, the gas is both cooled and saturated. The cooling and saturation occurs in accordance with direct adiabatic saturation. Psychrometric curves and tables are used to determine the outlet volume of the wet scrubber. All wet scrubbers are sized on the saturated outlet gas volume. Therefore, it is absolutely necessary to know the exact inlet conditions so the properly sized equipment can be selected.

Wet scrubbers lend themselves to controlling hot and difficult to handle corrosive gases. But because the collected material is mixed with the liquid, it, in turn, can create a slurry handling or disposal problem. In some processes it is possible to return the slurry back to the process. However, a wet scrubber improperly applied can turn an air pollution problem into a water pollution problem. Properly applied, it can be a highly efficient, relatively inexpensive solution.

Spray Chambers. The spray chamber is the simplest wet scrubber. It can be round or rectangular in shape. The scrubbing liquor is introduced by means of spray nozzles. The gas velocity decreases as it enters the spray chamber; the dust particles, which are wetted by sprayed liquor, settle and are collected at the bottom of the chamber. The scrubbing liquor rate is normally in the range of 0.67 to 1.34 LPM of liquor per CMM of gas (5 to 10 GPM per 1,000 ACFM).

There are three main flow configurations used in spray chambers:

1. Concurrent Flow. Both the dust-laden gas and the sprayed liquor flow through the spray chamber in the same direction. The collisions are caused by the velocity difference between the spray droplets and gas stream containing dust. The velocity difference is a minimum for this configuration and so is the collection efficiency.

2. Countercurrent Flow. The scrubbing liquor and the gas flow in opposite directions; normally the gas flows upward and the liquor flows downward. As a result of countercurrent flow, the relative velocity of the particulate matter and liquor droplets is at a maximum, thus providing maximum collection efficiency.

3. Cross Flow. In this configuration, the liquor is introduced at 90 degrees to the gas direction. The gas flow can be upward or downward in the chamber or it can flow in a horizontal direction. The relative velocity is somewhat higher than that for concurrent flow but lower than that for countercurrent flow.

Normally, a mixed flow configuration exists in a spray chamber as a result of turbulence, liquid droplet inertia and gravitational forces.

In addition to removing coarse particles from the gas at low-pressure drops, the spray chamber acts as a cooler and humidifier. It can also provide preconditioning of the particulate matter by water vapor condensation.

The gas velocity and the proper pattern of sprays are the important design parameters.

The spray chamber has a low dust collection efficiency for all except coarse dust particles (> 10 μm). Compared to packed scrubbers, the spray chambers are inefficient. Where collection efficiency below 80 percent is satisfactory, spray chambers can be an economical solution.

A partial list of suppliers of spray chambers is shown in Appendix J.

Cyclonic and Centrifugal Scrubbers. In cyclonic and centrifugal scrubbers, the dirty gas enters tangentially, which imparts a spinning motion to the gas stream. The centrifugal force thus produced increases the velocity difference between that of the collecting droplets and the gas stream. The net effect of this is a higher collection efficiency than can be achieved with spray towers and spray chambers.

The scrubbing liquor is introduced into the gas path by spraying through nozzles mounted on the walls of the scrubber or from nozzles mounted on a pipe in the center of the vessel. The swirling gas stream imparts a tangential motion to the droplets. If, however, the scrubbing liquor is introduced (or

sprayed) tangentially inward from the wall, an additional centrifugal motion is imparted to the gas. In a third method, the spinning motion is produced by fixed vaned baffles or by fixed vanes and impellers. Another method is to use helical baffles to prolong the centrifugal action of the gas.

Dust particles in the gas are collected by the droplets as a result of impaction and interception. The centrifugal force accelerates both dust particles and liquor droplets to the vessel wall, where collection of dust particles takes place. The wetted wall can also act as a collecting surface for dust and thus enhances the collection. The cleaned gas stream exits through the top.

The pressure drop across these scrubbers ranges from 2.5 to 20 cm of H_2O (1 to 8 inches H_2O), and the scrubbing liquor rates vary from 0.5 to 1.3 LPM of liquor per CMM of gas handled (4 to 10 GPM per 1,000 ACFM). The tangential velocities at the entrance are in the range of 30 to 37 m/sec (100 to 120 ft/sec). The scrubbing liquor is introduced at pressures of 345,000 to 2.7×10^6 N/M^2 (50 to 400 psig). The smaller the particles (down to 1 μm size), the higher the pressure used (up to 400 psig). These scrubbers are ineffective for the collection of submicron range particles.

Low pressure drops on the gas side, low liquor flow rate requirements and ease of fabrication and maintenance are some of the advantages of cyclonic scrubbers; inability to handle scrubbing liquors containing solids (due to nozzle plugging), inadequate removal of submicron particles and the requirement for higher liquor supply pressures are the disadvantages.

The composite efficiency, based on particle size distribution, for a cyclonic spray scrubber is presented in Table 22.

A partial list of suppliers of cyclonic and centrifugal scrubbers is shown in Appendix J.

Table 22. Performance Data for the Cyclonic Spray Scrubber

Particle Size Range (μm)	Efficiency (%)
0 - 0.5	78.6
0.5 - 1.0	83.4
1.0 - 2.0	89.7
2.0 - 3.0	94.0
3 - 4	96.4
4 - 6	97.5
6 - 8	98.6
8 - 10	99.2

Impingement and Orifice Scrubbers. In the *impingement or orifice type scrubbers*, the high-velocity gas, impinging on the liquor surface, results in an intimate contact between the two phases. The flow of gases through a restricted passage partially filled with scrubbing liquor disperses the liquor. Dust collection occurs as a result of centrifugal forces, impingement, and turbulence. A preagglomerating stage is sometimes provided to enhance

the collection efficiency of fine particles. In the self-induced spray scrubbers, a spray curtain is induced by the gas flow through a partially submerged orifice or through streamlined baffles. These are low-pressure drop scrubbers and are efficient on dust particles larger than 1 μm when used as a single stage.

In this same category are the *direct-contact scrubbers.* These have the advantage that the scrubbing liquor with up to 65 percent solids can be recirculated. Scrubbing liquor requirements range from 0.4 to 0.7 LPM per CMM of gas (3 to 5 gallons per 1,000 cubic feet). The gas pressure drop through the scrubber depends on the application and the number and type of stages used. The pressure drop for a low-velocity scrubber ranges from 2.5 to 20 cm H_2O (1 to 8 inches H_2O), while for high-velocity units it can be up to 100 cm H_2O (40 inches H_2O).

Impingement baffle plate scrubbers provide over 97 percent removal by weight of particles above 1 μm, and a considerable percentage for smaller particles. High-velocity scrubbers that incorporate the high-velocity agglomerating slot stage can achieve 99 percent removal of submicron particles from blast furnace gases. At 76 cm H_2O pressure drop (30 inches H_2O , outlet dust loadings of 0.02 and 0.01 gr/SCF can be attained on merchant iron furnace gas and on basic iron furnace gas, respectively. This scrubber also removes 99+ percent by weight of dust entrained from pyrites roasters, and by its use, the dust loading in the gas generated from an incinerator is reduced from 2 to 5 grains per standard cubic foot to 0.2 grain per standard cubic foot. Overall efficiency for a single stage may range from 90 to 98 percent for 1 μm or larger particles. Typical applications include pyrites roaster flue gas, incincerator

flue gas, blast furnace, merchant iron furnace, basic iron furnace gases, dryers, kilns and sinter machines.

In *orifice scrubbers,* the gas stream accelerates through the orifices and liquor, and in so doing, the particles are wetted and collected as a result of impingement, turbulence and centrifugal forces. The degree of dispersion is, however, less than that attained by spray nozzles and impingement baffles and so is the efficiency.

Roto-Clones. *Roto-clones* are widely used in taconite beneficiating and pelletizing plants. The gas streams are cleaned by the combined action of centrifugal force and a thorough intermixing of scrubbing liquor and dust-laden gas stream. In the type N roto-clone, the gas stream is ducted through a stationary impeller at high velocity, forcing the scrubbing liquor to form a heavy turbulent sheet. The centrifugal force exerted by the rapid changes in the direction of flow causes the dust particles to penetrate the water film and get collected. The scrubbing liquor is continually reused, and since the water curtain (sheet) is produced by the gas flow, no pumps or nozzles are required. The scrubbing liquor level is maintained at the same elevation on the clean gas side. Baffle plates (zig-zag) are incorporated to remove the entrained liquor droplets. In the type R roto-clone (quite common in iron ore beneficiation and pelletizing operations), the scrubbing liquor, introduced into each cone, is carried to the periphery by the centrifugal force of the high-velocity, dust laden gas entering the two tangential inlets of each cone. Dust particles impinge against the wetted peripheral surfaces.

Typical applications of this design include material handling, crushing and grinding, kilns, dryers, coolers, tumbling mills and lead battery plants. Test data for those used in the iron ore industry showed an average efficiency of 98.5 percent.

Some suppliers of impingement type scrubbers are shown in Appendix J.

Venturi Scrubbers. *Venturi scrubbers* have come into prominence because of their ability to provide high collection efficiency for submicron dust particles and their simplicity of installation and maintenance.

The dust-laden gas entering a venturi scrubber is accelerated to a high velocity while passing through the converging section and approaching the throat section of a venturi. The velocity of the gas is the maximum at and in the throat section of the scrubber. The high-velocity gas impinges (impacts) upon a liquid stream in the throat, thereby atomizing the liquor into large numbers of fine droplets. The high differential velocity between the gas and the atomized droplets causes liquor droplets and dust particles to collide, impact and agglomerate. As the gas decelerates, further impaction and agglomeration of the droplets take place. After the particles have been trapped within the liquor droplets, the resulting agglomerates are readily removed from the gas stream in an attached separator.

Energy in the form of pressure drop is expended to perform the scrubbing action. Low pressure drops are required for particles larger than 1 μm; higher pressure drops are needed for submicron particles. In fact, the higher the pressure drop, the higher the removal efficiency of submicron particles.

The pressure drop can be increased in a venturi scrubber by increasing the gas velocity and/or the scrubbing liquor flow rate, but the former is more effective.

The size of the dust particles, and of the liquor droplets formed by atomization, plays a very important role in determining the collection efficiency and the collection mechanism. If the particles are 0.1 μm or smaller in diameter, the collection mechanism by which they may be collected is Brownian diffusion, whereas if the particles are larger than 0.1 μm, the predominant mechanism is impaction.

The only variation between the several venturi scrubber designs is in the method of liquor introduction in the throat and in the types and shapes of throats. The performance of all types of venturi scrubbers will be essentially the same for the same application, provided the throat pressure drop is the same.

The most common types and shapes of throats are rectangular, circular, oval and annular. The width and length of the throat (or diameter in the case of a circular throat) are very important to insure full coverage of the throat with scrubbing liquor. The circular throat could be of any diameter when the scrubbing liquor is introduced by spray nozzles located above the throat. This type is normally used for low pressure drop applications. In the case of high pressure drop applications and when the liquor is introduced in the throat by horizontal sprays or by other methods, the maximum opening size used is 46 to 51 cm (18 to 20 inches). In case of rectangular or oval throat cross sections, the maximum width is about 46 to 51 cm (18 to 20 inches); the lengths are approximately 2.4 to 3 meters (8 to 10 feet). The requirement for complete coverage of the throat

by scrubbing liquor limits the width of the throat (otherwise a blow hole can be developed by the high-velocity gas), whereas the limitation on throat length is due to the limitation on available scrubbing liquor flow.

To handle larger gas volumes, a more commonly used throat type is an annulus formed by two circles. Here again the throat gap is maintained at about 46 to 51 cm (18 to 20 inches). The scrubbing liquor is introduced by spray nozzles located either in or above the throat by weir arrangement or by tangential pipe nozzles.

The collection efficiency, dust particle size and pressure drop are interrelated, with the pressure drop as the main criterion for collection efficiency. Dust collection efficiency can be maintained constant by maintaining the pressure drop across the throat essentially constant. For varying gas flow rates, an adjustable throat is used to adjust the gas velocity, and hence the pressure drop across the throat. Following each of the venturi scrubbers, an efficient entrainment separator must be installed to remove the entrained liquor from the gas.

There are a multitude of designs of venturi scrubbers. They typically require pressure drops of 15 to 200 cm H_2O (6 to 80 inches) and liquor flows of 1.3 to 2.7 LPM per CMM (10 to 20 GPM/1000 ACFM). Their collection efficiencies are typically more than 99 percent for particles 1 μm or larger and 90 to 99 percent for particles smaller than 1 μm. Low pressure venturi scrubbers are used in taconite beneficiating and pelletizing plants, especially on crushers and on screening operations. A few high-pressure scrubbers are being used to control emissions from dry, semi-autogenous grinding operations.

A partial list of suppliers of venturi scrubbers is shown in Appendix J.

Electrostatic Precipitators. Electrostatic, or electrical, precipitators (ESP's) are a variety of equipment utilizing electric forces to separate particulate matter and aerosols from gases. Some types are truly electrostatic while others are not. The fundamental steps of operation involved are 1) electrical charging of suspended particles, 2) collection of the charged particles in an electric field and 3) removal of the collected material to an external receptacle.

The high-voltage direct-current corona method is used for charging the particles. Usually the corona is established between the fine wire (the active electrode) and a smooth cylindrical or plate electrode at ground potential. In industrial precipitators, the wire has negative polarity and the positive ions formed in the corona glow are attracted to the wire. The negative ions are also formed in the corona, and these are attracted to the ground electrode. Therefore, most of the gas space between the two electrodes contains negative ions. Particles in the gas are bombarded by these negative ions and quickly become charged. Typical particle charges achieved are 300 electron charges for 1 μm size particles and 30,000 electron charges for 10 μm particles.

The charged particles are collected by subjecting them to an electric field. This collecting field may be a continuation of the corona, as in the Cottrell (or single-stage type) design, or it may be an electrostatic field between nondischarging electrodes (the two-stage design). Single-stage designs are used in cleaning industrial gases and the two-stage type is used principally for cleaning air when low-ozone generation is necessary. In either case, the coulomb force, which is proportional to the product of the

particle charge and the electric field intensity, is the separating force on the particle. The motion of the particle is resisted by viscous forces governed at least approximately by Stokes' law. Thus, a particle attains a steady state velocity determined by the equilibrium between the coulomb and Stokes forces. This velocity is called the migration velocity and is about 3 cm/sec for 0.5 μm particles at normal precipitator conditions.

The last phase is the removal of the collected material to external receivers. Some solid particles are very susceptible to reentrainment in the (turbulent) gas stream, and therefore are difficult to remove from the precipitator. Reentrainment normally does not occur with liquid droplets or with solid particles that are cohesive and form larger agglomerates.

The size and type of precipitator are determined by the physical properties of the particles and of the carrier gas, the gas flow rate, and the required collection efficiency. For collection of liquid droplets and for smaller gas flow rates, the cylindrical type electrode is used; plate type systems are used for dry solids and large gas flow rates.

Electrical precipitators have many advantages over other types of particulate collection devices. Precipitators are unique in that the collecting force is applied only to the material being collected and not to the total gas stream. This results in relatively low operating costs, because the pressure drop through the system is small and the power requirements are low. Precipitators have the ability to handle very large gas rates and to remove very small particles at high efficiency. They can operate over a wide range of conditions--temperatures up to 800°C and pressures of 50 atmospheres.

Their largest disadvantage is the high initial cost; the investment for the precipitator is normally greater than for any other equipment for air pollution control. Another disadvantage is that precipitators are not easily adapted to changing process conditions. Automatic voltage control helps this situation, yet precipitators are most efficient at constant operating conditions. Also the high-voltage equipment in electrical precipitation necessitates special safety precautions.

The advantages of ESP's are that they have high efficiencies (90 to 99.5 percent) on a wide range of particle sizes including small particles (< 0.1 μm to > 200 μm) and their power requirements are relatively low. The average efficiency of those reported in the iron ore industry is 99 percent.

ESP's are just beginning to find their place in the taconite industry. At least one plant has ESP's for pollution control on their main waste gas streams. Another plant has tested wet wall ESP's and found them to be very effective on particulates as well as on some gaseous pollutants (e.g., fluorides).

A partial list of supplies of ESP's is shown in Appendix J.

Field Testing

Four air emissions sources were selected for field testing: a crushing operation controlled by a baghouse, a vertical shaft furnace fired with fuel oil, a shovel loading site in a mine, and an uncontrolled annular cooler. The results of those tests are summarized in this section. The first two test sources were located at one plant, and the latter two at another plant. Process descriptions and operational information on these four sources are presented in Appendix A. The sampling and analytical procedures used are presented in Appendix B and other supporting information such as actual data, computer printouts, sample calculations and analyses are included in other appendices as noted in the text.

Crusher with Baghouse. The Pea Ridge Mine, Meramec Mining Company, Sullivan, Missouri, (owned jointly by Bethlehem Steel Corporation and St. Joseph Minerals Corporation) was the test site for a baghouse on a crushing operation. The baghouse, controlling emissions from the secondary crushers, was sampled, on the three inlets and the outlet, for total mass, trace metals, and silica content. Outlet samples were also analyzed for absestiform material.

The three inlets were designated A, B, and C. Inlet A controlled dust from a conveyor belt feeding a crusher and another conveyor belt removing crushed ore from this and one other crusher; inlet B controlled dust generated by three vibratory screens; and inlet C controlled dust generated by transfer of ore between conveyor belt systems. Figure A-1 of Appendix A schematically identifies the sources controlled by these three inlet ducts.

Mass results for the crusher baghouse are summarized in Table 23. Data are presented in units of grains per dry standard cubic foot (gr/dscf), pounds emitted per hour (lb/hr), milligrams per normal cubic meter (mg/Nm^3), and kilograms emitted per hour (kg/hr); the baghouse efficiency is also included. Values in Table 23 represent the process while operating continuously. These values should not be used to calculate the corresponding 24-hour values since this process normally operates intermittently, with frequent periods of inactivity during which there are no emissions. Computer printouts of the field data and data reductions are presented in Appendix C. Sample calculations can be found in Appendix D.

A summary of the measured *air flows* in each of the crusher baghouse ducts is presented in Table 24. Note that the total air flow into the baghouse is about 29 percent less than the outlet air flow rate. This is not surprising because the sampling site locations available for testing were far from ideal (in or near bends, directly downstream of the fan on the outlet site, etc.). Although the air flow rates are reflected in the mass results presented in Table 24, the mass results are believed to be indicative of the process and are therefore useful for the purpose of this study.

The *silica results* for the baghouse samples are summarized in Table 25. The data are given in units of micrograms of silica (as SiO_2) per gram of sample (µg/g), grains ($\times 10^{-7}$) per dry standard cubic foot (gr $\times 10^{-7}$/dscf), and micrograms per normal cubic meter ($\mu g/Nm^3$)

Table 23. Summary of Mass Results Meramec Crusher

Date	Run Number / English Units	Inlet A		Inlet B		Inlet C		Total Inlet	Outlet		Baghouse Efficiency
		gr/dscf[a]	lb/hr[b]	gr/dscf	lb/hr	gr/dscf	lb/hr	lb/hr	gr/dscf	lb/hr	Percent
A	1	2.164	151	0.369	26	2.442	83	260	0.234	60	76.9
	2	3.593	300	0.307	23	2.549	95	418	0.174	46	89.0
	Average	2.879	225	0.338	25	2.495	89	339	0.204	53	84.4
	Metric Units	mg/Nm^3[c]	kg/hr[d]	mg/Nm^3	kg/hr	mg/Nm^3	kg/hr	kg/hr	mg/Nm^3	kg/hr	
B	1	4,955	68	843	12	5,590	38	118	535	27	
	2	8,220	136	700	10	5,835	43	190	400	21	
	Average	6,590	100	770	11	5,710	40	155	465	24	

[a] gr/dscf = grains per dry standard cubic foot.

[b] lb/hr = pounds per hour.

[c] mg/Nm^3 = milligrams per normal cubic meter.

[d] kg/hr = kilograms per hour.

Table 24. Summary of Duct Air Flows--Meramec Crusher

Date	Run Number English Units	Inlet A dscfm[(a)]	Inlet B dscfm	Inlet C dscfm	Total Inlet dscfm	Outlet dscfm
A	1	8,120	8,300	3,975	20,395	29,890
	2	9,745	8,675	4,355	22,775	30,660
	Average	8,930	8,490	4,165	21,585	30,275
Date	Metric Units	Nm^3m[(b)]	Nm^3m	Nm^3m	Nm^3m	Nm^3m
B	1	230	235	113	578	846
	2	276	246	123	645	868
	Average	253	240	118	611	857

(a) dscfm = dry standard cubic feet per minute.

(b) Nm^3m = normal cubic meters per minute.

Table 25. Summary of Silica Results--Meramec Crusher

Date	Run	Location	Silica		
			µg/g[a]	gr/dscf[b] (x 10^{-7})	µg/Nm^3[c]
28 April 1977	3-A	Inlet A	58	36.08	8.26
	3-B	Inlet B	19	2.63	0.60
	3-C	Inlet C	4.5	0.99	0.23
	3-O[d]	Outlet	29	3.26	0.75
3 May 1977	7-O[e]	Outlet	43	2.67	0.61
Average of 4 Blank Filters			0.012		

[a] µg/g = micrograms per gram of sample.

[b] gr/dscf = grains per dry standard cubic foot.

[c] µg/Nm^3 = micrograms per normal cubic meter.

[d] Run at 110.6 percent isokinetic.

[e] Run at 82.9 percent isokinetic.

The samples used for silica analysis were collected with the same equipment as used for particulate testing, however, only the particulates collected on the filter were analyzed for silica content. Thus, the silica results presented in Table 25 represent the free silica content of small particles only--particles less than about 10 microns in size. There were two reasons for limiting the silica analysis to small particles: one, from a health aspect, it would be more informative to know the silica content of the emissions in a particle size range close to the respirable range (less than 2 microns); and two, larger particles would have altered the calibration of the infrared analysis used to quantify the silica content and would have lowered the sensitivity of the analysis for small particles.

Silica runs 3-0 and 7-0 on the outlet were made outside the 90 and 110 percent isokinectic range required for obtaining representative samples. This should not, however, affect the validity of the results because only the smaller particle size fraction was analyzed for silica content and particles of this size are not adversely biased at sampling rates slightly outside of the normal sampling range.

Asbestos tests were run on samples collected at the crusher outlet only. In none of the three samples analyzed was asbestiform material detected above the detection limits. The detectable limits were, in fibers per liter of air: 810 for Run 4-0 (sample 149); 1100 for Run 5-0 (Sample 150); and 1400 for Run 6-0 (Sample 151). Some inorganic fibers less than 3 microns in length and containing principally iron were detected. A complete presentation on the asbestos analysis, including photographs, is given in Appendix E.

Trace Metals analyses were performed on the particular mass samples after the mass loading had been determined. The metals analyzed for were: arsenic, cadmium, cobalt, total chromium, copper, molybdenum, lead, nickel, vanadium and zinc. The results are tabulated in units of micrograms per gram of sample (μg/g) in Table 26, in units of grains per dry standard cubic foot (gr x 10^{-4}/dscf) in Table 27, and in milligrams per normal cubic meter (mg/Nm^3) in Table 28. Detailed information on the sampling and analytical procedures used to obtain the trace metals data are given in Appendix B.

Particle size results for the crusher are shown in Table 29; shown are the cumulative weight fraction and the Stokes equivalent diameter by stage for both the Brink and Anderson impactor test results (the Brink impactor results are for the inlet and the Anderson results for the outlet). Figure 4 is a plot of $\Delta C/\Delta \log D$ versus GMD (differential of the cumulative mass curve for a particle size band normalized by the sample air volume), and expressed in concentration--C--units of mg/Nm^3 versus the geometric mean diameter--GMD--in microns for the crusher inlet; similarily, Figure 5 is the plot for the crusher outlet. Supporting data for the table and plots of particle size are found in Appendix F and sample calculations are presented in Appendix D.

Comparing the curves in Figure 4 with those in Figure 5 reveals that the curves for the crusher outlet are not displaced to any significant degree from the curves for the inlet, particularly for particle sizes under 2 microns. In other words, the concentration of particles in various size bands, under approximately 10 microns in size, in the crusher inlet and outlet are not

Table 26. Summary of Trace Metal Results--Meramec Crusher (µg/g).

µg/g

Date	Run	Location	Arsenic	Cadmium	Cobalt	Total Chromium	Copper	Molybdenum	Lead	Nickel	Vanadium	Zinc
27 April 1977	1-A	Inlet A	80	<10[b]	700	100	1,400	406	<100	500	8,000	2,700
	1-B	Inlet B	130	22	848	57	2,600	<450	3,467	565	6,790	1,920
	1-C	Inlet C	60	<10	750	50	1,600	<400	<106	600	6,000	1,800
	1-O	Outlet	105	<9.9	747	597	1,790	<400	<99	896	5,970	2,990
28 April 1977	2-A	Inlet A	100	<9.9	846	1,140	1,390	<400	<99	996	5,970	339
	2-B	Inlet B	122	27	811	338	2,160	<540	135	600	4,050	7,160
	2-C	Inlet C	59	<9.9	892	2,080	1,730	<400	99	1,390	5,950	377
	2-O	Outlet	54	27	672	1,410	1,880	<540	<130	1,210	5,370	19,900
	Average	Inlet A	90	<10	773	620	1,395	<400	<100	748	6,985	1,520
	Average	Inlet B	126	25	830	198	2,380	<495	1,801	583	5,420	4,540
	Average	Inlet C	60	40	821	1,065	1,690	<400	<100	995	5,975	1,089
	Average	Outlet	80	<18	710	1,004	1,795	<470	<115	1,053	5,670	11,445

(a) µg/g = micrograms per gram of sample

(b) < = less than (below detection limit).

Table 27. Summary of Trace Metal Results--Meramec Crusher (gr/dscf)

gr (x 10^{-4})/dscf[a]

Date	Run	Location	Arsenic	Cadmium	Cobalt	Total Chromium	Copper	Molybdenum	Lead	Nickel	Vanadium	Zinc
27 April 1977	1-A	Inlet A	1.73	<0.22[b]	15.16	2.17	30.31	8.79	<2.17	10.83	173	58.46
	1-B	Inlet B	0.48	0.08	3.13	0.21	9.58	<1.66	12.78	2.08	25	7.08
	1-C	Inlet C	1.46	<0.24	18.31	1.22	39.06	<9.77	<2.59	14.65	146	43.95
	1-O	Outlet	0.25	<0.02	1.75	1.40	4.18	<0.93	<0.23	2.09	14	6.99
28 April 1977	2-A	Inlet A	3.59	<0.36	30.40	40.97	49.95	<14.37	<3.56	35.79	215	12.18
	2-B	Inlet B	0.37	0.08	2.49	1.04	6.62	<1.66	0.41	1.84	12	21.95
	2-C	Inlet C	1.50	<0.25	22.74	53.02	45.38	<10.20	2.52	35.43	152	9.61
	2-O	Outlet	0.09	0.05	1.17	2.45	3.27	<0.94	<0.23	2.11	9	34.64

[a] gr (x 10^{-4})/dscf = grains (x 10^{-4}) per dry standard cubic foot.

[b] < = less than (below detection limit).

Table 28. Summary of Trace Metal Results--Meramec Crusher (mg/Nm^3)

Date	Run	Location	Arsenic	Cadmium	Cobalt	Total Chromium	Copper	Molybdenum	Lead	Nickel	Vanadium	Zinc
			mg/Nm^3[a]									
27 April 1977	1-A	Inlet A	0.396	<0.050[b]	3.468	0.495	6.936	2.012	<0.495	2.477	39.64	13.38
	1-B	Inlet B	0.110	0.019	0.715	0.048	2.193	<0.379	2.924	0.476	5.73	1.62
	1-C	Inlet C	0.335	<0.056	4.190	0.279	8.939	<2.235	<0.592	3.352	33.52	10.06
	1-O	Outlet	0.056	<0.005	0.399	0.319	0.957	<0.214	<0.053	0.479	3.19	1.60
28 April 1977	2-A	Inlet A	0.822	<0.081	6.957	9.374	11.430	<3.289	<0.814	8.190	49.09	2.79
	2-B	Inlet B	0.086	0.019	0.569	0.237	1.515	<0.379	0.095	0.421	2.84	5.02
	2-C	Inlet C	0.344	<0.058	5.203	12.133	10.383	<2.333	0.578	8.108	34.71	2.20
	2-O	Outlet	0.022	0.011	0.268	0.562	0.749	<0.215	<0.052	0.482	2.14	7.93

[a] mg/Nm^3 = milligrams per normal cubic meter.

[b] < = less than (below detection limit).

Table 29. Summary of Particle Size Results--Meramec Crusher

A. Cumulative Weight Fraction

Run No. / Location / Date / Stage	Percent of Total Weight Less Than Given Stage							
	1-AB[a]	2-BB[a]	4-CB[a]	5-CB[a]	1-OA[b]	2-OA[b]	3-OA[b]	4-OA[b]
	Inlet A	Inlet B	Inlet C	Inlet C	Outlet	Outlet	Outlet	Outlet
	27 April	28 April	28 April	28 April	27 April	28 April	28 April	28 April
Cyclone	100.0	100.0	100.0	100.0				
1	1.9	10.6	2.3	1.2	100.0	100.0	100.0	100.0
2	0.8	8.7	1.5	0.4	70.8	48.8	22.3	26.8
3	0.4	4.8	1.1	0.2	42.1	23.3	9.3	11.6
4	0.2	2.7	0.4	0.1	15.9	10.3	3.8	3.9
5	0.1	1.2	0.1	0.1	4.6	6.6	2.4	1.5
6					1.1	5.5	1.4	0.7
7					0.1	0.4	0.7	0.5
8						0.2	0.4	0.2
Filter	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

B. Stokes D_{50} Diameter

	Stokes D_{50} Diameter (Microns)							
Cyclone	7	7	7	7				
1	2.39	2.17	2.03	2.03	7.2	7.2	7.2	7.2
2	1.40	1.28	1.19	1.19	4.5	4.5	4.5	4.5
3	0.96	0.87	0.81	0.81	3.0	3.0	3.0	3.0
4	0.50	0.45	0.42	0.42	2.1	2.1	2.0	2.0
5	0.32	0.29	0.26	0.26	1.3	1.3	1.3	1.3
6					0.6	0.6	0.6	0.6
7					0.4	0.4	0.4	0.4
8					0.3	0.3	0.3	0.3

[a] Brink Impactor

[b] Andersen Impactor

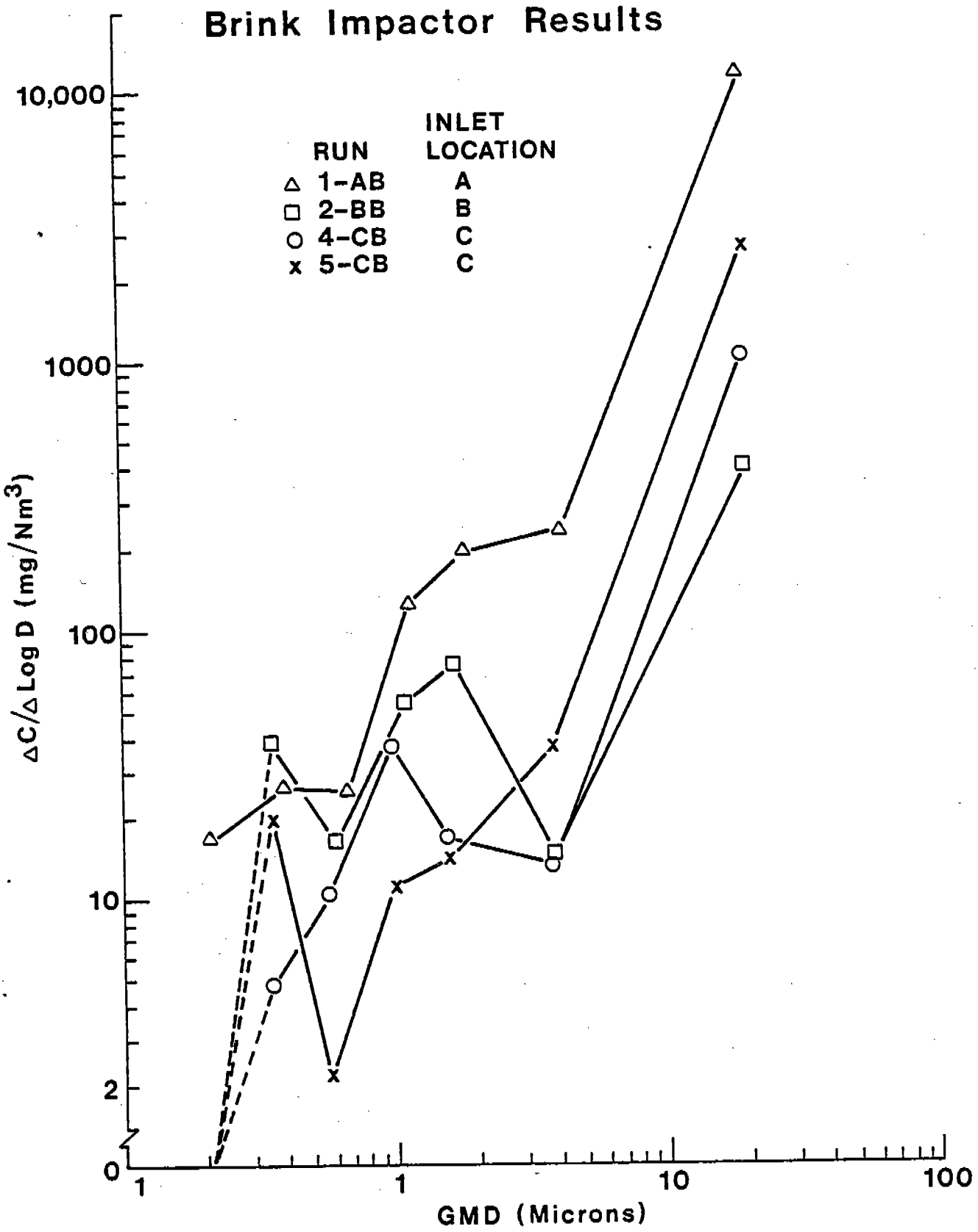

Figure 4. ΔC/ΔLogD versus Geometric Mean Diameter - Crusher Inlet

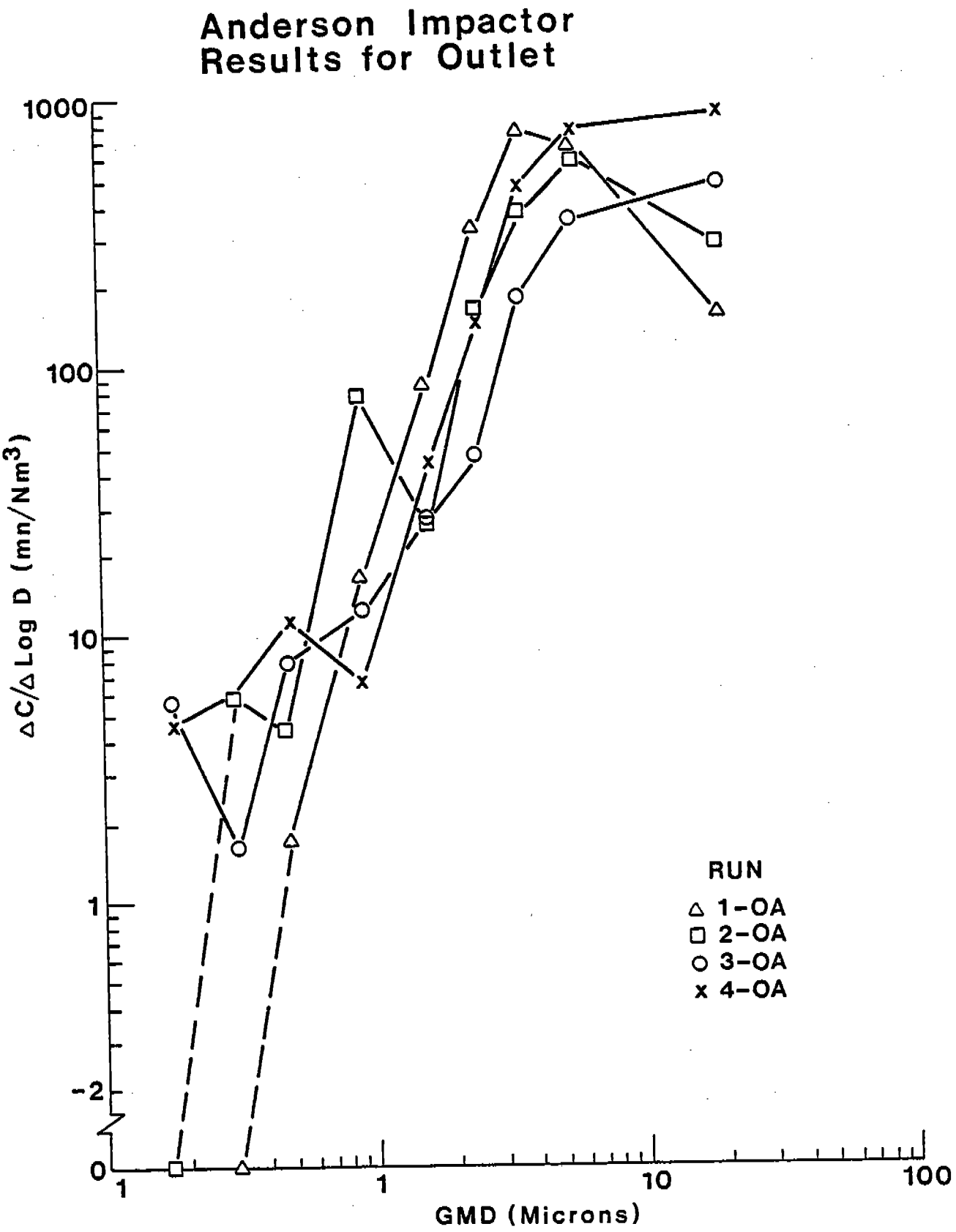

Figure 5. ΔC/ΔLogD versus Geometric Mean Diameter - Crusher Outlet

too different. This establishes that the collection efficiency of the crusher baghouse for particles under 10 microns in size, as measured by the particle size testing, was poor.

Vertical Shaft Furnace. The Meramec Mining Company operation at Sullivan, Missouri, uses No. 6 fuel oil in five vertical shaft furnaces for induration. Emissions from furnace No. 1 were field tested on this program for total mass, particle size and sulfur dioxide concentration. Samples were collected from both the top gas (which includes combustion gases) and the cooler (or bottom) gas. Sampling locations on both streams were downstream of cyclone-type collectors and thus the results for particulates represent controlled emissions. Sampling before controls was not possible because the control devices were integral to the shaft furnace. A description of the induration process and of the sampling locations and procedures are presented in Appendices A and B.

Controlled *mass loading* results for the vertical shaft furnace are summarized in Table 30. For a nominal production rate of 45 MT per hour per furnace the average measured emission rates are 0.30 kg/MT of pellets (.67 lb/MT) for the cooler gas and 1.08 kg/MT of pellets (2.38 lb/MT) for the top gas or a combined rate of 1.38 kg/MT. This controlled emission rate of 1.38 kg/MT is more than four times the average value of 0.44 kg/MT for waste gas emissions from the induration process, as listed in Table 12. Computer printouts of the field data reductions are presented in Appendix C.

Table 30. Summary of Mass Results--Meramec Furnace

Date	Run	Cooler Duct				Top Gas Duct			
		gr/dscf[a]	lb/hr[b]	mg/Nm^3[c]	kg/hr[d]	gr/dscf	lb/hr	mg/Nm^3	kg/hr
2 May 1977	4-L	0.234	42.5	535	19.3				
3 May 1977	5-L	0.121	22.7	277	10.3				
	5-T					0.187	95.8	428	43.4
	6-L	0.126	25.2	289	11.4				
	6-T					0.212	108.3	485	49.1
	7-T					0.226	117.8	516	53.4
	Average	0.161	30.1	367	13.7	0.208	107.3	476	48.7

[a] gr/dscf = grains per dry standard cubic foot.

[b] lb/hr = pounds per hour.

[c] mg/Nm^3 = milligrams per normal cubic meter.

[d] kg/hr = kilograms per hour.

Sulfur dioxide concentrations for the furnace top gas are presented in Table 31; sulfur dioxide measurements were not made for the cooler duct since it contains only air and no combustion gases. The data of Table 31 are in units of pounds per dry standard cubic foot (lb/dscf), milligrams per normal cubic meter (mg/Nm^3), and parts per million (ppm). Computer printouts of the field data are given in Appendix G and sample calculations in Appendix D.

Cumulative weight fraction and *particle size test results* for the vertical shaft furnace are summarized in Table 32. Run No. 8LB--the first Brink sampler run on the cooler gas duct--was run at too high a flow rate for too short a time period; hence, the results of this run are very questionable. The particle size results, except those for Run No. 8LB, are also presented in Figure 6 as plots of $\Delta C/\Delta \log D$ versus GMD. Curves for two Runs (Nos. 7-TB and 9-LB), which were run at approximately the same time, indicate similar concentrations of emissions as a function of particle size for both the top and bottom gases. However, the duplicate run on the top gas--Run No. 6-TB--which was run a day earlier, indicates a higher loading as a function of particle size. This implies that the emission rate for the top gas can vary. In fact, this was observed not only at this plant but also at another with a vertical shaft furnace. Industry personnel claim that higher quality pellets produce less emissions and that an increase in the opacity of plume from a vertical shaft furnace indicates a decrease in the quality of the green pellets being fed into the furnace. Computer printouts of the data are in Appendix F and supporting data in Appendix D.

Table 31. Summary of SO_2 Results--Meramec Furnace

Date	Run	Top Gas Duct		
		lb/dscf[a] (x 10^{-5})	mg/Nm^3[b]	ppm[c]
2 May 1977	1	3.06	0.49	185
	2	4.44	0.71	268
	Average	3.75	0.60	226
3 May 1977	3	5.26	0.84	318
	4	4.79	0.77	290
	Average	5.03	0.81	304
	5	4.42	0.71	267
	6	4.85	0.78	293
	Average	4.63	0.75	280

(a) lb/dscf = pounds per dry standard cubic foot.

(b) mg/Nm^3 = milligrams per normal cubic meter.

(c) ppm = parts per million.

Table 32. Summary of Particle Size Results--Meramec Vertical Shaft Furnace

A. Cumulative Weight Fraction

Run No. / Date / Stage	Percent of Total Weight Less than Given Stage			
	6-TB[a,b]	7-TB[a,b]	8-LB[a,c]	9-LB[a,c]
	2 May	3 May	3 May	3 May
Cyclone	100.0	100.0	100.0	100.0
1	8.6	9.0	100.0	20.7
2	3.4	5.9	100.0	13.1
3	1.8	4.7	100.0	7.6
4	1.0	3.6	43.0	5.9
5	0.5	0.7	20.9	3.0
Filter	0.0	0.0	0.0	0.0

B. Stokes D_{50} Diameter

Stage	Stokes D_{50} Diameter (Microns)			
Cyclone	7	7	7	7
1	2.66	2.51	2.61	2.88
2	1.57	1.48	1.54	1.70
3	1.07	1.01	1.05	1.16
4	0.56	0.53	0.55	0.62
5	0.36	0.34	0.35	0.40

(a) Brink Impactor.

(b) Top gas duct.

(c) Cooler duct.

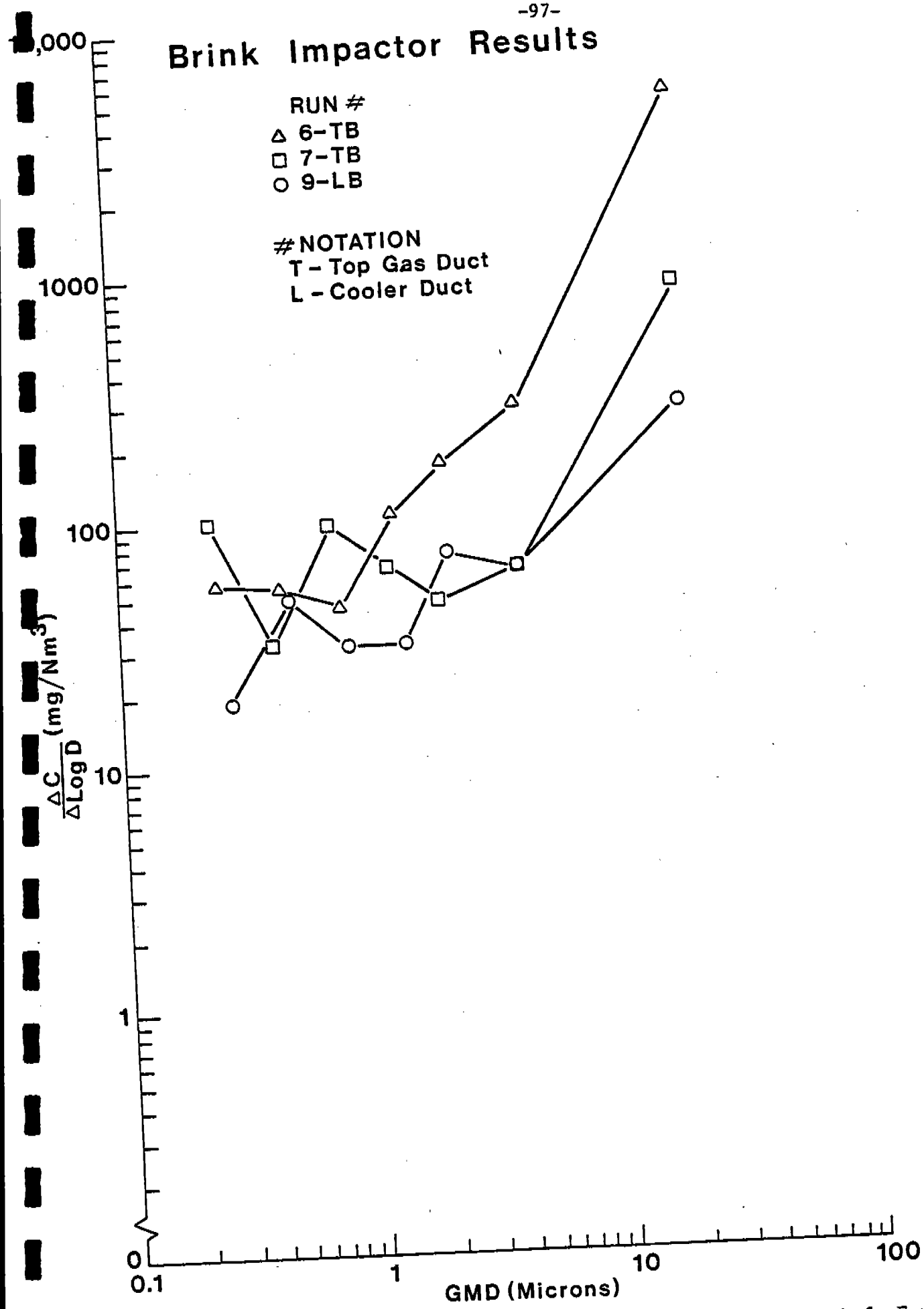

Figure 6. ΔC/ΔLogD Versus Geometric Mean Diameter--Meramec Vertical Shaft Furnace

Mine Shovel Loading Site. The Minntac Mine owned and operated by the U.S. Steel Corporation, and located in Mountain Iron, Minnesota, was the site tested for total mass, particle size, and asbestos content of emissions generated by shovel loading of rail cars. This site was selected because: 1) the absence of trucks in the mine eliminated an additional source of emissions; 2) sampling crews could work without getting in the way of the mining operation; and 3) the mine was still shallow enough so as to minimize the effect on air currents.

Particulate samplers for *mass loadings* were arranged at five positions as shown in Figure 7. The mass results for the only successfully completed run are summarized in Table 33, where the data are presented in grains per dry standard cubic foot (gr/dscf), and milligrams per normal cubic meter (mg/Nm^3). Also given in Table 33 are the mass results for upstream and downstream high-volume samplers; the results for the upstream sampler show that the background concentration is quite insignificant. Information on the site description and the sample locations and procedures is given in Appendices A and B; supplemental data may be found in Appendix H.

Particulate mass concentrations as a function of sampler location are shown in Figure 8 for the horizontal direction and Figure 9 for the vertical direction. Had the sampling grid been located near the center of the plume, then the intermediate value for the three values shown in Figures 8 and 9 would be the largest. As can be seen from the figures, the sampling grid was obviously horizontally off to one side of the peak concentration and too low, even though attempts were made, within the physical and safety

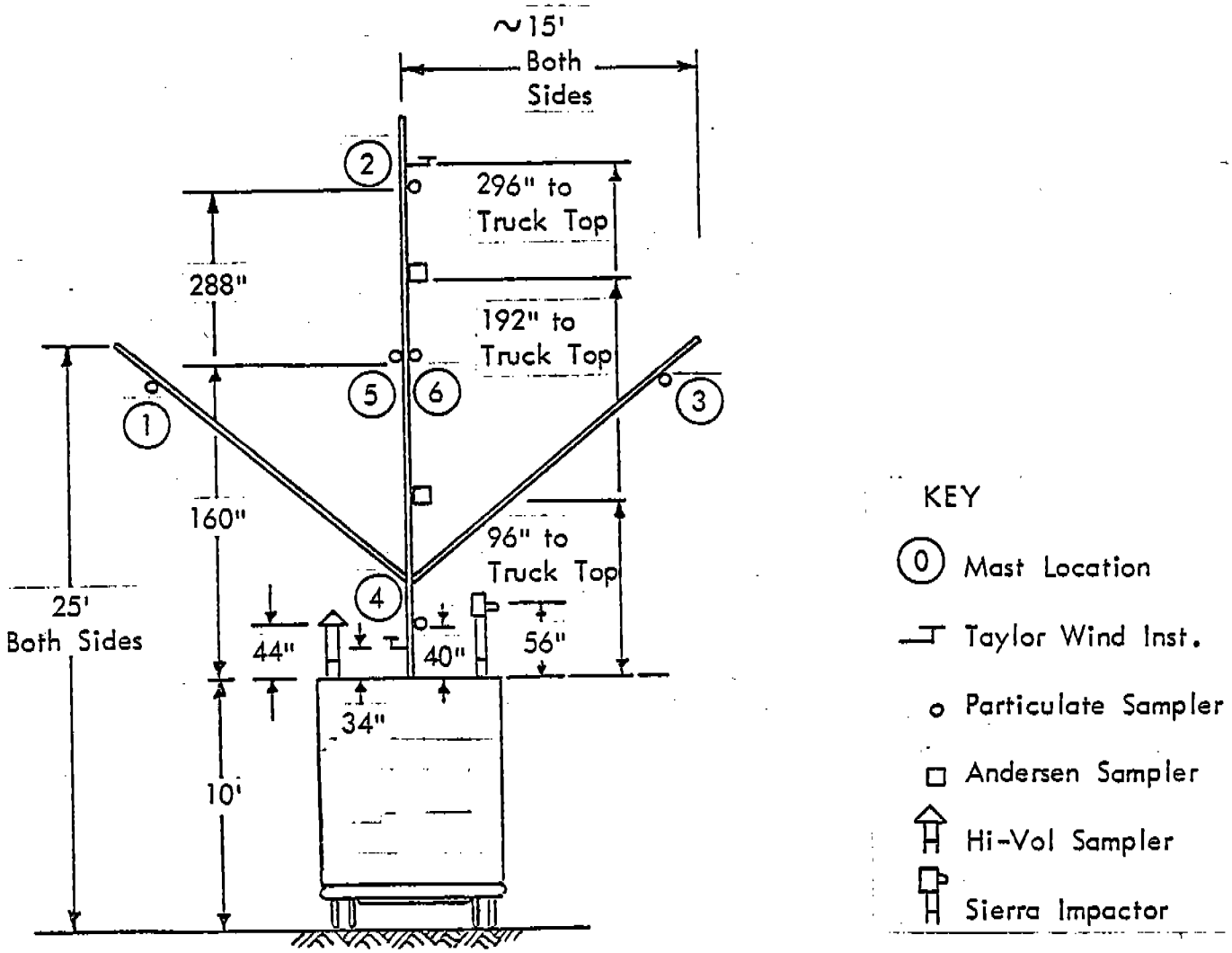

Figure 7. Mast/Sampler Location on Truck

Table 33. Summary of Mass Results--Minntac Shovel Site

Particulate Concentration	Mast Location					High Volume Sampler	
	1[a]	2[a]	3[a]	4[a]	5[a]	U[b]	D[c]
gr/dscf[d]	0.002609	0.025227	0.002059	0.004356	0.002001	0.000027	0.000646
mg/Nm^3[d]	5.97	57.73	4.71	9.97	4.58	0.06	1.48
Particulate Concentration Excluding Background							
gr/dscf	0.02582	0.0252	0.002032	0.004329	0.001974	0	0.000619
mg/Nm^3	5.91	57.67	4.65	9.91	4.52	0	1.42

(a) See Figure 4.

(b) U = Upwind sampler, see Figure A-11.

(c) D = Downwind sampler mounted on truck, see Figure 4.

(d) gr/dscf = Grains per dry standard cubic foot.

mg/Nm^3 = Milligrams per normal cubic meter.

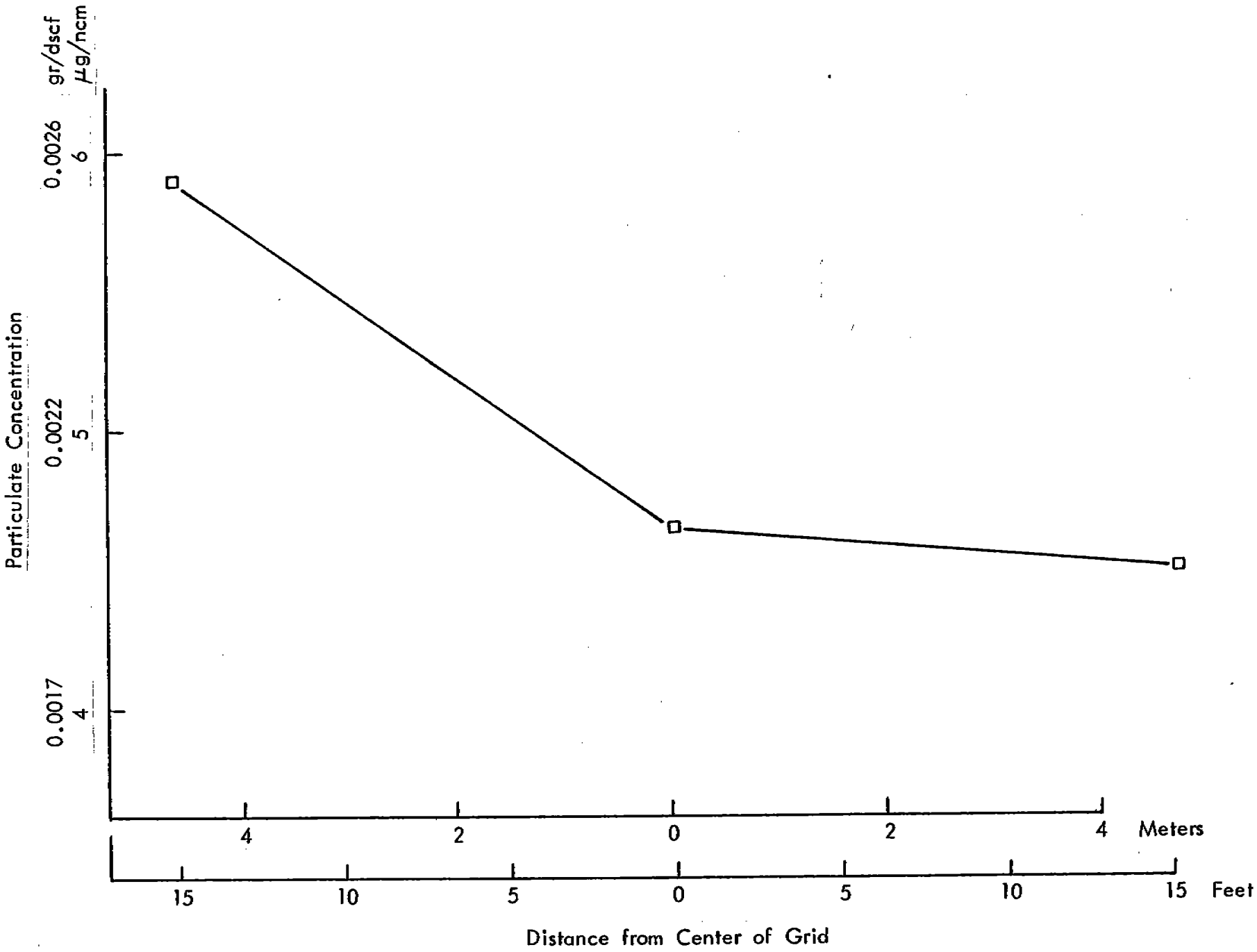

Figure 8. Particulate Concentration Versus Grid Location in Horizontal Direction

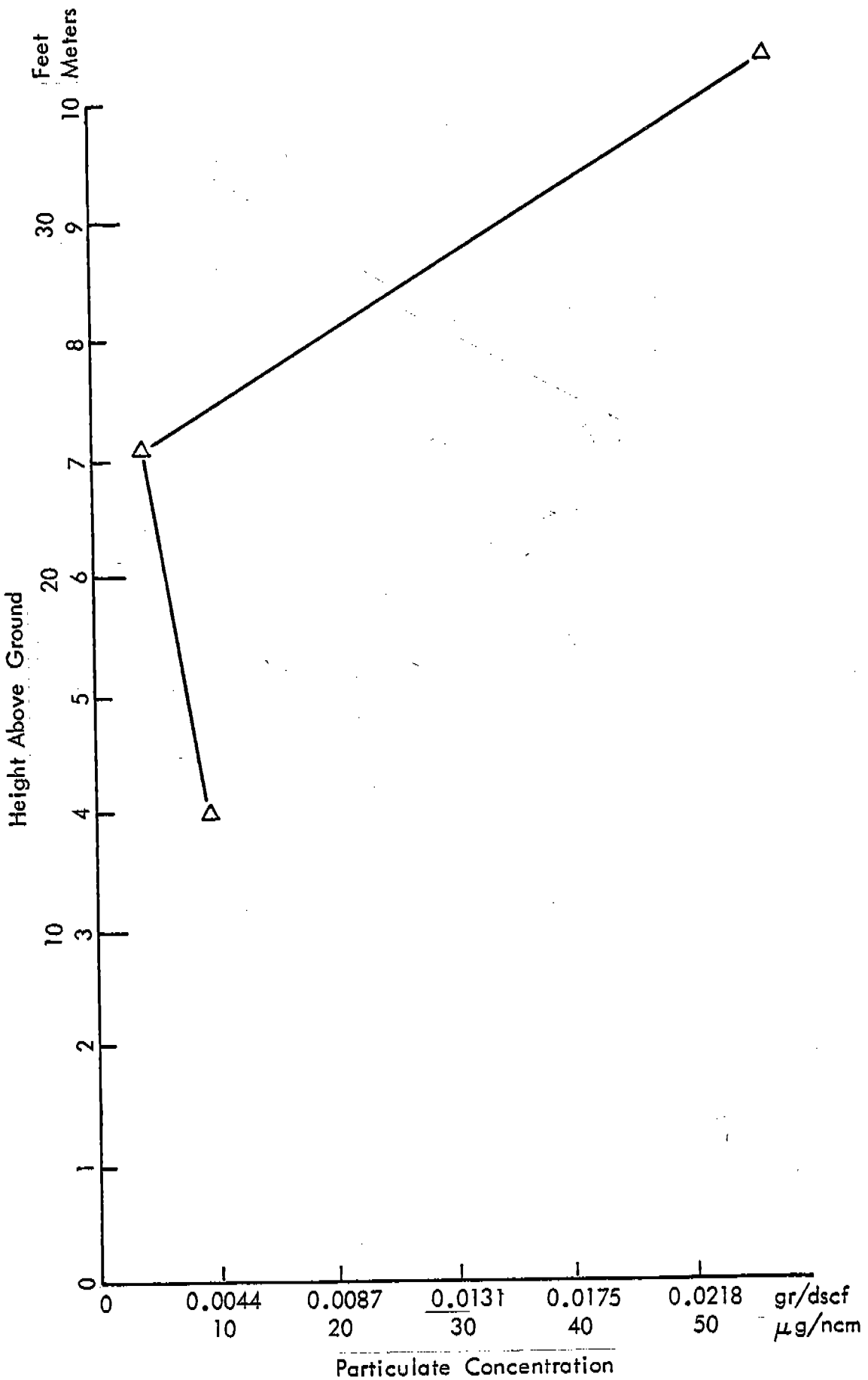

Figure 9. Particulate Concentration Versus Grid Location in Vertical Direction

constraints of the site, to visually locate the grid in the center of the plume. One constraint that made this difficult was the distance that had to be maintained between the grid and the source--about 30 meters (100 feet).

The *emission rate* of particulates for shovel loading of rail cars at this site cannot be computed with a great deal of accuracy as a result of the grid being off center of the plume. However, an estimate of the emission rate is possible by making simplifying assumptions as to the slope/intercepts of horizontal profiles (net mass versus distance from sampling center) and vertical profiles (sample height versus net mass). Basically, triangular-shaped mass profiles were assumed. These assumptions resulted in an estimate of the emission factor of 0.025 pounds per ton of ore loaded. This compares well with an emission factor of 0.032 pounds per ton derived from the following equation:

$$EF_p = 0.0018 \left(\frac{S}{5}\right)\left(\frac{U}{5}\right)\left(\frac{2}{M}\right)^2 \left(\frac{6}{Y}\right)$$

Where EF_p = Predicted emission factor (lb/ton loaded).

S = Material site content (percent), i.e., the mass portion of aggregate sample smaller than 75 micrometers in diameter as determined by dry sieving.

U = Mean wind speed.

M = Material moisture content (percent).

Y = Loader bucket capacity (cu yd).

The values used in this equation were: (given) U = 8 mph and Y = 12 cu yd; (assumed) S = 7 percent and M = 0.5 percent.

The above equation was derived in another MRI study for the U. S. Environmental Protection Agency* entitled "Fugitive Emissions from Integrated Iron and Steel Plants" and was developed by profiling the measured fugitive emissions from the load-out of crushed steel slag and crushed limestone. Actual measured emissions factors for eight tests as part of that study ranged between 0.011 and 0.063 pounds per ton loaded with an average of 0.039 pounds per ton. Consequently, the estimated emission factor of 0.025 pounds per ton for taconite ore loading of rail cars lies within the same range as found in the other study.

The *particle size results* for the one emission test at the shovel site are shown in Table 34; shown are the cumulative weight fraction and the equivalent stokes diameter for various impactor stages. Blanks appear in the column for Run No. 7-SS because it was run with a three-stage Sierra impactor. The data of Table 34 were used to generate the three curves of $\Delta C/\Delta \text{LogD}$ versus GMD shown in Figure 10. These curves indicate a bimodal particle size distribution. However, the results for the two Anderson impactors are somewhat questionable because the total weight of samples collected was quite light--approximately 1 mg. In addition, several stages of the Anderson impactor contained no measurable sample; such points are connected with non-zero points in Figure 10 by dashed lines to indicate

*EPA Contract No. 68-02-2120, Draft Final Report, February 17, 1978

Table 34. Summary of Particle Size Results--Minntac Mine Shovel Site

A. Cumulative Weight Fraction			
Run No. / Date / Stage	Percent of Total Weight Less than Given Stage		
	7-SAT[a]	7-SAB[b]	7-SS[c]
	6 June 1977	6 June 1977	6 June 1977
Cyclone			100.0
1	87.1	54.2	
2	76.7	28.9	
3	76.7	15.7	13.4
4	65.5	14.5	6.8
5	53.4	14.5	4.7
6	45.7	14.5	
7	45.7	14.5	
8	36.2	14.5	
Filter	0	0	0

B. Stokes D_{50} Diameter			
Stage	Stokes D_{50} Diameter (Microns)		
Cyclone			5
1	8.00	8.00	
2	4.98	4.98	
3	3.37	3.37	2.4
4	2.29	2.29	1.1
5	1.46	1.46	0.6
6	0.72	0.72	
7	0.43	0.43	
8	0.29	0.29	

[a] Andersen, top site, see Figure 4.

[b] Andersen, bottom site, see Figure 4.

[c] Sierra, see Figure 4.

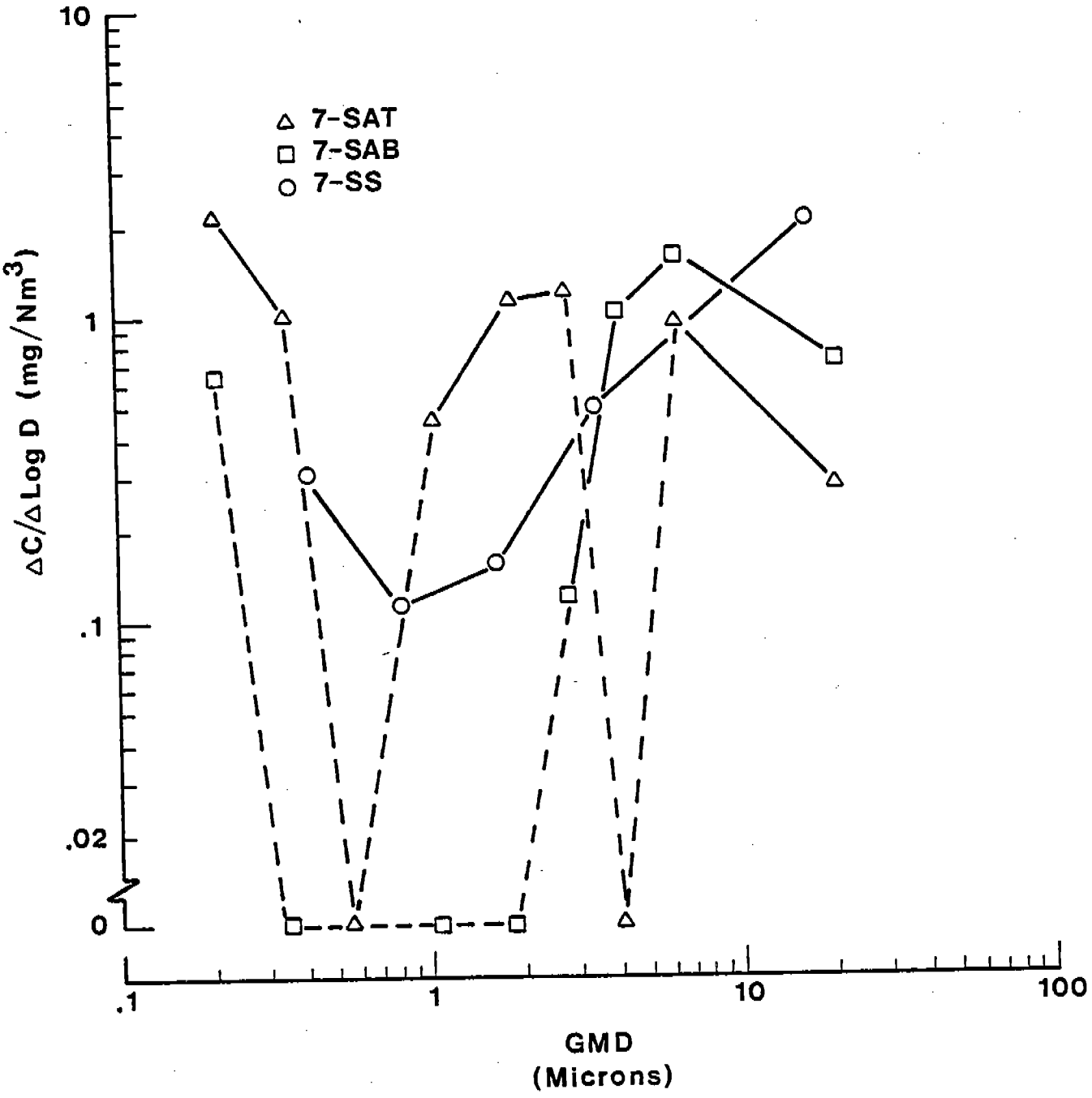

Figure 10. ΔC/ΔLog D Versus GMD--Minntac Mine Shovel Site

uncertainty in the zero values. A longer sampling run, or locating the sampling grid closer to the source, would most likely have resulted in more reliable results. Under the given circumstances, however, plume direction and conditions could only be considered as quasi stable for about 30 to 40 minutes--the actual sampling time was 39 minutes--and locating the grid closer to the source was not possible. Computer printouts of the Anderson data and a tabulation of the data for Figure 10 are presented in Appendix I.

An *asbestos* sample was taken at the center of the sampling grid (location 6 in Figure 7). Analysis of this sample revealed no asbestiform material above the detectable limit of 45 fibers per liter of air. Additional information including photographs are found in Appendix E.

Trace metal analyses, although originally planned for, were not conducted because insufficient sample was collected.

Annular Cooler. The uncontrolled vent stack of annular cooler No. 4 at the Minntac Plant was sampled for total mass and particle size; vent stack No. 5 was sampled for asbestos and particle size. Both stacks No. 4 and No. 5 are part of identical pelletization lines. All testing was scheduled for stack No. 4 but a line shutdown forced a change to stack No. 5 for the last two runs--1-MA with the Anderson impactor and 6M for an asbestos sample.

The *mass results* for the annular cooler are summarized in Table 35 in essentially the same format as used for Table 23--Meramec crusher baghouse

Table 35. Summary of Mass Results--Minntac Annular Cooler

Date	Run	Mass Emissions				Percent Filter Catch
		gr/dscf[a]	mg/Nm^3[b]	lb/hr[c]	kg/hr[d]	
24 May 1977	1	0.189	433	227	103	3.32
25 May 1977	2	0.153	349	174	79	3.95
	3	0.084	193	102	46	0.65
	Average	0.142	325	168	76	2.64

[a] gr/dscf = grains per dry standard cubic foot.

[b] mg/Nm^3 = milligrams per normal cubic meter.

[c] lb/hr = pounds per hour.

[d] kg/hr = kilograms per hour.

results. Table 35 also presents the percent of the total catch collected on the filter (i.e., that portion of the total sample not collected in the probe rinse but on the filter). These data show that the majority of mass emissions sampled was collected in the probe. In fact, the major portion of mass emissions from the annular cooler were in the form of small "chips" (approximately 0.05 inch in diameter). These chips were observed to "rain out" soon after leaving the stack forming a thick covering on the roof in the area of the stack. Computer printouts of the field data and data reduction on mass emissions are presented in Appendix H.

Particle size test results for the annular cooler are summarized in Table 36. Shown are the results for two runs with the Brink impactor and one with the Anderson. From the cumulative weight fractions shown, the results obviously are not in good agreement. This is believed to be caused by the severe conditions encountered in sampling the stack. These included:

- High stack gas velocities that required a higher than recommended flow rate through the Brink impactor to maintain isokinetic sampling conditions. This high flow rate may have resulted in particle bounce or re-entrainment on the various stages of the impactor, resulting in a size distribution skewed towards the small particles. Hence, a run with the Anderson impactor was made as a check.

Table 36. Summary of Particle Size Results--Minntac Annular Cooler

A. Cumulative Weight Fraction			
Run No. / Date / Stage	Percent of Total Weight Less than Given Stage		
	1-MB[a]	2-MB[a]	1-MA[b]
	24 May	25 May	26 May
Cyclone	100.0	100.0	
1	2.4	100.0	
2	2.4	100.0	
3	2.2	100.0	100.0
4	1.4	0.6	98.2
5	0.8	0.6	93.1
6			80.2
7			61.0
8			40.6
Filter	0.0	0.0	0.0

B. Stokes D_{50} Diameter			
Stage	Stokes D_{50} Diameter (Microns)		
Cyclone	7	7	
1	2.68	2.72	9.8
2	1.58	1.60	6.1
3	1.08	1.09	4.1
4	0.57	0.58	2.8
5	0.36	0.37	1.8
6			0.9
7			0.5
8			0.4

[a] Brink Impactor.

[b] Andersen Impactor.

- Extremely high gas temperatures of about 550-600°C (1020-1110°F). These temperatures were beyond the normal operating temperature range for the impactors requiring sample acquisition by extractive rather than *in situ* techniques. A probe, therefore, had to be adapted to the Anderson; however, this probe acted as a cyclone removing the larger particles that otherwise would have been collected on the first two stages. Furthermore, corrosion of the probe prevented a probe wash and an oily deposition on the final filter rendered it unusable.

Consequently, the $\Delta C/\Delta LogD$ versus GMD curves derived from the particle size test results and shown in Figure 11 are of limited value and subject to interpretation.

Of the two curves in Figure 11 for the Brink results, designated runs 1-MB and 2-MB, the results for run 1-MB are believed to be far more representative, at least for smaller particle sizes. This is because three times more total mass was collected during run 1-MB and because many stages for run 2-MB had no measurable sample. Even so, it is very possible that the lower end of the curve for run 1-MA (that portion below 2-3 microns) indicates higher than actual concentrations of the smaller particles. On the other hand, the results for the one run with the Anderson impactor--Run No. 1-MA--should be even more representative for the lower particle size portion of the curve; as previously mentioned, the upper portion of the curve for Run No. 1-MA is

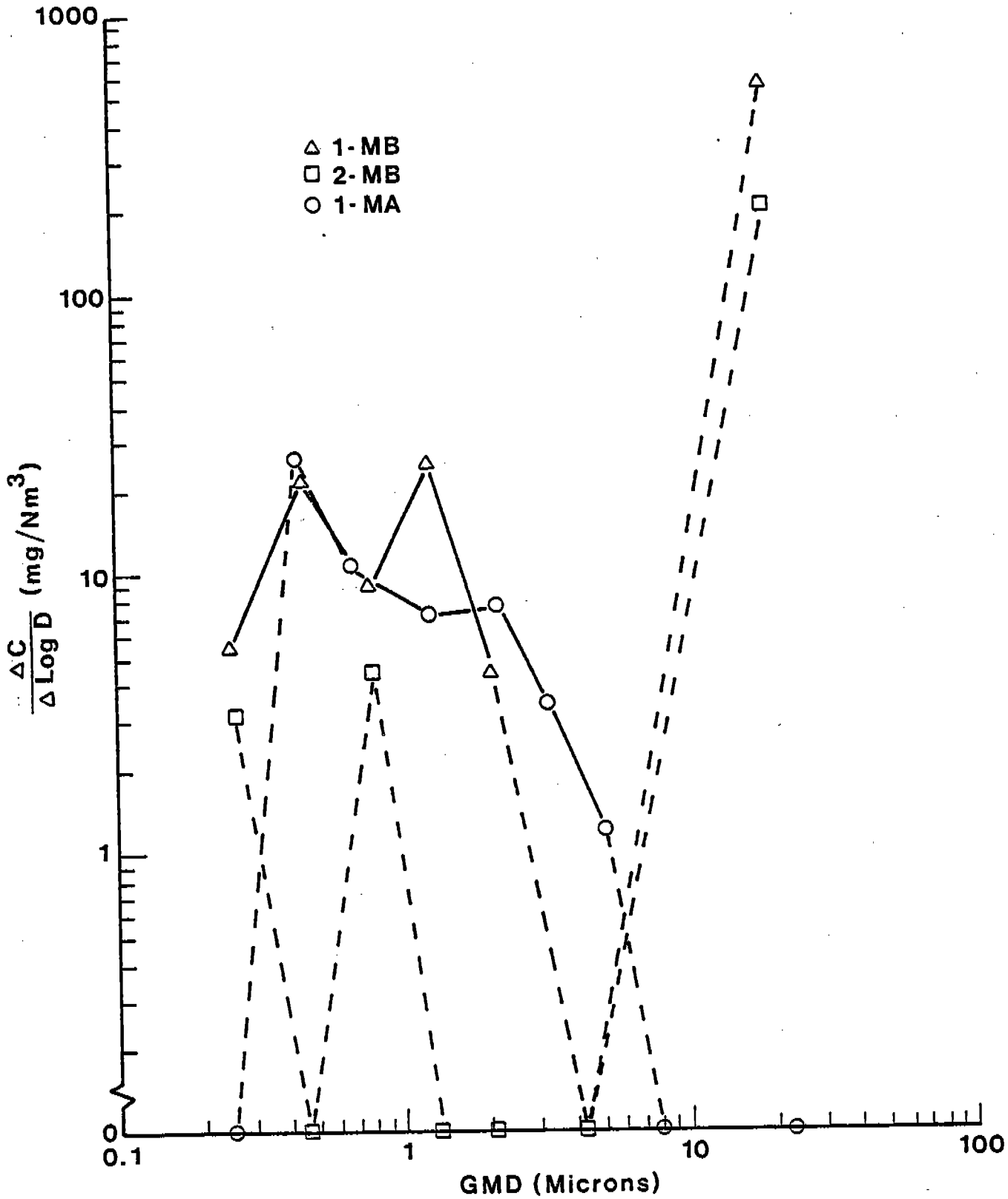

Figure 11. ΔC/ΔLog D Versus GMD--Minntac Annular Cooler

not representative because of deposition of large particles in the probe. Interpretation of the results therefore leads to the conclusion that only the lower portion of the curves for Run Nos. 1-MB and 1-MA shown in Figure 11 are representative of the annular cooler emissions. Actually, for the purposes of this study, the emissions corresponding to the small particle sizes are of greater concern than the larger particle sizes because these are the particulates that are most likely to remain airborne. Supporting data for the particle size test results are presented in Appendix I with sample calculations given in Appendix D.

One *asbestos* sample (6M) was collected from the No. 5 annular cooler stack. As with the crusher outlet and mine shovel loading samples, no asbestiform material was detected above the detection limit, which for the cooler stack sample was 300 fibers per liter of air.

Summary and Discussions. A summary and discussion of the major findings of the field test results are presented in the following paragraphs.

Mass emission results for the baghouse used to control emissions from secondary crushing of ore reveal that the baghouse collection efficiency was about 84 percent. This is a relatively low efficiency for a baghouse when compared with reported baghouse efficiencies used by this industry to control other sources, such as bentonite blending where the reported efficiency is 99 plus percent. In addition, it is much less than the 98.0 percent control efficiency value listed in Table 15 as the average for fine (secondary)

crushing. The 98.0 percent value represents the average performance for scrubbers and rotoclones.

Emission rates for the crushing operation sampled would be 0.11 and 0.67 kg/MT of pellets produced for the controlled and uncontrolled values, respectively, if crushing was a 24-hour operation. Actually these values would be somewhat higher under normal operation since the crushing operation is usually intermittent. The average emission rates listed in Table 12 for fine crushing are 0.18 kg/MT for controlled emissions and 39.9 kg/MT for uncontrolled emissions. Considering the effect of intermittent operations, therefore, it would appear that the controlled emission rate for this crushing operation would be close to the industry average but that the uncontrolled rate would be much less. Consequently, if the baghouse collection efficiency was not so low, the controlled emission rate for this operation would also be much lower than the industry average. The reason for the lower uncontrolled emission rate is that the ore from this mine was easily crushed and therefore did not require extensive staging of crushers or considerable recycling as is done in most taconite crushing operations.

The poor measured collection efficiency of the baghouse is believed to be due to bag failure. Further evidence of this was the results of the particle size tests, which showed no significant removal of particles less than 10 micrometers in diameter. The abrasiveness of the ore dust is believed to cause premature bag failure and this may be the reason that baghouses are not commonly used to control emissions from crushing emissions.

The bags (fabric filters) in place at the time of field sampling were installed about five months prior to the field test sampling period.

The controlled emission rate for the sampled vertical furnace was about four times greater than the industry reported average as listed in Table 12 at 0.44 kg/MT. Although it was not possible to sample ahead of the controls, it is very unlikely that the cyclone-type controls being used on both the top and bottom gases are achieving an efficiency anywhere near the average value of 96.5 percent listed for waste gas control in Table 15. This 96.5 percent value represents the performance of scrubbers, cyclones, multiclones, and electrostatic precipitators.

Fugitive emissions from shovel loading of taconite ore into rail cars is estimated at 0.03 pounds per ton loaded. This value approximates the measured fugitive emission factors for load-out of crushed steel slag and crushed limestone as noted earlier. Also, this factor of 0.03 pounds per ton of ore when expressed as pounds per ton of pellets would be about a factor of three greater and would approximate 0.10 pounds per ton of pellets (0.05 kg/ton). Compared with the other controlled emission rates for point sources listed in Table 12, this emission factor would only be less than three out of the ten listed (i.e., waste gas, fine crushing and dump pockets). However, the first two out of these three sources are about three and eight times greater. The significance of ore loading of rail cars relative to other sources therefore does not appear too relevant.

Measured mass emissions from the annular cooler average 76 kg/hr. At a production rate of 350 tons per hour, the emission factor for this source would be 0.22 kg/MT. Again relative to the values for the ten sources listed in Table 12, this emission factor appears significant with only the value for waste gas being greater. However, as noted in Table 35, less than four percent of the particulates by weight were small enough to pass through the mass sampling probe without settling out. Therefore, it is likely that only about 0.01 kg/MT of the emissions are capable of remaining airborne for an extended time. At that level this source is not too significant. In fact, while sampling the annular cooler stack, it was obvious from observing emissions from the nearby waste gas stack that perturbation in the induration process would produce very heavy emissions. Consequently, either better controls or improved process controls are needed to reduce emissions from waste gases.

Asbestos analysis of samples from three of the sources sampled did not reveal the presence of asbestiform material. The other site, the vertical shaft furnace, was not sampled for asbestos because the emissions from fine crushing at this same plant were analyzed and if asbestos was not present at this source the same would be expected for the vertical shaft furnace emissions.

The measured silica content of the fines for both the controlled and uncontrolled fine crushing emissions, as seen in Table 25, were never greater than 58 μg/g or 8.3 $\mu g/m^3$. Compared with the calculable Threshold

Limit Values for silica as crystalline quartz,[1] which for these measured values are approximately 5,000 $\mu g/m^3$ for respirable dust or 10,000 $\mu g/m^3$ for total dust, these measured values appear insignificant. This is the case even before the dilution effects of mixing with ambient air are considered--dilution effects could lower the concentration by a factor of 10^3 or 10^4.

The concentration of trace metals in the particulates emitted by the fine crushing source, as listed in Tables 27 and 28, are much greater (by about a factor of 1,000) than the corresponding concentration of these pollutants in normal fugitive dust[2] (i.e., earth's crust). Also, when compared with the threshold limit values (TLV) for these metals,[1] values for some of these trace metals such as cobalt exceed the TLV's for time-weighted-average exposure. But, when a dilution factor of 1,000 is used for an estimate of the maximum ground level concentration, the concentration of these metals will not exceed the TLV's.

Water

All available data sources contained very sketchy information on water use and no analytical data on the pollution load of the wastewaters. Although data on water use was presented in several ways, it was possible to determine the total plant circuit flow rate, which includes water used for beneficiation and pelletization, for eight taconite operations. The production in these plants totalled approximately 50 percent of the total U.S. production and average 4.8 million MTPY, which could be considered as representative of a medium-sized plant. Average water use in the plant circuit for these eight plants was 38 liters per kilogram of pellets produced (4.6 gal/lb); individual plant values varied, however, from 12 ℓ/kg (1.4 gal/lb) to 86 ℓ/kg (10.3 gal/lb) although five of the eight plants had values within thirty percent of the overall average. Frequently the higher flow values were for plants using flotation in the ore concentration process.

Plants using flotation must prevent deterioration of the process by controlling the chemical nature of the water used. In the past this was accomplished in part by recycling little if any wastewater. As a result, excess accumulation of wastewater in the tailings basins had to be discharged. Currently, however, with the enforcement of stringent discharge requirements, such plants have found that less treatment is needed for reuse of the wastewater than for discharge. Consequently, plants using flotation will probably soon discontinue direct discharging of wastewater if they have not already done so.

Approximately 5 percent of the water used in a typical plant circuit is makeup water. Thus for a plant with a circuit flow rate of 95,000 gpm, the average for the eight plants mentioned above, the makeup would be 4,750 gpm (6.8 million gallons per day). Makeup water primarily replaces that lost by carryover with the green pellets and evaporation/percolation from the large tailings basins. Green pellets typically contain 10 percent water by weight which is evaporated off to the atmosphere; this loss, using the average values of the eight plants, would amount to about 240 gpm or about 5 percent of the total makeup water. Consequently, losses from the tailings basin could account for 95 percent of the makeup water requirements.

Even though few if any plants now discharge, it is possible that percolation leakage from tailings basins could contaminate ground waters or surface bodies of water indirectly (i.e., as a non-point source versus a point source). The extent of the contamination is not predictable because no analytical data exist on the wastewater quality. It is also possible that plants using flotation could contribute a greater pollutional load since these operations add a number of chemicals (e.g., fatty acids, surfactants, kerosene, amines, caustics, etc.) for flocculation-desliming and flotation. Certainly, defining the pollution potential due to leakage warrants further study as does establishing feasible means of curbing leakage from tailings basins.

Solid Waste

Solid waste generation in the iron ore industry results almost entirely from beneficiation. Normally, no waste is generated in the

pelletization process because all the material is product; so it is recovered. Some companies consider the removal of overburden in mining as solid waste; however, in a strict sense, overburden is not a solid waste because it is not disposed of, but stockpiled.

Another source of solid waste is refuse from office waste, food waste, waste from housekeeping and maintenance activities, etc. The quantities of such waste as reported by one plant amounted to only 1.5 kg/MT (3.4 lb/MT) of production. This is quite insiginificant on a weight basis when compared to that from beneficiation; however, the environmental impact of this refuse could possibly be significant because of its nature, which has not been characterized.

Gangue, the low- or non-iron bearing waste, resulting from beneficiation amounts to nearly twice the tonnage of pellets produced on a dry basis (i.e., 2,000 kg/MT of pellets). The gangue is separated from the iron bearing particles following both crushing and grinding operations. Hence, both coarse and fine gangue (or tailings) are produced and both are disposed of in tailings basins. Coarse tailings are hauled to tailings basis and used in basin construction; fine tailings are contained in the underflow from thickeners and are pumped to the basins as a slurry.

Material collected by in-plant air pollution control equipment is usually recycled through the plant and thus does not generate waste. This is especially true in the agglomeration and induration steps where this material has already been concentrated. Thus, installing additional air pollution control equipment would result in more product recovery and not more waste.

Potential problems associated with solid waste disposal in tailings basins are related to the nature of the tailings and the vastness of the basins. Tailings are very inert minerals and as such do not support much vegetative life. This, together with the immense areas involved, results in the loss of these areas as habitat for most wildlife. Additionally, wind erosion does aerosolize fine tailings which could pose a potential health hazard depending to a large degree upon the chemical makeup of the fines. The nature and extent of these problems have yet to be determined.

Energy Considerations

Energy in the taconite industry is consumed in mining, ore hauling, and in beneficiating and pelletizing processes. The major sources of energy are natural gas, electricity, diesel fuel and coal. Electricity and natural gas are primarily used as direct energy sources for production, diesel fuel for transportation and coal for electrical generation.

According to a recent study[5], the energy requirements of the Minnesota iron ore and taconite industry were about 51 trillion Btu's in 1973 with an overall energy consumption of 64.6 trillion Btu's. The overall energy accounts for a loss of 13.5 trillion Btu's in electric generation by mining company-owned private power plants. Of that energy consumption, over 90 percent is used by the taconite industry and this percent is expected to grow with them as the natural ore reserves are already low. The energy consumption per ton of taconite pellets produced is 924,300 Btu's for direct energy and 1.5 million Btu's for gross energy. Electricity and natural gas supply 87.5 percent of the direct (net) energy used in taconite processes and 95.7 percent of the net energy used in production alone--i.e., processing and mining except for transportation. Additionally, electricity and natural gas account for 33 and 63 percent, respectively, of the net energy used in production. Obviously, natural gas supplies the major portion of the energy consumed by the taconite industry--however, this will have to change in the future as the U.S. reserves of natural gas dwindle. This same study predicted that coal would gradually replace natural gas and would supply about 57 percent of the gross energy by 1980 and 85 percent by 1985.

A limited amount of information concerning energy consumption in the taconite processing industry was available in the data compiled in this program. Data were available for nine plants, some of it quite detailed and some difficult to decipher. Three plants broke down their energy consumption into fuel for induration and electrical process energy. Those three used an average of 8.6×10^5 Btu per metric ton of production for induration with fuels and 3.9×10^5 Btu/MT for electricity. Thus, those three plants average using 1.25×10^6 Btu/MT for beneficiation and pelletizing. Two plants gave their total plant energy consumption--1.06×10^6 Btu/MT, and 1.12×10^6 Btu/MT. The remaining four plants reported either induration fuel or electricity, but not both. Consumption per ton of production in three of those plants agree fairly well with the other plants. The fourth plant shows electricity use lower than the other plants by a factor of ten. That figure is assumed to be incorrect. An analysis of the available data from all nine plants indicates approximately 850,000 Btu/MT for induration and 380,000 Btu/MT for process electricity, a total energy consumption of 1,230,000 Btu/MT of production. This value is within the range reported of 924,000 to 1,500,000 Btu/MT (which includes transportation) in the Minnesota study mentioned above. The total fuel that is consumed to provide this energy--1.23×10^6 Btu/MT--is equivalent to approximately 2,115,000 Btu/MT when the electricity generation and transmission losses are considered.

Six plants included data on the energy consumption of emissions control systems. Their use varies from approximately 1.5 percent to 7.5 percent of total electricity consumption and averages approximately 1.5 percent of total

energy consumption. Thus, some additions of energy-consuming control equipment would not greatly impact on the total energy consumption of the industry.

The vast majority of the U.S. iron mining industry is located in northern Minnesota and Upper Michigan. Most expansion of the industry is also in that region. By 1981, when the presently contemplated expansions have been completed, the availability of natural gas for industrial use, at least in that area, will be doubtful. The industry estimates that by 1981 diesel fuel usage will increase by 67 percent, induration heat requirements by 86 percent, and electrical energy by 96 percent. That is an overall energy increase of 88 percent for the industry. Fuel oil might also be difficult to obtain and very expensive so it appears that coal is very important to the future of this industry.

Much has been done to conserve energy in the past 10-15 years, especially in the area of heat recovery systems. In the typical induration system of 1965, 60 percent of the heat came from fuel and 40 percent was exothermic heat. By recouping heat from the pellet cooler and bringing the hot gases back into the induration process, the fuel now has to provide only 50 percent of the heat requirements. The resultant fuel savings are 16 percent. There are still many improvements that could be made to reduce energy consumption. Even more energy can be recovered from the waste gas without creating negative side effects. This could possibly be used for electricity generation, or for some steam generation to operate control devices (e.g., scrubbers). Some of the heat being lost by radiation and convection can also be saved.

It is evident in visiting taconite processing plants that electrical energy use for lighting has been considered insignificant compared to process electrical demand, so it has been largely ignored. These huge plants with very high cielings have general ceiling lighting of thousands of watts but because of their distance from work areas and the dirty conditions, this lighting is ineffective. Task lighting at work stations where it could be properly directed and cleaned regularly would require only a small fraction of the energy and provide better working conditions.

CONCLUSIONS

As a result of this study, it was concluded that emissions from natural iron ore mining and beneficiating were insignificant relative to those from taconite mining and processing. This conclusion is primarily based upon the intrinsic differences in the ores (natural versus taconite ores) and the processes and upon visual observations. Another consideration was that natural ores have been largely depleted and their portion of total ore shipments has been declining steadily since the mid-1950's. Consequently, this study concentrated upon emissions from the rapidly growing taconite industry.

Ten in-plant (point) sources of emissions were identified, quantified, and ranked by the magnitude of their controlled emissions rates for taconite processing--i.e., taconite beneficiation and pelletization. These ten sources, their ranking, and their median controlled and uncontrolled emissions rates, in kilograms per metric ton of pellets, are:

Rank	Source	Emissions Rate (kg/MT of pellets) Controlled	Uncontrolled
1	Waste gas	0.44	14.6
2	Fine crushing	0.18	39.9
3	Dump pockets	0.07	0.44
4	Pellet handling	0.008	1.7
5	Coarse crushing	0.006	0.10
6	Grate discharge	0.005	0.66
7	Grate feed	0.004	0.32
8	Ore transfer	0.001	0.05
9	Bentonite blending	<0.001	0.11
10	Bentonite transfer	<0.001	0.02

Although the actual plant processes are known to vary somewhat among plants, these ten sources are representative of the processes found at all taconite processing plants. As can be seen from the tabulated data, ranking of the ten sources by uncontrolled emissions rates does not significantly alter the rankings from those listed above, except for coarse crushing, where emissions are not controlled to a high degree. Based upon these median emissions rates, the waste gas and fine crushing sources account for over 86 and 94 percent of the controlled and uncontrolled emissions, respectively, for the ten sources.

In addition to the ten point sources, there is also another source--annular coolers--associated with grate-kiln induration systems, which are used in many new plants. Although this source is not controlled, the particle loading for the annular cooler is quite low (0.05 gr/SCF), but the flow rate is high (100,000 SCFM). Field testing of an annular cooler as part of this study revealed an uncontrolled mass emissions rate in the stack of 0.22 kg/MT, which is somewhat significant relative to other uncontrolled sources. However, particle size measurements showed that most of the emissions by mass were of large particle size. From this it was estimated that less than 0.01 kg/MT of emissions are small enough in size to remain airborne for any length of time. At this value, the uncontrolled annular cooler is not a significant source even when compared to other controlled emissions.

This study also established that a wide variety of devices is used to control the ten identifiable point sources in taconite processing. These

controls include: scrubbers, cyclones, multiclones, electrostatic precipitators, bag collectors, mechanical and centrifugal and dry devices. Of these, the scrubber is the most widely used on the various sources; it was found in use on nine out of the ten point sources, the exception being the crude ore dump pockets. The remaining control devices are limited in their application, probably because of the characteristics of the emissions or because of costs or maintenance problems. Control efficiencies by type of control device were highest for scrubbers, rotoclones, bag collectors, and electrostatic precipitators. These four devices had average reported control efficiencies between 97.3 and 99.2 percent by weight; the others had efficiencies between 88.3 and 95.6 percent.

Average efficiencies for various combinations of control devices used on each source varied between 97.9 and 99.7 percent by weight for seven out of the ten sources. Average control of the other three sources (dump pockets, coarse crushing, and waste gas) ranged from 88.3 to 96.5 percent by weight. Overall control of all emissions from the ten sources is estimated to be around 98 to 99 percent. Furthermore, based upon a U.S. production rate of pellets of 80 million metric tons per year, it is estimated that the national emission rate from the ten identifiable sources in the iron ore beneficiation and pelletization processes is around 100,000 tons per year.

Non-point sources of emissions were also identified in this study. However, because of a paucity of emissions data for these sources, it was not possible to quantify and rank non-point sources.

The identifiable (non-point) sources of fugitive emissions associated with mining are:

- Crude ore haul roads
- Loading of crude ore into trucks or rail cars
- Transfer of crude ore at transfer points while enroute to the processing plant
- Load in and load out of waste rock
- Load in and load out of overburden
- Drilling
- Blasting
- Wind erosion of the open pit mine areas
- Wind erosion of dump sites for waste rock and overburden
- Haul roads between mine sites and dump sites.

Non-point sources associated with processing are:

- Disposal of tailings in basins
- Load in and load out of pellets
- Unprotected pellet storage piles
- Unprotected concentrate surge piles
- Load in, load out, and storage of coal.

These non-point sources are believed to be the most significant, even though additional sources besides these may exist. Furthermore, of the non-point sources listed, haul roads and tailings basins are believed to be the most significant sources of fugitive dusts. Unfortunately, this cannot be supported

by test data for haul roads since none exist, whereas for tailings basins, limited data do support this contention. From visual observation, however, haul roads appear to be the largest source of fugitive emissions. The wetting down of haul roads is the only widespread control method currently being used, but it appears to be rather ineffective.

One estimate for the expected fugitive emissions rate due to wind erosion and truck traffic to and from a tailings basin is 14.5 MT/day for a 11.3 square kilometer basin; this is roughly equal to 70,000 MT/yr. Compared to the industry-wide estimate of 100,000 MT/yr for the ten point sources, this expected emissions rate from just one tailings basin is very significant. Revegetation of the outer dike walls and the completely filled areas of the basins is the only means of control presently in use.

Emissions from shovel loading of crude ore into rail cars was field tested during this study. This testing led to an estimated emissions rate of 0.03 kg/MT of crude ore or about 0.10 kg/MT of pellets. Relative to the controlled median values for the ten point sources, this value for ore loading is of somewhat intermediate significance--it falls between those for the third- and fourth-ranked point sources. It should be noted, however, that this value was estimated from limited data that were collected about two days after heavy rain.

Field tests were conducted on four different sources as part of this study. Two of these sources were already mentioned--the annular cooler and shovel loading of rail cars. The other two sources were an ore crushing

operation controlled by a baghouse and a vertical shaft indurating furnace fired with fuel oil and controlled by cyclone-type controls. In addition to those field test conclusions previously mentioned, other field test results include:

- A measured baghouse collection efficiency of 84 percent. This value is far below the typical value reported of 98 percent in spite of a challenging load less than normal. It is believed that failure of the fabric was responsible for this low value.

- A measured cyclone-controlled emissions rate from two vertical shaft furnaces of about four times the reported median value for waste gas. The collection efficiency of these controls is not known because sampling ahead of the controls was not possible. However, it is unlikely that an efficiency as high as the median for waste gas--96.5 percent--was being achieved since this implies an unusually high uncontrolled loading.

- No detectable asbestiform materials were found in samples collected at three of the sources tested. An asbestos sample was not taken at the fourth source tested--the vertical shaft furnace.

- The silica and trace metal contents of the measured emissions from fine crushing should not pose a potential health problem, particularly after dilution is considered in estimating the maximum ground level concentration.

Plant tours to several plants with the grate-kiln indurating system revealed noticeable variation in waste gas emissions. Apparently, abrupt changes in the processing rate is the cause. Another observation was that ineffective or non-control of in-plant sources, such as materials transfer points, often resulted in emissions that are ultimately discharged through uncontrolled ventilation systems.

Available data were also reviewed to evaluate the impacts that the taconite industry has on water, solid waste, and energy. Although water use is very high (about 38 liters per kilogram of pellets), almost all plants have closed systems and therefore do not adversely impact on receiving bodies of water. Those few plants that do have a discharge are expected to establish a no-discharge status in the near future. Solid waste impacts are primarily the result of disposing of the tailings generated in beneficiating. The vastness of tailings basins and their inability to support rapid revegetation both modify the local area and contribute to fugitive emissions. Energy consumption by the industry is very high--about 1.3 million Btu's per metric ton of pellets. Natural gas currently is the largest source of direct energy input at about 60 percent of the total. Bacause of the impending natural gas crisis in this country, a switch to coal as the major fuel is anticipated in the early 1980's.

In summary, ten universal point sources of emissions from taconite processing were identified and quantified. The controlled emissions from three of these sources--waste gas, fine crushing, and dump pockets--were found to generate over 97 percent of the total for the ten sources. If additional or improved control is required at the industry, these three point sources would be likely candidates for better control. Fifteen non-point sources of emissions were also identified but these could not be ranked because of insufficient emissions data. At least three of these non-point sources could be significant relative to the controlled point sources. These three major sources of fugitive emissions are ore haul roads, tailings basins, and ore loading. Considerable field testing is needed not only to quantify the emissions from these sources but also to evaluate alternative methods of controlling them.

RECOMMENDATIONS

Analysis of the existing data, direct experiences, and observations resulting from field sampling activities and plant tours are the bases for the following recommendations. The recommendations are made in hopes that future research and development efforts directed at the taconite mining, beneficiation, and pelletizing industry will lead to a greater understanding of the sources and methods of controlling or eliminating of emissions from these sources. The recommendations are:

1. Conduct fugitive emissions-type field sampling on haul roads, open pit mines, and tailings basins to obtain reliable fugitive emissions data. These data are needed to quantify the relative contribution of these fugitive emission sources to the total for the industry.

2. Establish and quantify alternative methods for controlling fugitive emissions sources such as haul roads and tailings basins. The economic feasibility of each control method should also be established.

3. Conduct research on methods of reducing certain in-plant emissions sources that could become fugitive sources if uncontrolled. Some of these emissions are generated continuously, e.g., emissions from conveyor belt systems. Fine particles

cling to these belts after their loads have been dumped and are released along the return leg of their cycle. Other in-plant sources become fugitive emissions as a result of perturbations in the air handling system. For example, such perturbations sometimes reduce the pressure differences between a building and a hood or other scavenging device to the point where emissions are not channeled into a control unit and instead become fugitive emissions. These emissions are usually emitted to the outside through uncontrolled ventilation systems.

4. Determine how important process perturbations are compared to smooth continuous operation in generating emissions. For example, a perturbation in any of a number of processing zones within the grate-kiln system was observed to produce noticeable increases in the waste gas emissions.

5. Sample a waste gas stack before and after conversion from natural gas to coal firing. This should also be done on a system converted to heavy oil firing. This will establish the additional increase in emissions for a point source that already is ranked number 1.

6. Investigate the effectiveness of various control technologies now used on natural gas fired induration

when applied to coal/heavy oil induration. The data obtained in (5) would be part of what is needed in this work.

SUMMARY OF EMISSION FACTORS PRESENTED IN TACONITE ORE PROCESSING
NEW REFERENCE 2: EMISSIONS FROM IRON ORE MINING, BENEFICIATION, AND PELLETIZATION

CRUDE ORE DUMP POCKETS

Process rate, tons/hr	Flow rate, SCFM	Control device	No. of tests	Emission rate, gr/SCF uncontrolled	Emission rate, gr/SCF controlled	Emission rate, lb/hr uncontrolled	Emission rate, lb/hr controlled	Emission factor, uncontrolled kg/Mg	Emission factor, uncontrolled lb/ton	Emission factor, controlled kg/Mg	Emission factor, controlled lb/ton
3417	47,000	cyclone	1	0.33	0.049	132	20	0.019	0.039	0.0029	0.0058
3417	47,000	cyclone	1	0.42	0.063	169	25	0.025	0.050	0.0037	0.0074
						Average	uncontrolled	0.022	0.044		
							cyclone			0.0033	0.0066

COARSE CRUSHING

Process rate, tons/hr	Flow rate, SCFM	Control device	No. of tests	Emission rate, gr/SCF uncontrolled	Emission rate, gr/SCF controlled	Emission rate, lb/hr uncontrolled	Emission rate, lb/hr controlled	Emission factor, uncontrolled kg/Mg	Emission factor, uncontrolled lb/ton	Emission factor, controlled kg/Mg	Emission factor, controlled lb/ton
960	17,871	dry mech.	1	1.1	0.165	168	25.3	0.088	0.18	0.013	0.026
1,022	18,000	multiclone	1	0.389	0.031	60	4.8	0.029	0.059	0.0023	0.0047
1,165	18,400	multiclone	1	0.36	0.043	57	6.8	0.024	0.049	0.0029	0.0058
1,267	13,308	rotoclone	4	0.473	0.04	54	4.6	0.021	0.043	0.0018	0.0036
383	15,000	scrubber	2	0.237	0.012	30	1.5	0.040	0.080	0.0020	0.0040
1,034	18,000	multiclone	1	0.419	0.034	65	5.2	0.031	0.063	0.0025	0.0051
1,054	18,400	multiclone	1	0.388	0.047	61	7.4	0.029	0.058	0.0035	0.0070
4,523	13,308	scrubber	4	0.48	0.04	55	4.6	0.0061	0.012	0.00050	0.0010
824	17,871	cyclone	1	0.77	0.116	118	18	0.072	0.14	0.011	0.022
						Average	uncontrolled	0.028893	0.0577861		
							dry mech.	0.088	0.18	0.013	0.026
							multiclone	0.029	0.057	0.0028	0.0057
							rotoclone	0.021	0.043	0.0018	0.0036
							scrubber	0.017	0.035	0.0010	0.0020
							cyclone	0.072	0.143	0.011	0.022

ORE TRANSFER

Process rate, tons/hr	Flow rate, SCFM	Control device	No. of tests	Emission rate, gr/SCF uncontrolled	Emission rate, gr/SCF controlled	Emission rate, lb/hr uncontrolled	Emission rate, lb/hr controlled	Emission factor, uncontrolled kg/Mg	Emission factor, uncontrolled lb/ton	Emission factor, controlled kg/Mg	Emission factor, controlled lb/ton
4,338	11,500	scrubber	1	0.333	0.010	32.8	0.99	0.00378	0.0076	0.000114	0.000227
1,450	20,700	scrubber	1	0.333	0.010	59	1.8	0.0204	0.0407	0.00061	0.0012
1,450	13,200	scrubber	1	0.333	0.010	38	1.1	0.013	0.026	0.00039	0.00078
1,450	15,800	scrubber	1	0.333	0.010	45	1.4	0.016	0.031	0.00047	0.00093
1,986	9,800	scrubber	1	1	0.010	84	0.8	0.021	0.042	0.00021	0.00042
1,057	10,300	multiclone	1		0.032		2.8	0.00	0.00	0.0013	0.0027
1,043	10,500	scrubber	6	9	0.045	810	4.1	0.4	0.8	0.0019	0.0039
1,043	31,400	scrubber	1	9	0.045	2,422	12.1	1.16	2.3	0.0058	0.0116
1,043	250	scrubber	5	9	0.045	19	0.1	0.0092	0.018	0.0000	0.0001
1,043	16,400	scrubber	1	11.8	0.059	1,659	8.3	0.80	1.6	0.0040	0.0080
1,037	10,300	multiclone	1		0.037		3.3			0.0016	0.003
1,024	10,500	scrubber	5	13.1	0.131	1,179	11.8	0.6	1.2	0.0058	0.012
1,024	32,000	scrubber	1	9.8	0.049	2,688	13.4	1.3	2.6	0.0066	0.013
1,024	25,000	scrubber	4	9.8	0.049	2,100	10.5	1.0	2.1	0.0051	0.0103
1,024	16,800	scrubber	1		0.053		7.6			0.0037	0.0075
822	11,969	rotoclone	1	3.59	0.061	368	6.3	0.22	0.45	0.0038	0.0076
822	3,931	dry mech.	1	0.313	0.047	11	1.6	0.0064	0.013	0.0010	0.0019
						Average	uncontrolled	0.43	0.86		
							scrubber	0.45	0.91	0.0029	0.0057
							multiclone			0.0015	0.0029
							rotoclone	0.22	0.45	0.0038	0.0076
							dry mech.	0.0064	0.013	0.0010	0.0019

FINE CRUSHING

Process rate, tons/hr	Flow rate, SCFM	Control device	No. of tests	Emission rate, gr/SCF uncontrolled	Emission rate, gr/SCF controlled	Emission rate, lb/hr uncontrolled	Emission rate, lb/hr controlled	Emission factor, uncontrolled kg/Mg	Emission factor, uncontrolled lb/ton	Emission factor, controlled kg/Mg	Emission factor, controlled lb/ton
741	29,825	rotoclone	7	4.33	0.013	1,107	3.3	0.75	1.5	0.0022	0.0045
240	24,865	rotoclone	1	2.1	0.042	448	9.0	0.93	1.9	0.019	0.037
240	22,647	rotoclone	1	1.35	0.027	262	5.2	0.55	1.1	0.011	0.022
240	19,665	rotoclone	1	1.9	0.038	320	6.4	0.67	1.3	0.013	0.027
240	19,222	rotoclone	1	1.2	0.024	198	4.0	0.41	0.82	0.0082	0.016
204	44,000	scrubber	5	12	0.06	4,526	23	11.09	22	0.055	0.11
194	44,000	scrubber	6	14.2	0.057	5,355	21	13.80	28	0.055	0.11
						Average	uncontrolled	6.6	13		
							rotoclone	0.71	1.4	0.0061	0.012
							scrubber	12	25	0.055	0.11

note if Ref is averaged in then 0.0056 0.011

BENTONITE TRANSFER

Process rate, tons/hr	Flow rate, SCFM	Control device	No. of tests	Emission rate, gr/SCF uncontrolled	Emission rate, gr/SCF controlled	Emission rate, lb/hr uncontrolled	Emission rate, lb/hr controlled	Emission factor, uncontrolled kg/Mg	Emission factor, uncontrolled lb/ton	Emission factor, controlled kg/Mg	Emission factor, controlled lb/ton
2.85	8,860	scrubber	1	0.2	0.004	15.19	0.30	2.7	5.3	0.053	0.11
2.85	3,780	unknown	1	0.1	0.001	3.24	0.03	0.57	1.1	0.0057	0.011
						Average	uncontrolled	1.6	3.2		
							scrubber	2.7	5.3	0.053	0.11

BENTONITE BLENDING

Process rate, tons/hr	Flow rate, SCFM	Control device	No. of tests	Emission rate, gr/SCF uncontrolled	Emission rate, gr/SCF controlled	Emission rate, lb/hr uncontrolled	Emission rate, lb/hr controlled	Emission factor, uncontrolled kg/Mg	Emission factor, uncontrolled lb/ton	Emission factor, controlled kg/Mg	Emission factor, controlled lb/ton
2.4	3,500	scrubber	1	1.67	0.022	50	0.66	10	21	0.14	0.28
2.4	1,500	baghouse	1	1.1	0.011	14	0.14	2.9	5.9	0.029	0.059
2.66	3,500	scrubber	1	3.14	0.02	94	0.60	18	35	0.11	0.23
2.66	2,800	baghouse	1	1.65	0.017	40	0.41	7	15	0.077	0.15
						Average	uncontrolled	9.6	19		
							scrubber	14	28	0.13	0.25
							baghouse	5.2	10.4	0.053	0.11

GRATE FEED

Process rate, tons/hr	Flow rate, SCFM	Control device	No. of tests	Emission rate, gr/SCF uncontrolled	Emission rate, gr/SCF controlled	Emission rate, lb/hr uncontrolled	Emission rate, lb/hr controlled	Emission factor, uncontrolled kg/Mg	Emission factor, uncontrolled lb/ton	Emission factor, controlled kg/Mg	Emission factor, controlled lb/ton
311	9,600	scrubber	1	2.15	0.028	177	2.30	0.28	0.57	0.0037	0.0074
315	12,300	scrubber	1	2.08	0.027	219	2.85	0.35	0.70	0.0045	0.0090
						Average	uncontrolled	0.32	0.63		
							scrubber	0.32	0.63	0.0041	0.0082

GRATE DISCHARGE

Process rate, tons/hr	Flow rate, SCFM	Control device	No. of tests	Emission rate, gr/SCF uncontrolled	Emission rate, gr/SCF controlled	Emission rate, lb/hr uncontrolled	Emission rate, lb/hr controlled	Emission factor, uncontrolled kg/Mg	Emission factor, uncontrolled lb/ton	Emission factor, controlled kg/Mg	Emission factor, controlled lb/ton
311	11,100	scrubber	1	4	0.028	381	2.7	0.61	1.2	0.0043	0.0086
315	14,500	scrubber	1	3.86	0.027	480	3.4	0.76	1.5	0.0053	0.011
						Average	uncontrolled	0.69	1.4		
							scrubber	0.69	1.4	0.0048	0.0096

WASTE GAS (KILN) EMISSIONS

Process rate, tons/hr	Flow rate, SCFM	Control device	No. of tests	Emission rate, gr/SCF uncontrolled	Emission rate, gr/SCF controlled	Emission rate, lb/hr uncontrolled	Emission rate, lb/hr controlled	Emission factor, uncontrolled kg/Mg	Emission factor, uncontrolled lb/ton	Emission factor, controlled kg/Mg	Emission factor, controlled lb/ton
31.5	260,000	cyclone	29		0.097		216			3.4	6.9
31.1	240,000	cyclone	29		0.099		204			3.3	6.5
182	241,000	ESP	1	4.124	0.045	8,519	93	23	47	0.26	0.51
203	255,000	ESP	1	3.053	0.034	6,673	74	16	33	0.18	0.37
213	202,000	ESP	1	3.534	0.042	6,119	73	14	29	0.17	0.34
						Average	uncontrolled	18	36		
							cyclone			3.4	6.7
							ESP	18	36	0.20	0.41

PELLET HANDLING

Process rate, tons/hr	Flow rate, SCFM	Control device	No. of tests	Emission rate, gr/SCF uncontrolled	Emission rate, gr/SCF controlled	Emission rate, lb/hr uncontrolled	Emission rate, lb/hr controlled	Emission factor, uncontrolled kg/Mg	Emission factor, uncontrolled lb/ton	Emission factor, controlled kg/Mg	Emission factor, controlled lb/ton
274	7,700	rotoclone	1	0.075	0.0015	5.0	0.10	0.0090	0.018	0.00018	0.00036
352	15,500	scrubber	1	3.44	0.024	457	3.2	0.65	1.3	0.0045	0.0091
352	10,800	scrubber	1	6.33	0.019	586	1.8	0.83	1.7	0.0025	0.0050
310	17,200	scrubber	1	3.14	0.022	463	3.2	0.75	1.5	0.0052	0.010
310	8,500	scrubber	1	3.9	0.039	284	2.8	0.46	0.92	0.0046	0.0092
310	16,000	scrubber	1	3.4	0.034	466	4.7	0.75	1.5	0.0075	0.015
1,698	7,335	scrubber	1	11.3	0.283	710	18	0.21	0.42	0.0052	0.010
						Average	uncontrolled	0.52	1.0		
							rotoclone	0.0090	0.018	0.00018	0.00036
							scrubber	0.61	1.2	0.0049	0.0099