DETERMINATION OF MAGNETITE CONTENT THROUGH

THE USE OF MAGNETIC

SUSCEPTIBILITY IN LARGE DIAMETER BLAST HOLES

A Thesis

Presented In Partial Fulfillment of the Requirement for The

DEGREE OF MASTER OF SCIENCE

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By

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LIST OF ILLUSTRATIONS

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INTRODUCTION

A prototype probe for measuring magnetite content in large diameter blast holes was built in 1978 by the United States Steel Corporation. This was a new concept in the taconite mining Industry. To transform this prototype into a production sampling tool for quality control, considerable work was done.
The design was based upon research done by C. J. Zablocki, working for the U. S. Geological Survey. His limited studies showed an excellent correlation between apparent magnetic susceptibility and magnetic content. His studies also Indicated that a single calibration curve might not suffice, due to variation In the mode of occurrence of the magnetite.

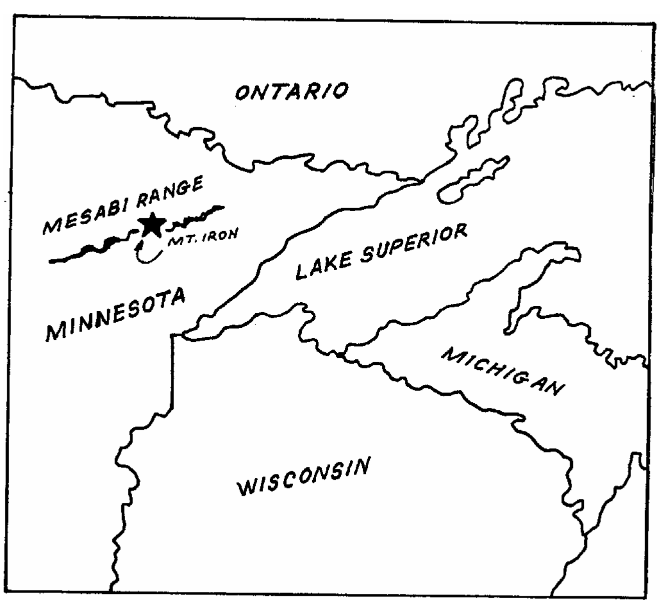
The purpose of this paper is to report the results of the following investigations:

1. Develop a general calibration between apparent magnetic susceptibility and percent magnetite.
2. Develop specific calibration relationships for various modes of occurrence.
3. Assess impact on mine operation.

BACKGROUND INFORMATION

GEOLOGY OF THE MESABI RANGE

The Biwabik Iron Formation outcrops along a 125-mile long, northeast trending line In northeastern Minnesota. Along with an Algoman age (2.4 billion years old) granite, it forms a continental divide known as the Mesabi Range. U. S. Steel Corporation's Minntac Mine Is located near the middle of the range adjacent to the city of Mt. Iron, Minnesota, 70 miles northwest of Duluth. (See Figure 1) The Biwabik Iron Formation Is believed to be a product of marine sedimentation. It has a thickness of



<u>FIGURE</u> <u>1</u> Regional Map of Lake Superior Area

approximately 600 feet. Highly uniform beds dip to the southeast 4 to 8 degrees, conforming to the northwest flank of the Lake Superior syncline. (See Figure 2) Fine-grained magnetite lies in a hard, siliceous gangue of chert, iron silicates and Iron carbonates. The following four major horizons make up the formation:

Upper Slate - 60 feet thick
Upper Chert - 230 feet thick
Lower Slate - 130 feet thick
Lower Chert - 180 feet thick

The "slate" horizons are actually fine-grained, laminated argillites. The coarser-grained cherts make up the bulk of treatable ores. Dispersion of the magnetite varies from homogenous to thinly bedded to thick beds up to nearly an inch of pure magnetite. Tectonic activity has not been extensive in the area, but jointing Is prevalent as these rocks are in the neighborhood of 2 billion years old. These joints have accelerated weathering by allowing water and air to penetrate the rocks. Magnetite has been oxidized to hematite and limonite along joint planes. Water has leached out the silica, in places, to form high grade hematite deposits.

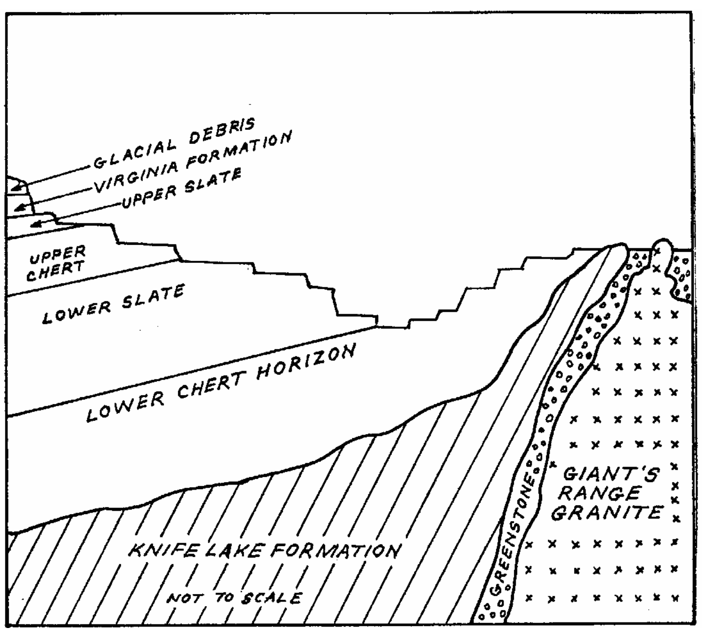


Figure 2. Typical Section of Biwabik Iron Formation (Looking West)

These deposits have been essentially depleted due to nearly a century of mining. This has led to the mining of much lower grade ores that require substantial beneficiation to increase their iron content and to decrease their silica content. Partially oxidized zones along vertical joints and along horizontal bedding planes form scattered and unpredictable areas of non-magnetic waste. These zones have "knife-edge" boundaries (i.e. lacking gradational zones) that can fall between exploration holes and go undetected until mining is under way. The structure and mineralogy have a profound impact on the electromagnetic response of the Iron formation. The anisotropic nature of the horizontally bedded magnetite layers creates a set of circumstances unique to the Mesabi Range. Applicability of similar technology to other mining districts may require careful geologic consideration.

TACONITE HISTORY

Iron has been mined on the Mesabi Range since the late 1800's. The technology of mining and beneficiating these ores has evolved through time. Prior to two world wars and the post World War II industrial expansion, the bulk of the ores were high-grade hematite, requiring little or no beneficiation. These soft, earthy ores were first mined by underground methods. Following technological improvements in surface mining equipment, spurred by the Panama Canal project, surface mining became dominant on the Mesabi Range. John C. Greenwood, who charged up San Juan Hill alongside Teddy Roosevelt, was Instrumental In developing surface mining techniques. He also Invented several "washing" machines (which were the forerunners of today's spiral classifiers) to upgrade high silica ores.

Despite the technological Improvements, only a finite amount of hematite ore was available. The bulk of the Biwabik Iron Formation was not weathered to hematite, but remained as low grade magnetite locked In a hard matrix of chert and iron silicates. Had it not been for the great foresight and years of research by Dr. E. W. Davis, Iron mining might no longer be taking place on the Mesabi Range. His work formed the basis for the taconite process. In this process, ore is first crushed and ground to the fineness of face powder, then separated by magnetic concentration, and finally pelletized by adding clay and firing to over 2,000F. The pelletizing is done to simplify handling and Improve gas flow in the blast furnace.

The name "taconite" began as a misnomer. Early geologists passing through what was to become Minnesota, mistakenly Identified outcrops along the Mesabi Range as being related to those near Taconia, New York. By the time the error was discovered, the name had stuck. The Minnesota State Legislature has a legal definition of taconites and semi-taconites for special consideration for purposes of taxation. The cities of Taconite, and Taconite Harbor also take their names from a geologist's mistake.

MINNTAC MINE

The Minntac Mine is a large scale, open pit taconite mine. As much as 62,000,000 tons of crude ore, 35,000,000 tons of waste rock, and 10,000,000 cubic yards of surface have been hauled in a single year. Natural conditions, including cold winters (often -40F), the abrasive, hard ore (60,000+ psi), along with the great logistical problems of such a large-scale materials handling project, combine to create an immense engineering challenge. Surface overburden composed of glacial clays and gravels are removed using 14 cubic yard shovels loading into 120-ton electric wheeled trucks. Waste rock is also removed in this way. The ore and waste rock are drilled on a 30 X 30 foot grid using 12" and 15" rotary drills. ANFO is the principle blasting agent. The ore Is transported on a standard gauge rail system. Eighty-ton side dump rail cars are loaded by 14 cubic yard electric shovels. Diesel-electric locomotives haul the ten-car trains out of the pit to four 60" X 109" gyratory crushers.

ORE BLENDING

REQUIREMENTS

To economically produce chemically uniform taconite pellets, producers must carefully blend various grades of ore. A wide range of grades of ore must be mined simultaneously in order to provide a uniform blend of weight recovery and of product quality (constant silica content). The range of ore weight recovery is 20% to 40%. The concentrate silica content ranges from *27a* to nearly 15X silica. These ores are blended to result in a composite analysis of about 6% +/- .2% silica and 30% weight recovery.

PROCEDURE

At U.S. Steel's Minntac Mine In Northeastern Minnesota, mine planning is based on diamond core drilling. Holes are placed on 300 foot by 300-foot centers. Drill cores are logged and partitioned into 10 to 20 foot samples. Samples are first ground to increasing degrees
of fineness, and then concentrated using standard Davis tube methods. Wet lab chemistry Is used to determine concentrate analysis. These lab results are summarized on liberation-grind curves. Ore parameters are then fed into a computer where a weighted average scheme fits the data into a bench block format. A single value for each parameter can then
be assigned to each ore block. The blocks, measuring 100 feet by 300 feet by 40 feet deep each represent about 100,000 tons. In plan view the spatial relationship between drill holes and blocks shows that one drill hole represents three blocks, or 321,000 tons; which is about 18 day's production from one shovel. (See Figure 3)

PROBLEMS

These grade control measures are no longer sufficient, due to recent variations in production levels in conjunction with lower grade ores. Ten shovels are generally needed to provide the blending flexibility and gross tonnage requirements. Several events can upset the blending program:

1. Loss of a shovel due to a breakdown or railroading problem.
2. Sudden change in ore quality at one or more shovels.
3. Reduced operating level requiring lower tonnages and fewer shovels.

The pit was initiated on the north edge of the iron formation outcrop. This approach provided access to the high grade cherty ores which lie near the footwall of the gently sloping ore body (See Figure 2). As the deposit has been worked down dip to the south, lower grade, slaty ores predominate.

Variations In concentrator weight recovery occur at considerable expense. Low weight recovery results in Idle time In the Agglomerator Plant. Conversely, high weight recovery In the Concentrator requires stock piling and expensive double-handling of concentrates. Accurate weight recovery prediction is necessary for maintaining a consistent and low silica content In the concentrate. Excess silica Is expensive to remove in the blast furnaces. Silica blending has proven to be a greater blend problem than weight recovery.

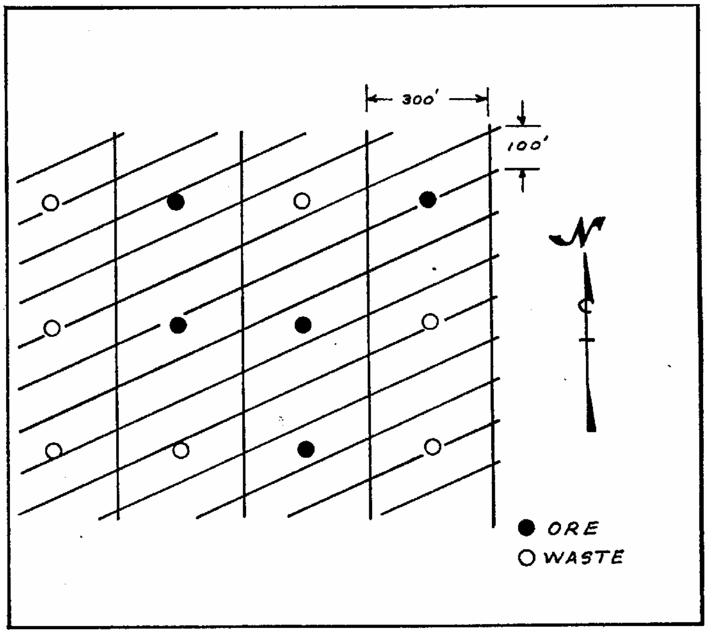


FIGURE #3

Plan View of Diamond Drill Holes and Block System

ALTERNATIVES

Many attempts have been made to reduce the short-term variability of ore shipped to the crusher. On a yearly, or even monthly time frame, the blend Is sufficiently uniform. The problem, therefore. Is not one of Incorrect or biased sampling, but one of a lack of samples. Clearly, the samples taken on 300 foot centers are too widely spaced. Considering the high cost of Increased diamond drilling, other alternatives have been sought.

Bank Sampling

Bank sampling, popular in many mining districts is limited by the blocky character of blasted taconite. Grabbing representative samples from chunks commonly up to four feet in size, poses both statistical and logistical problems.

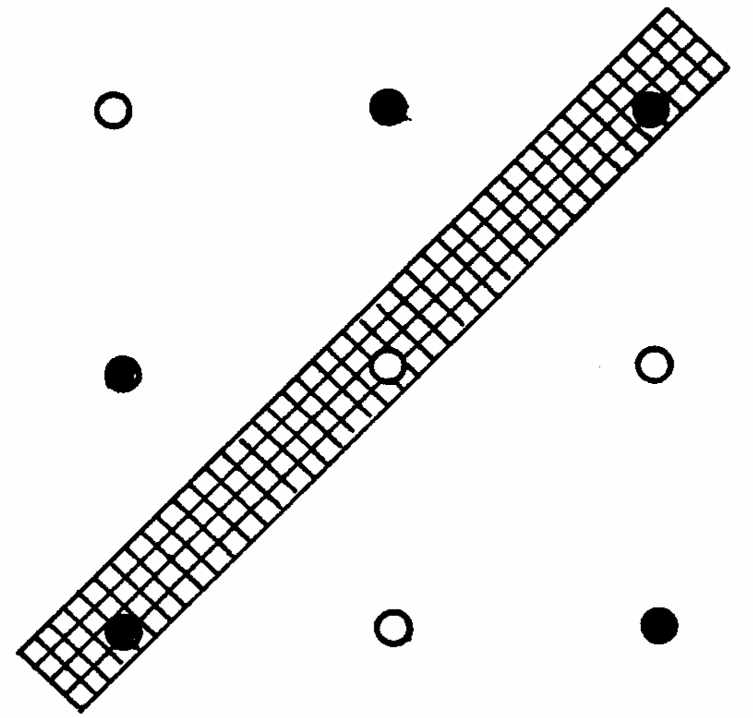
Drill Cuttings

Blast hole drill cuttings are successfully used by many mining companies. The Minntac Mine has used this method for over ten years. The advantages of sampling cuttings are:

1. Drilling produces small, easily handled chips.
2. Drilling precedes loading usually by at least one month, allowing time for efficient lab analysis.
3. Blast holes are drilled on 30 foot by 30 foot centers resulting in a 100-fold increase of sample density over diamond drilling. (See Figure 4) Despite the promising potential, sampling blast hole cuttings has not

significantly improved blending. Some of the problems with this method include:

Typical 32' X 32' Blast Pattern



Filled circles = ore

FIGURE #4

Plan View of Diamond Drill Holes and Typical Blast Pattern

1. Sample collection during the freezing months (October through April) is difficult.
2. Wet holes produce a type of muck which does not lend Itself to good sampling.
3. Dry, windy conditions promote segregation of heavy and light minerals.
4. A 15-Inch diameter blast hole, 40 feet deep, produces over four tons of cuttings.

Mechanized, field mobile sample splitters would be needed to reduce samples to a manageable size. As a result, comparisons between drill core and cuttings (drilled on the same spot) have not shown close correlation.

Geophysical Probes

The blast holes could be geophysically probed. They are closely spaced and require no extra expense. Down hole geophysical Instrumentation with the advent of microprocessing technology has become available for numerous mineral commodities. Many are available commercially. Minntac personnel felt that expensive, in-house research could be avoided by contracting a down hole logging company to test their available techniques for any statistical correlation to percent magnetic iron. Two geophysical companies, both prominent in the oil field logging industry, ran tests with the hope of finding an empirical relationship with percent magnetic iron. Although no direct relationships were known, Minntac geologists felt that some indirect indicator, such as bedding structures or associated trace elements, could be used. After extensive statistical evaluation, no reliable indicators were found.

Magnetic Susceptibility

Magnetite content has been accurately estimated by the magnetic susceptibility method. Drill core, powdered samples, outcrop surfaces, blasted muck piles, and small diameter boreholes have all been successfully measured. Generally, the Instruments have been desktop units, or small portable units which can be carried with a shoulder strap. Lacking any winch, depth gauge, or data storage capacity, these measurements tend to be ill suited to routine production requirements. Given this starting point, plus the field tests done by Zablocki, a commitment was made to create a useable tool for production.

THE BLAST HOLE SUSCEPTIBILITY METHOD

Development

Zablocki's measurements of down hole susceptibility showed excellent correlation with percent magnetite assays from Davis tube methods. He cited evidence from earlier investigators who showed an empirical correlation between magnetite concentration and magnetic susceptibility; (Slichter, 1929), (Kato, 1941), (Mooney and Bleifuss, 1953). A fundamental basis for this empirical correlation was established by Laurila (1961), Werner (1954), Puzicha (1941), Jahren (1963), Bath (1963), Shandley and Bacon (1966), and Shultz (1963). In addition, bore hole susceptibility measurement methods have been done by Broding et al (1952), Veshev et al (1957), Zablocki (1960), Laurila (1963), andAnderson (1968).

Similar equipment has been developed using induction measurements to infer magnetite content. The following is a list of available meters.

Device	Material	Manufacturer
Susceptimeter II	Small Diameter Bore Holes (in-situ)	HarrIson-Cooper Assoc. Salt Lake City, Utah
Iron Content Meter	Blasted Muck Piles (underground)	LKAB International Stockholm, Sweden
Model 3000 NB multi-parameter logger	Small Diameter Bore Holes (in-situ)	Mount Sopris Instrument Co. Delta, Colorado
Model 3101 Magnetic Susceptibility System	Drill Core or Outcrop Surface	Bison Instruments St. Louis Park, Minn
Satmagan M3-1-131	Small Solid or Powdered Samples	Outokumpu Oy Tapiola, Finland

Principle of Operation

The self inductance of a coil is the voltage induced In the coil by the changing magnetic flux it sets up when current is changing at one ampere per second. The wall rock acts like the core of a transformer. Changing the core changes the voltage. An Inductance bridge Is nulled while the coil hangs In air. (See Figure 5) The resistance of the coil drifts according to temperature variations, requiring a zeroing adjustment by means of a rheostat wired in series with the coil. With the zeroing and nulling complete, the coil is lowered into a blast hole. The magnetic Intensity will increase as a ratio of the magnetite content of the wall rock. An increase in

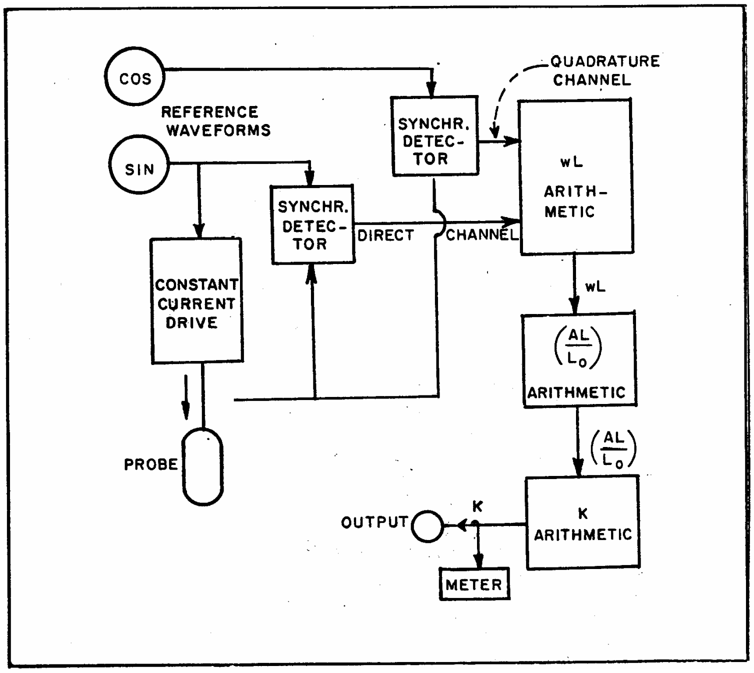


Figure #5 Schematic Diagram of Susceptibility Probe (Bison Instruments)

magnetic Intensity will Increase the self inductance of the coil resulting in a higher Induced voltage. Measurement of this voltage change Is the basic output of the downhole meter.

DESCRIPTION OF APPARATUS

Winch and Recording Equipment

A Chevrolet carry-all Is used to transport the equipment. A hydraulic winch Is mounted In the rear cargo area. (See Figure 6) Armored cable passes through an overhead boom to connect the probe to the on-board computer The front passenger's seat has been removed to make room for the electronics cabinet. Three functions are accomplished within the cabinet. First, the incoming signal is converted to susceptibility units from 0 to 128 emv (cgs units) which are displayed on a large light emitting diode (LED). As the hoisting drum rotates, magnets attached to the drum rim pass a magnetic read switch. Each time a magnet passes the switch, the susceptibility reading displayed on the LED is picked off and placed In the buffer memory and displayed on a cathode ray tube (CRT) profile of the hole. The six-inch spacing of magnets results in 80 readings for a standard forty-foot blast hole. As readings go into memory, footage is accumulated and displayed on another LED on the console. When the hole is completed, the entire profile can be viewed on the CRT. A cursor can be moved up and down the profile to display the footage and the associated susceptibility value. The susceptibility

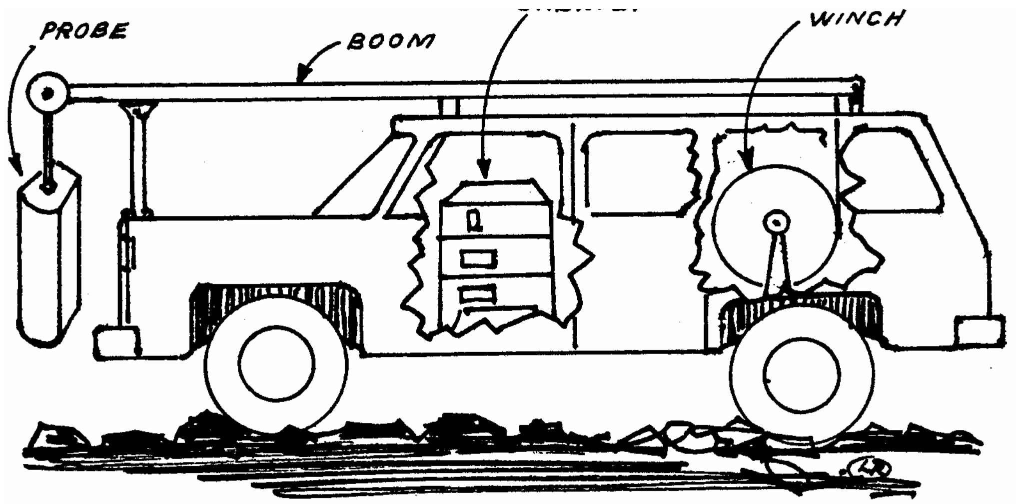


FIGURE #6

Cut-Away View of Susceptibility Truck

values are converted to percent magnetic iron and averaged for the entire hole.

Strip chart and magnetic tape recorders are built in to make a record of the hole. The tape recorder has thumb wheels for entering additional header information on the tape. This information Includes: hole number, blast pattern number, and date.

The control panel also has controls to operate the winch and boom. Also, two rheostats for nulling the meter and standardizing the probe resistance are located on the control panel. The console receives filtered air from a small fan which provides a positive pressure to prevent dust from entering. The truck is equipped with air conditioning and filtering to reduce environmental dust and humidity which would otherwise disable printed circuits and magnetic tapes

Probe Configuration

In terms of basic electronics, a simple loop no more complex than a coat hanger could act as the measuring element. In specific terms, however, the requirements of a satisfactory probe are more elaborate. The blast holes often contain water or viscous sludge composed of drill cuttings and water. The probe must work In both 12-Inch and 15-Inch blast holes. It must also be able to pass smoothly through rough, Irregular holes where the formation is heavily jointed. Since the field density of the coil drops as an inverse square of the distance from the wall rock; the probe must be held uniformly close. Rough areas In the blast holes cause hang-up problems.

The coil length must be matched to the vertical distance between readings. Excessive coil length will result In multiple readings of a single, rich magnetite bed. The resulting data may be biased upward due to convolution.

The first probe was constructed from a 4-foot section of 10-inch diameter,)I-inch wall aluminum pipe. Nylon bogie wheels were inset on retractable spring mounts. Perforations on each end were cut to allow water to flow through. The coil was wound according to Zablocki's design (See Figure 7).

Field testing of the probe turned up several problems. The)I-Inch aluminum wall caused severe attenuation of the coil's signal. Also, the nylon wheels failed to retract or stand up to rugged conditions. The aluminum pipe was replaced with polypropylene sewer pipe. With the plastic pipe, the coil response appeared satisfactory until a water filled hole was encountered. The capacitance of the coil changed dramatically when the coil had a water core instead of air. A polymer caulk (RTV) filling Inside the coil cured the capacitance problem but created a neutral buoyancy condition in the water filled holes. Also, since water could not flow through the probe. It created a piston action where the water was forced through the annular space surrounding the probe, causing further hang-up difficulties.

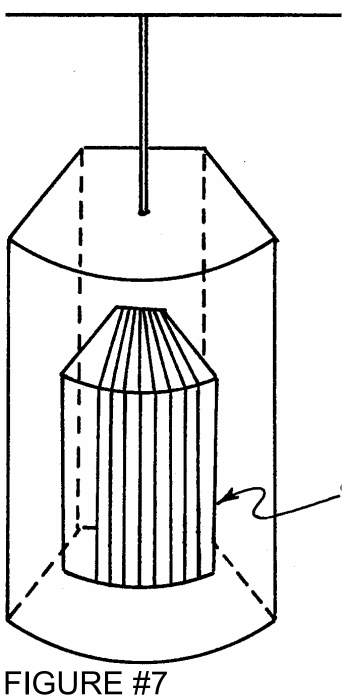


FIGURE #7

Cut-Away View of Coil Inside of Probe

As a result of the experience with these probes, a new design emerged. A shortened, 12-Inch coil was cast in urethane with lead added for ballast. Urethane bows were designed to insure close wall rock contact. A reduced cross-sectional area reduces the piston effect and the urethane surface resists hanging up. These benefits have been realized while reducing the cost to a fraction of the original. The low cost has proven beneficial as about one probe is lost each year due to jamming by spalling rock down the hole.

CALIBRATION METHODS AND TECHNIQUES

The prototype unit was built to read In susceptibility. Since no usable relationships were known to directly convert susceptibility to percent magnetic Iron, It was necessary to calibrate the unit. Five diamond drill holes were drilled to a depth of 50 feet. Representative locations, including all pertinent geologic layers, plus oxidized zones were chosen. (See Figure 8) Drill core was retrieved and grouped into 2-foot samples. It was then split, one half for the lab and one half could be stored for further Inspection and testing. Samples were subjected to the standard Davis Tube Test to determine the following parameters:

1. % Magnetic iron
2. % Weight recovery
3. % Silica

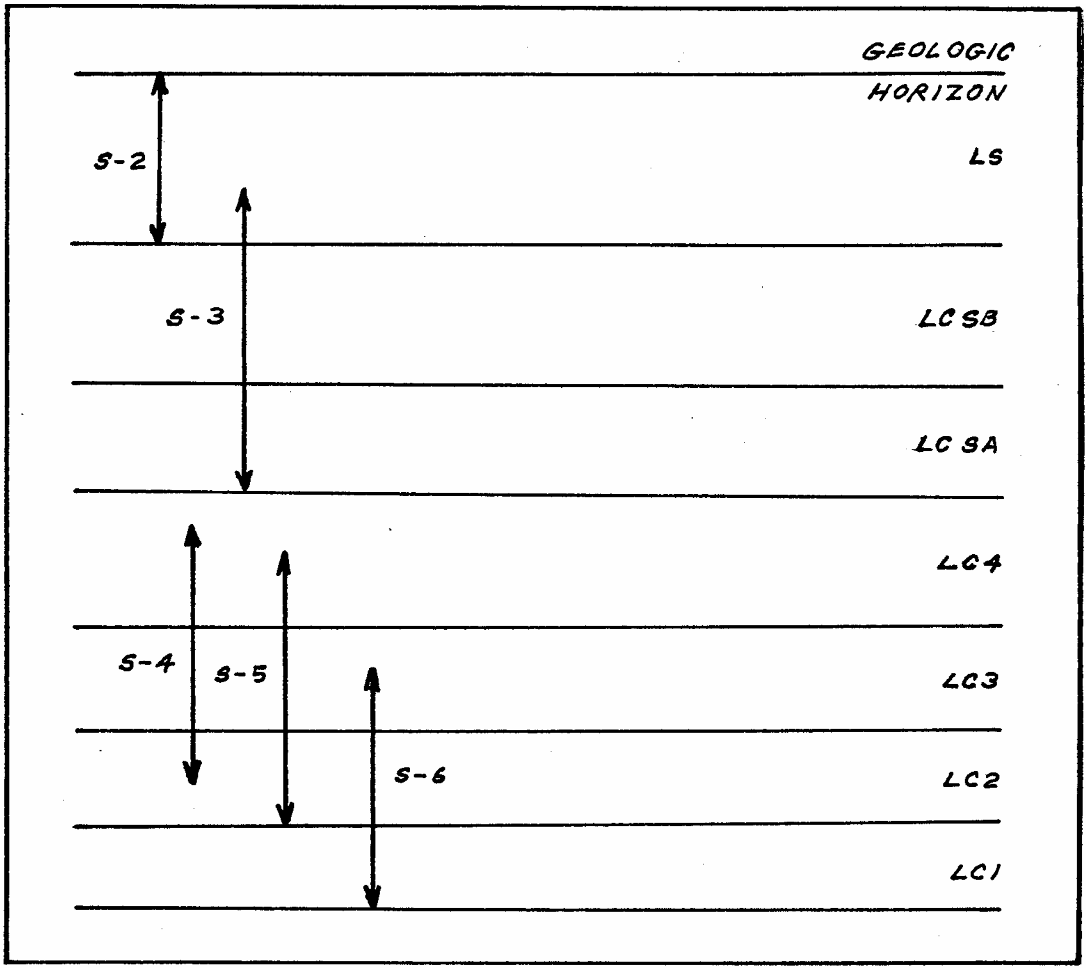


FIGURE #8

Schematic View of the Five Test Holes and their Respective Geologic Horizons

The diamond drill holes were then reamed to a diameter of 15", using a rotary blast hole drill. The cuttings were sampled on a 2-foot interval for lab analysis. The susceptibility meter was used to test each hole. This resulted in one reading for each 6-inch interval. Readings were grouped to correspond to the 2-foot samples of drill core. In this manner, 130 data points comparing susceptibility to wet lab chemistry became available.

RESULTS

The scattergram shown In Figure 9 summarizes 130 two-foot samples. (See Figure 9) Clearly, no usable relationship could be inferred unless the data was "cleaned up". At this point. It was unclear whether the scatter was due to real differences In susceptibility, or were they due to various errors inherent to the methods of measurement. This question had to be addressed before accurate calibration could be insured.

SOURCES OF ERRORS

In this analysis, the data was screened for outliers. These anomalous points were viewed as resulting from limitations In measuring methods. In the percent magnetic iron measurement, there are two major sources of error: drill core integrity and wet lab procedures.

Drill Core Errors

Drill core, once pulled from the hole, is no longer a part of the formation being measured by the probe. Its reliability as an indicator

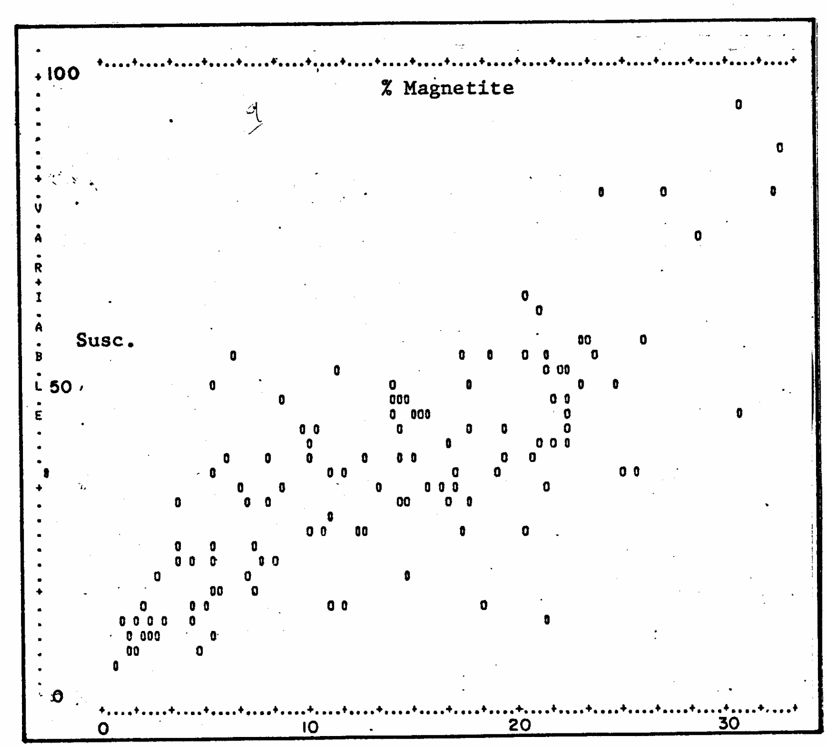


FIGURE #9

Scatter Diagram of Magnetic Iron Versus Magnetic Susceptibility

is based upon a premise of lateral continuity between drill holes. The chosen 300-foot drill hole spacing at Minntac was arrived at on an economic basis. The high uniformity of the Biwabik Iron formation and the large number of shovel locations being blended both act to make this spacing workable. The drill core, when averaged into 40-foot deep blocks, becomes blind to local variations that show up on 2-foot samples. Inspection of hand samples shows the pinching and swelling of thin beds of nearly pure magnetite. For this reason, even drill core halves, split longitudinally, exhibit marked magnetic Iron variation between halves. Therefore, It Is understandable that when the cored holes were reamed to a 15-Inch diameter that a further loss of spatial integrity would occur. The formation measured by the induction coil is an arc shaped section along the blast hole circumference. Tests done on magnetite concentrate Indicate a penetration depth of one to three Inches. Similar coils used for measuring magnetic iron in blasted muck piles are manufactured by LKAB In Sweden. Their studies indicate a measurement depth of 4 to 25 Inches, depending upon magnetic concentration. In addition, core is occasionally lost when It slips from the core barrel, or Is ground up and washed away in the drilling mud. These low core recovery Intervals can introduce scatter to the data.

Lab Errors

Once the halved drill core reaches the lab it is subjected to wet lab testing. Errors in lab testing can result from many causes:

1. Worn Tyler screens
2. Excessive grinding
3. Sample loss in exhaust fans
4. Short cuts in splitting and mixing
5. Increments of titration
6. Curve fit smoothing
7. Variations in water flow in Davis tube
8. Variations in magnetic field in Davis tube

As a result, the lab reproducibility of percent magnetic Iron has a reliability of about +/-0.5%.

Susceptibility Errors

So far, discussion has been limited to errors in the "known" quality, magnetic iron content. Measurement of susceptibility in the field is also subject to various errors. Irregular blast hole walls where sloughing or spalling has left Indentations result in Increased distance between the coil and the wall rock. The Intensity of the magnetic field drops off as an inverse square of the distance. This problem is particularly evident at the hole collars. Fluted tops may extend as much as three to five feet down the hole. Zero susceptibility readings will get recorded for these intervals.

Down hole reproducibility is also adversely affected by geologic changes across the blast hole. Zablocki showed that the north side of a hole differed from the south side. Since no rotational constraint of the probe is provided, slightly differing susceptibilities may be read for the same increment.

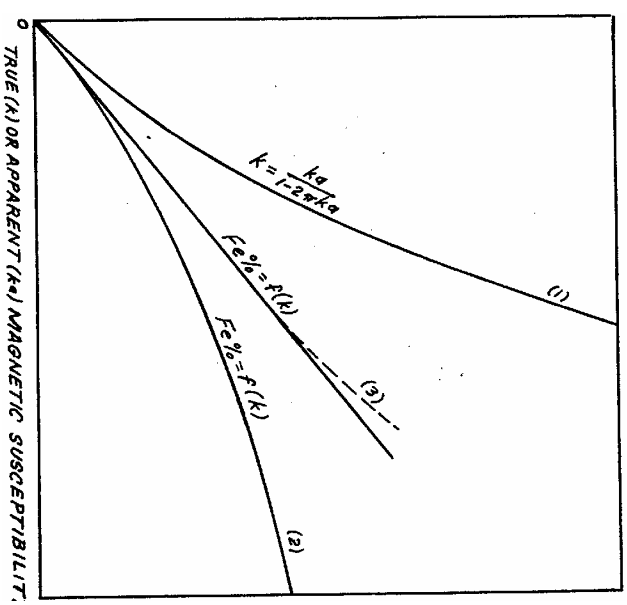
CURVE FITTTING

Matched pairs of magnetic versus susceptibility values were plotted. Taken from five representative holes from various pit locations and various stratigraphic locations, these 130 points were examined. Significant scatter resulted from the various sources of errors previously listed. Curve fitting was expedited by routine elimination of outliers, and the resulting points were then filled to two linear approximations:

Magnetic Iron = .32 susceptibility - 2.56 susc. < 50
Magnetic Iron = .12 susceptibility + 7.00 susc. >50

A scarcity of data in the upper range casts doubt on the exact reliability of the fit. Superimposing these two lines on ZablockI's plot indicates a general agreement in results.

In retrospect, the flow sheet for computing percent magnetic iron is unnecessarily complex. The arithmetic computation of "true susceptibility" is only an esoteric exercise. As Zablocki had shown a nearly linear relationship exists between apparent susceptibility and percent magnetic iron. (See Figure 10) At the time of design, it was felt, however, that generally recognized units (true magnetic susceptibility) should be the output. In this way, new data could be readily compared to published data. Calibration might be more accurate by eliminating calculation of true susceptibility In subsequent meter
designs.



WEIGHT PERCENT Fe AS MAGNETITE

FIGURE 10 Relationships between Percent Magnetite, True Magnetic Susceptibility, and Apparent Magnetic Susceptibility

(after Zablocki)

INVESTIGATION OF GEOLOGIC FACTORS

The electromagnetic response of magnetite bearing rocks would seem to weigh heavily on the mode of distribution of magnetite. If so, perhaps the wide scatter seen In the 130 matched pairs may not be spurious data, rather, they may be superimposed families of curves depicting various modes of magnetite distribution.

Investigation began by grouping data according to geologic criteria. Drill core halves from the 5 test holes were logged again with an eye toward magnetite distribution. Plots of magnetite content versus susceptibility were then made, based upon the following criteria:

1. Grain size
2. Bedding/Homogeneity
3. Geologic Horizon
4. Degree of Oxidation

The result of this test was Inconclusive; no clear trends could be seen in any of the re-grouped plots.

One of the factors, geologic horizon, was studied in further detail. This was accomplished by using drill core from old diamond drill holes from representative pit locations. The core susceptibility was measured using a Bison 3101A desk top core analyzer. The core was then subjected to standard laboratory analysis for magnetite content.

The results of measurements on 229 drill core samples are summarized on Figure II. (See Figure II) Three curves representing upper and lower chert, plus lower slate horizons, are very much alike. Differences In the higher ranges are not conclusive. Curve fitting effects, along with a shortage of data points, probably account for much of the divergence.

REVIEW AFTER TWO YEARS OPERATIONS

OPERATION

A two man crew operates the down hole meter. Scheduled on day shift only, five days per week, they keep up with a fleet of drills averaging 500 holes per week. Routine sampling is limited to 20% of the holes resulting In about 100 holes per week or about 20 holes per shift. In addition to this data which are routinely used for blend control, certain areas require special attention. In those areas where diamond drilling has Indicated an extreme change between 300 foot spaced hole

drilling has Indicated an extreme change between 300 foot spaced h

every hole may be checked to delineate the precise location of ore-waste contact. Erratic oxidation has, in many cases, created complex patterns of ore and waste (See Figure 12). Another special c concerns delineation of the foot wall contact. Localized monoclinal rolls often result in ore dilution or wasting of ore If undetected. The foot wall contact is located, often following each hole, and reported

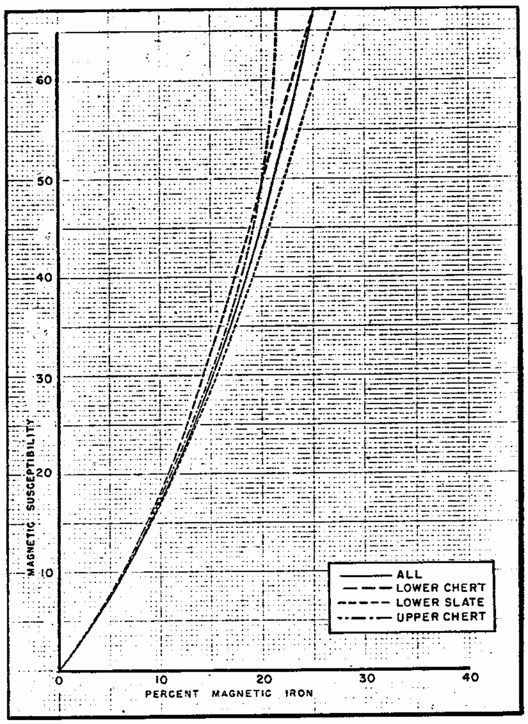


FIGURE 11

Magnetic Susceptibility Correlation with Davis Tube Magnetic Iron for Lower Chert, Lower Slate, and Upper Chert

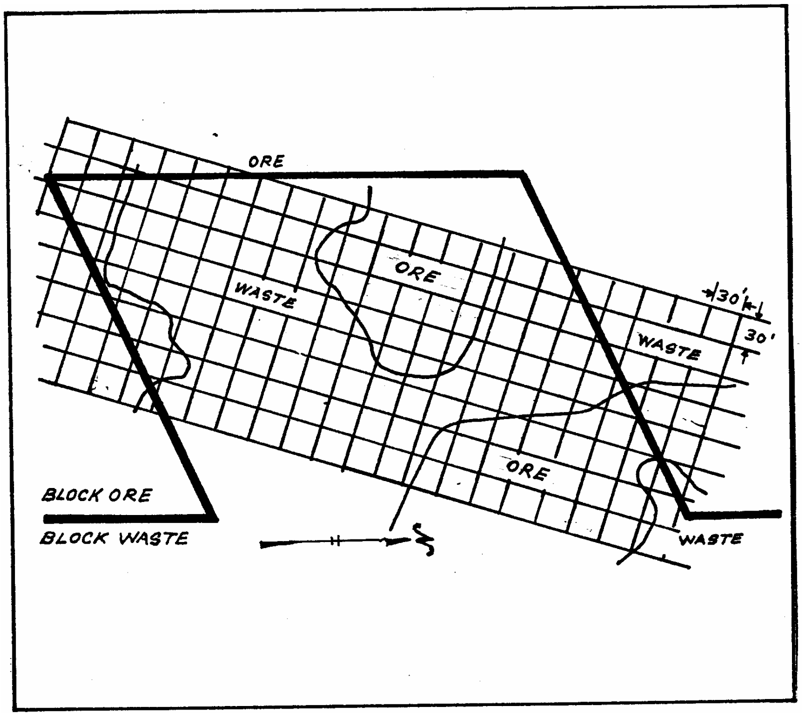


FIGURE # I2

Plan View of Ore Waste Contacts According to Blocks (heavy line) and According to Down Hole Probe (light line)

directly to the drilling department. These special sampling jobs together with routine sampling can result In a total workload of 40 to 50 holes per shift. Holes are spread over 2 pits up to 7 miles apart. A typical day Includes up to 1~ hours travel time traversing the pit roads and the extremely rough drill patterns. The crew must also spend about 2 hours each day on data reduction, as strip charts from each hole must be indexed to plan view summaries of drill patterns. Data reduction will be mechanized through the use of a computer plotter In the near future. This leaves about 4 hours per shift for actually probing up to 50 holes. Except for extreme winter conditions, this rate is easily achieved.

To probe a hole the assistant will start by removing the safety cover from the blast hole. The operator drives up to the hole and nulls the meter to read zero as slight drift continues even after warm-up due to temperature changes In the probe. The probe is lowered. As it enters the collar, the assistant signals the operator to hit the RESET button. This clears the buffer memory of data remaining from the previous hole. As the probe descends, a switch on the hoisting drum triggers a reading once every 6 Inches. In less than 30 seconds the probe reaches the bottom of a 40 foot hole. A tension switch detects slack in the cable and stops feeding cable so that no cable pile-ups can occur. The operator disables the trigger switch and hoists the probe out of the hole. He then

Inspects the magnetic profile of the hole as It is displayed on the CRT on the instrument panel. If it looks okay, he presses the STORE button which transfers the readings and associated footages to magnetic tape. The time required for each hole is about 3 minutes.

CORRELATION

Two follow up studies were done to evaluate the calibration accuracy of the down hole meter. The first one compared 1979 down hole meter data to lab data wherever probed blast holes fell near existing diamond drill holes. The second study compared daily predicted magnetic iron content (based on diamond drilling and subsequent lab analysis) to actual daily plant results. This study spanned the time from before the meter was used to when it was used extensively.

Drill Core Versus Down Hole Meter

Initial calibration was based on a limited number of data points. Considering the cost of diamond drilling, lab analysis of drill core and of blast hole drilling; the cost of each calibration test hole exceeded $1,000. To economically obtain more data points, existing blast holes and existing diamond drill holes were used. Since the ore body is already diamond drilled on a 300 foot by 300 foot grid; blast holes inevitably end up being drilled close by. Examination of 1979 west pit drilling resulted in 66 new data points. This was accomplished by recomposing the 15 foot diamond drill core samples to match the same horizon (bench) tested with the meter. This study served to compare wet lab testing of drill core to down hole meter results. The 66 new data points exhibited the same behavior as the original data points.

Mine Indicated Versus Plant Actual - (before and after use of meter)

Production records for the years from 1978 to 1981 were checked to evaluate what effect the down hole meter had on the daily blend of ore being sent to the plant. The following graph summarizes mine and plant weight recoveries for this period. (See Figure 13) Two problems have been considered. Has the meter introduced any noticeable bias to the mine vs. plant relationships? Has the day to day tracking of mine Indicated vs. plant actual improved for weight recovery?

Check for Bias

To evaluate the first question we must look at the two lower lines. There was considerable concern that the increased pessimistic bias resulting from the use of the meter, indicating Inaccurate calibration. From January 1980 to April 1981 use of meter information went from 2 shovels per shift to about 12 shovels per shift. But looking back to1978 and 1979 similar fluctuations occurred during the months of February and March. This led to another study concerning seasonal variations in concentrator efficiency. A literature search turned up similar observations at nearby taconite plants. Investigators have linked improved concentrator efficiencies to cooler process water as Is experienced during northern Minnesota winters

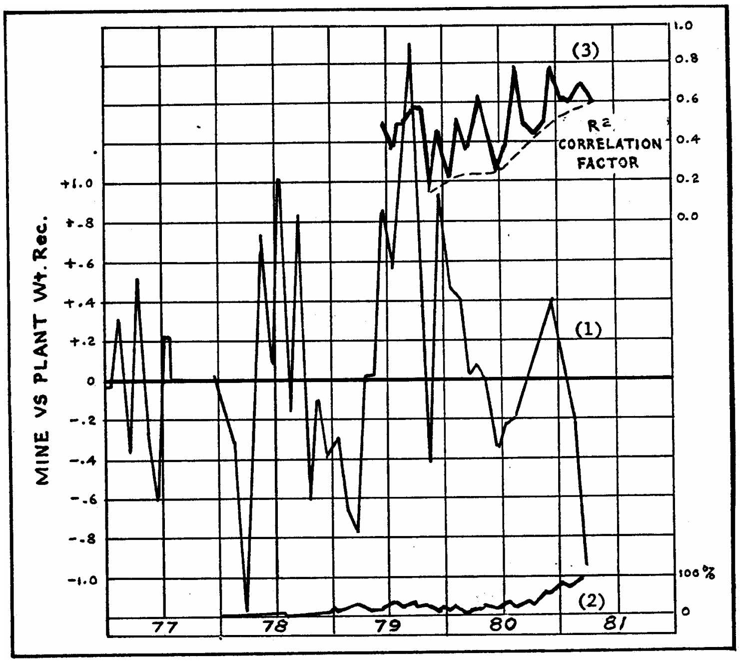


FIGURE #13_Five-Year Summary of (1) Mine Versus Plant Weight Recovery; (2) Usage Rate of Down Hole Meter; and (3) Correlation(r^2) of Mine Versus Plant Weight Recovery

Minor flow sheet changes have been made during this time period making absolute conclusions very difficult, but It appears that no major upward or downward bias has been Introduced.

Daily Tracking

To evaluate the question of day to day tracking of mine versus plant weight recoveries, the coefficient of correlation (r^2) was calculated on a monthly basis. This was done by linear regression where the data was fitted to the form: Y A+BX. The coefficient of correlation is a measure of how well the data fits the regressed line. Values of 2 range from 0 to l. As r^2 approaches l, a better fit Is indicated. The r^2 factor has apparently improved from early 1980 through February of 1981 (See Figure 12) Daily tracking of mine versus plant weight recovery (r^2) is not plotted prior to mld-1979, because of changes In reporting practices and flow sheet modifications. In mld-1978, six additional concentrator lines were added. In early 1979 fine screens were added to six other lines to help reduce silica. Late in 1979, flow sheet Improvements were made at the magnetic separators to Improve throughput. With these modifications In mind the erratic changes In r become less mysterious. Another way to look at r2 may be to look at the lower envelope of the plot. The worst months have clearly been Improved through Implementation of the meter.

CONCLUSIONS AND SUMMARY

The author worked in conjunction with other individuals on this project, however, the calibration, investigation of geologic factors, and the follow-up studies are solely the work of the author.
The down hole susceptibility meter has been judged a success by Minntac personnel. Since its inception, magnetite content prediction is now done almost entirely in this manner. At least two other Mesabi Range taconite mines now use susceptibility meters down blast holes.

Calibration has been achieved by using two linear approximations to relate magnetic susceptibility to percent magnetic iron. Calibration could be simplified, and perhaps improved, by by-passing the calculation of true magnetic susceptibility. As Zablocki showed, percent magnetic iron varies nearly linearly with a change In the inductance of the coil.

Effects of geologic factors (modes of occurrence) remain unsubstantiated. Future work should focus on effects of grain size, bedding, and oxidation, with respect to their influence on magnetic susceptibility. The only conclusive results concerned geologic horizons. The family of curves for the seven major horizons do not show significant differences to warrant individual consideration.

The Impact on mine operations has been favorable. Without interfering with established production and safety considerations, at least *207,* of all blast holes are probed in each blast pattern. No longer do small pockets of Isolated waste material suddenly show up in what was thought to be ore. The improved picture of ore-waste distribution has enhanced planning and has resulted in better deployment of equipment. Forecasting ore quality delivered to the plant has improved. As the Implementation of the susceptibility meter increased, so did the correlation between forecasts and actual results.

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