Fall 1983

# Separation of mineral particles in cyclones under the influence of a magnetic field

Kwasi Amoako-Gyampah

**Department:**

## Recommended Citation

Amoako-Gyampah, Kwasi, "Separation of mineral particles in cyclones under the influence of a magnetic field" (1983). *Masters Theses*. 17.
https://scholarsmine.mst.edu/masters_theses/17

# SEPARATION OF MINERAL PARTICLES IN CYCLONES UNDER THE INFLUENCE OF A MAGNETIC FIELD

BY

KWASI AMOAKO-GYAMPAH, 1954

A THESIS

Presented to the Faculty of the Graduate School of the
UNIVERSITY OF MISSOURI-ROLLA
in Partial Fullfillment of the Requirements for the Degree

MASTER OF SCIENCE IN METALLURGICAL ENGINEERING

1983

Approved by

(Advisor) M. H. Erten

T. O'Keefe

# ABSTRACT

The separation of mineral particles in a cyclone under the influence of a magnetic field was investigated using an electromagnetic - cyclone arrangement. Feed pulps of dolomite and magnetite were used in the study. Two different cyclone types were investigated: An air-type cyclone arrangement and a conventional cyclone arrangement. Magnetic field strengths of 0 to 3000 gauss (0 - 0.3 Tesla) were used in the study by varying the current through the coils of the electromagnet.

The parameters evaluated in the study were the grades and recoveries of the magnetic concentrates produced, the enrichment ratios, the improvement in recoveries achieved and the selectivity indices of the processes.

The air-type cyclones operating without the magnetic field (ie as a classifier) produced 50% recoveries of the magnetic fraction of the feed with an enrichment ratio of 1.0. The use of the magnetic field resulted in enrichment ratios as high as 1.8 and up to 25% improvement in recoveries.

Using a conventional cyclone (as distinct from the air-type cyclones) resulted in higher concentrate grades and recoveries when operated in the magnetic field. Recoveries of 88% or better were achieved with enrichment ratios as high as 2.35. Cast iron pieces were used to alter the magnetic field distribution around the cyclone yielding recoveries well above 90%.

The effects of pressure and percent solids in the feed were also investigated. The recovery and grade were observed to decrease at pressures above 8 psi. The grade increased with increasing percent solids in the feed whilst the recovery decreased at the same time. However, the changes in both pressure and percent solids had to be large for these to be significant.

Initially, the study investigated feed pulps containing 10% magnetite. Use of feed pulps containing 20 to 30% magnetite showed that the higher the percent magnetite in the feed, the less the field intensity required to achieve high recoveries under similar conditions.

To increase the concentrate grades, the feed to the cyclone should have particles with sizes just below the $d_{50}$ of the cyclone. The cyclone operating under the influence of the magnetic field would then recover mostly magnetic materials to the underflow resulting in higher grades.

# ACKNOWLEDGEMENTS

The author wishes to express his deepest appreciation to Dr. John L. Watson for suggesting this project and for his patience and guidance throughout the study. Without his help, this thesis would not have been possible.

The author is grateful to Mr. Dwayne Reynolds and Dr. D. R. Askeland, both of the Metallurgical Engineering Department for their respective help in the construction of the air-type and aluminium cyclones.

The author gratefully acknowledges the financial support provided by the Weldon Springs Fund and the Department of Metallurgical Engineering and also the U. S. Bureau of Mines for the use of sizing equipment.

Finally, the author wishes to dedicate this work to God.

## TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

## TABLE OF CONTENTS (Cont.)

## LIST OF ILLUSTRATIONS

## LIST OF ILLUSTRATIONS (Cont.)

Figures Page

## LIST OF TABLES

## LIST OF TABLES (Cont.)

# I. INTRODUCTION

A. General Introduction. The economic recession that has existed for the last two years has led to a severe slowdown in the expansion of the minerals industry. It has however led to increased activities in mineral processing equipment design. Mineral processing engineers and researchers are being challenged by economic restrictions on mill flowsheets to look for improvements and better, less expensive techniques for processing minerals. Small projects are being carried out in process equipment design with innovations in design, most often for cost savings, that will have significant effects on future processing applications.

One equipment in mineral processing flowsheet design that has gained wide prominence in recent research is the hydrocyclone. In the last ten years, efforts have been made to increase the capacity and efficiency of cyclones, to develop new equipment for minimising operating difficulties, and to develop mathematical models for simulating cyclone performance. Another interesting area is the development of new cyclone equipment for specialized applications.[1] An example of this specialized application is the concept of an air sparged hydrocyclone[2] developed by Miller and Van Camp which has been adapted to fine coal flotation[3].

The use of magnetic separators in mineral processing is another area which is finding more and more divergent applications. Whereas in the past magnetic separation devices have been restricted to separating strongly magnetic materials, a number of new devices are being developed with capabilities of separating very weakly paramagnetic materials.[4]

B. Basis of Project. Most mineral processing facilities utilize a hydrocyclone in one form or another either as a wet classifier or as a thickener, for desliming or degritting. The beneficiation of ores containing magnetic particles such as beach sands usually has separate classification and magnetic concentration units. The development of process equipment that could utilize simultaneously the specific gravity and/or size property in classification and the magnetic property of the mineral would enable the two processes to be conviently combined into one. The feasibility of such an equipment would enable substantial gains to be in terms of less processing times, floor space savings, lower operating cost with the possibilities of lower capital investments and increased capacities.

In this project an attempt has been made to combine the benefits of high capacity, simplicity, lower residence time and the generally high efficiency of a hydrocyclone with the principles of conventional magnetic separation devices to study the behaviour of mineral particles in an equipment incorporating classification and magnetic concentration as one unit. The device will be referred to as "the magnetic hydrocyclone" throughout this report.

Some theoretical discussions of hydrocyclone classification and magnetic separation are first offered in this presentation, followed by descriptions of various models of magnetic hydrocyclones used in the experiments. Some preliminary results indicative of the behaviour of mineral particles under the combined influence of magnetic fields and separating forces in a hydrocyclone are finally presented.

It is appropriate at this stage to note that the words "cyclone" and "hydrocyclone" will be used interchangeably throughout this report.

## II. THEORETICAL CONSIDERATIONS

This project makes considerable use of the principles behind the operations of both cyclones and conventional magnetic separators. It is therefore worthwhile reviewing and discussing the theories involved in the operations of these mineral processing units.

A. Hydrocyclone Classifier. Since its introduction in the 1950's, the hydrocyclone has become the most commonly used wet classifier in the minerals industry and currently is used for mill classification for particles between 150 and 5 microns[5], although separations of coarser particles are possible. High capacity, low initial and maintenance costs, less floor space requirement, short residence time of particles and comparable efficiency have made the hydrocyclone one of the most versatile and useful tools in mineral processing applications. Hydrocyclones have replaced mechanical classifiers in many modern grinding lines capable of processing in excess of 20,000 metric tons per day.[1]

Although classification is the main application in the minerals industry, cyclones have also found many other uses such as desliming, degritting, thickening and recently for the washing of fine coal.[6]

Basically, the cyclone utilizes fluid pressure energy to create rotational fluid motion.[7] This rotational motion causes relative movement of particles suspended in the fluid, thus permitting separation of these materials one from another or from the fluid. The rotation is as a result of the tangential injection of the fluid into the vessel. At the point of entry, the vessel is usually cylindrical. It can remain cylindrical over its entire length though conventionally, the lower ends take the shape of a cone.[7]

It is significant to note that the important criterion that distinguishes a cyclone is not the shape of the vessel but the use of fluid pressure to create rotational motion. This fact would be borne in mind throughout the developmental stages of this project.

The outlet for the bulk of the fluid entering the cyclone is usually located near to or on the axis of the vessel such that the rotating fluid is forced to spiral towards the centre to escape. The rotational motion has thus built into it an inward radial motion. Particles of a suspended material consequently have two opposing forces acting on them. One in an outward radial direction due to the centrifugal acceleration, and one in an inward radial direction due to the drag force of the inward moving fluid. The magnitude of these forces on the physical properties of both the fluid and the suspended material (eg. size and shape of particles, density of particles and of fluid, and viscosity of fluid), and the use of these properties can consequently be made to effect separations of one material from another or a single material from the fluid.

<u>1. Design features of a conventional cyclone</u>. The

principal features for a standard cyclone are shown in Fig. 1. These are the cyclone diameter which is defined as the approximate inside diameter of the cylindrical feed chamber (Dc). The feed chamber incorporates the tangential feed inlet (Di). The top of the cylindrical section is closed with a plate through which passes an axially mounted pipe for the main fluid outlet (Do). The overflow pipe extends into the body of the cyclone by a short removal section known as the vortex finder. The vortex finder extends below the feed entrance to minimize short-circuiting of feed directly into the overflow as will be shown later. The underflow is taken out axially through an apex of the conical section known as the spigot (Du).

Fig. 1 also illustrates the typical relationships between the various features of the cyclone. The conical section has an included angle of about 12 degrees for cyclones smaller than 10 inches. For larger cyclones, the cone angle is approximately 20 degrees.[8]

2. Theory of operation of hydrocyclone. Classification within a cyclone depends on the relative motion between the fluid and the solids. A full understanding of the mode of operation of the cyclone therefore requires a clear understanding of the flow patterns and velocity distributions within the cyclone body. The next two subsections will be devoted to a review of the flow patterns and velocity distributions.

a. Flow patterns in the cyclone. Several models have

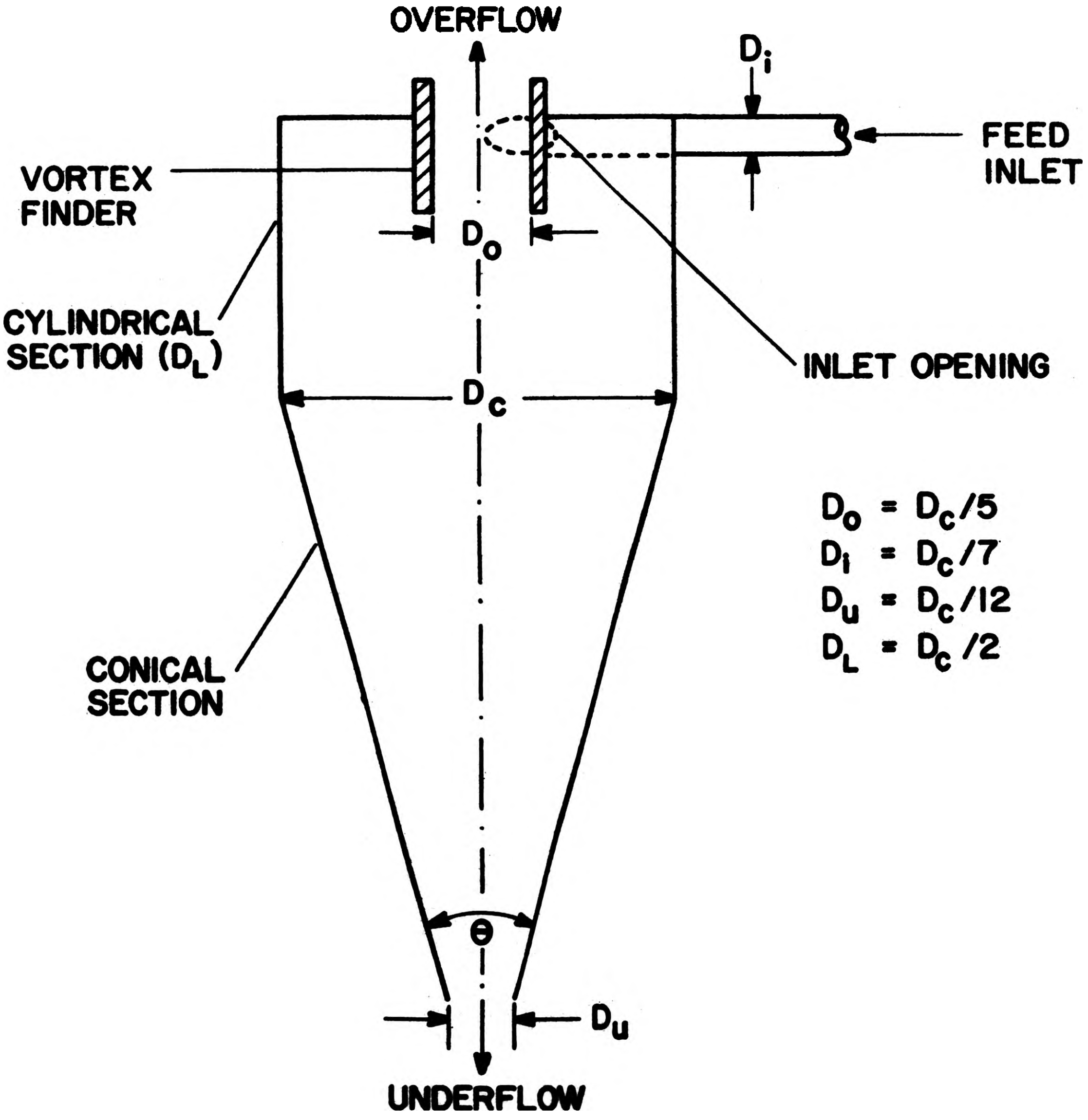


Fig. 1 Principal Features of a Standard Hydrocyclone

been suggested for the fluid flow patterns in cyclones. This is because of the complex nature of the flow patterns prevalent in the cyclone. One model that has gained wide acceptance is the double spiral pattern suggested by Bradley.[7] The fluid on entering the cyclone begins a downward flow in the outer portions of the cyclone body. The rotational motion caused by the pressure under which it enters the cyclone combines with the downward movement to create an outer spiral. This outer spiral moves towards the apex. The existence of a top central outlet and the inability, under normal feed pressure and flow rate conditions, for all fluid to leave at the cone apex outlet, assit the inward migration of some of the fluid from the external downward moving mass. The extent of inward migration increases towards the cone apex and the fluid flowing in this migrating system eventually reverses its vertical velocity direction and flows to the cyclone outlet through the vortex finder. This upward stream is also rotating and results in an inner spiral as shown in Fig. 2.

The lower pressure regions in the proximity of the cyclone walls, together with the lower pressure in the inner regions, cause a fraction of the feed liquid to pass directly across the cyclone roof and down the outside wall of the vortex finder to join the overflow stream within the vortex finder. This is known as the short circuit flow (Fig. 3) mentioned previously and can be as high as 15 percent of the feed flow. Recirculating flow known as eddies also occur in the

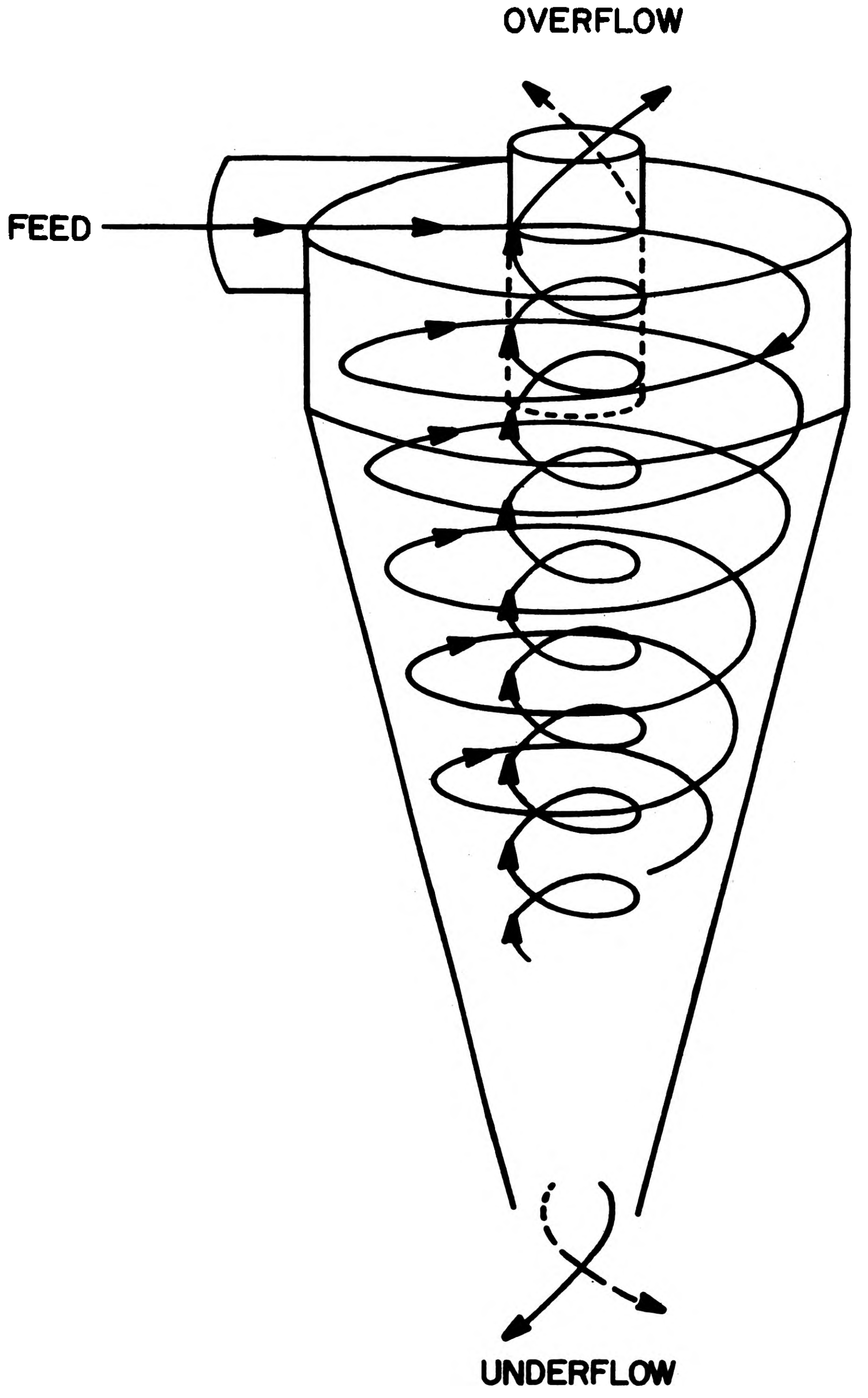


Fig. 2 Double Spiral Flow Pattern Within Cyclone

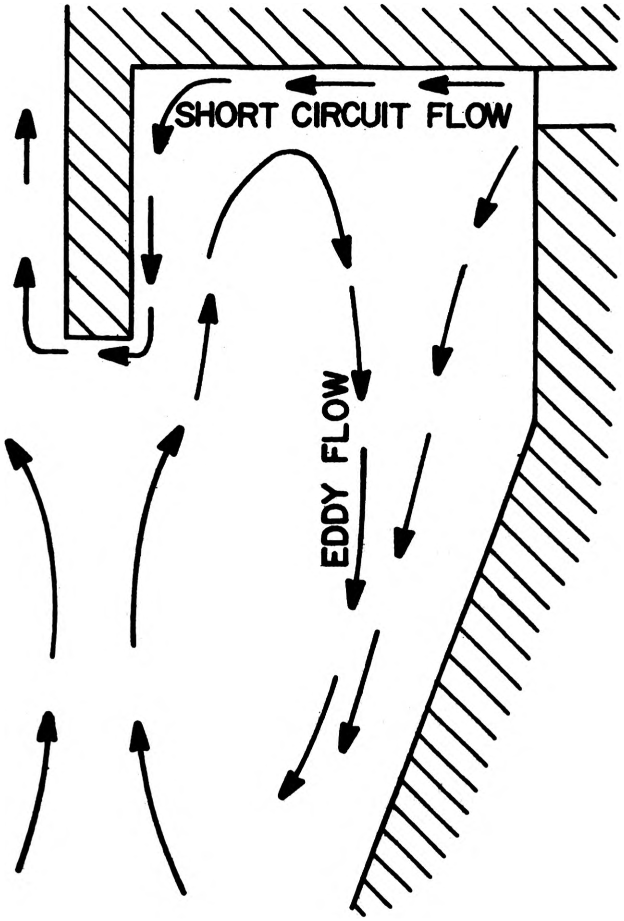


Fig. 3  Short Circuit and Eddy Flows Within Cyclone

region outside the radius of the outer wall of the vortex finder (Fig. 3). This is thought to be caused by the inability of the normal overflow opening to cope with the natural up flow in the vortex.

The existence of an outer region of downward flow and an inner region of upward flow implies a position at which there is no vertical velocity. This applies throughout the greater part of the cyclone body and results in the existence of an envelope of zero vertical velocity throughout the body of the cyclone.

Another feature of fluid flow in the hydrocyclone is the presence of an air core. The rotation of the fluid creates a low pressure axial core resulting in a free liquid surface. The core in a cyclone which communicates directly with the atmosphere at either one outlet or the other becomes air filled. It has been observed that the air core diameter increases with increase in overflow diameter but is unaffected by the change in underflow diameter[9]. Bradley[10] also reports an increase in air core diameter with increase in cone angle of cyclone.

<u>b. Distribution of velocities</u>. The velocity of feed material at any point within the cyclone may be resolved into three components: the vertical or axial component, the radial component and the tangential component. No completely satisfactory measure of these components has been made although an optical study using very dilute suspension of particles has given some reliable indications of the liquid

flow patterns.[11]

i. Tangential velocity. This is the most useful and significant of the velocity components and operates in the horizontal field. Below the vortex finder, envelopes of constant tangential velocities are coaxial within the hydrocyclone (Fig. 4) and the velocity is inversely related to the radius as given below:

$V_T r^n$ = constant., where

$V_T$ is the tangential velocity

$r$ is the radius

$n$ is a constant with typical values between 0.4 and 0.9

This is known as the free vortex flow.

With decrease in radius from cyclone wall, the tangential velocity decreases and the relationship becomes

$V_T r^{-1}$ = constant.

The above relationship holds for the forced vortex until the cylindrical air core is reached.

ii. Vertical velocity. The vertical velocity component relates to the volumetric distribution of product between the underflow and the overflow. The most significant feature of the vertical component shown in Fig. 5 is the locus of zero vertical velocity. Below the vortex finder, all liquid moves upward inside the envelope and downward outside. In each case the velocity component increases with distance from the locus or envelope.

iii. Radial velocity. The radial velocity is the smallest

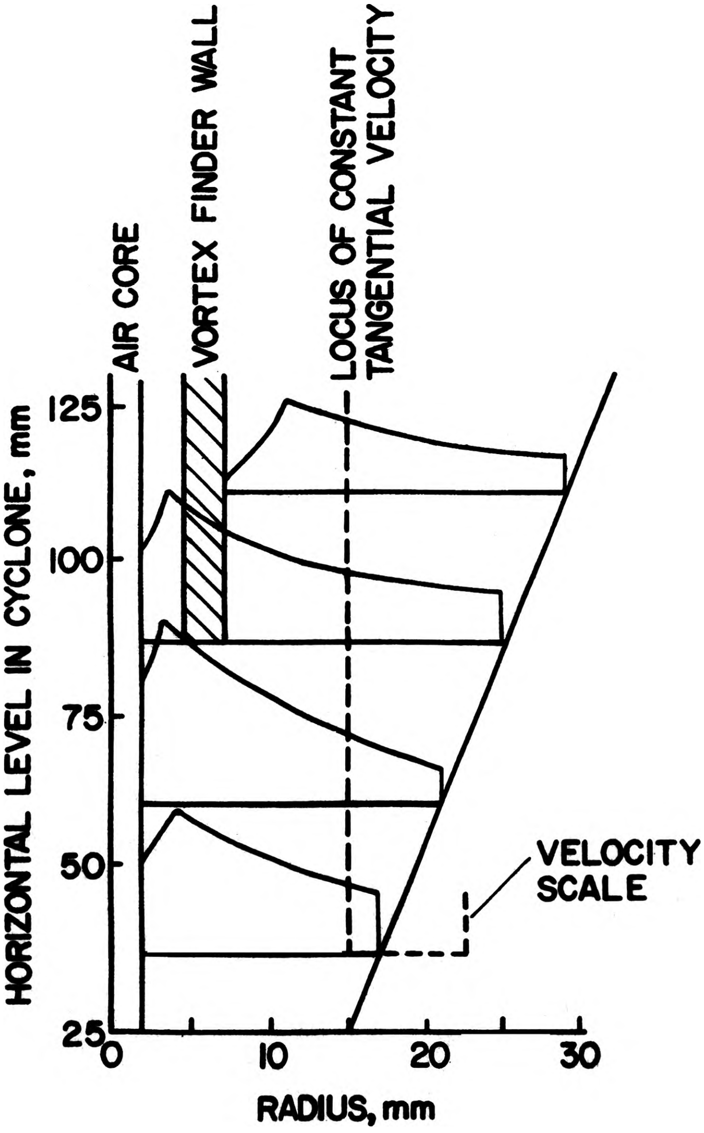


Fig. 4 Tangential Velocity Distribution in Cyclone (After Bradley[7])

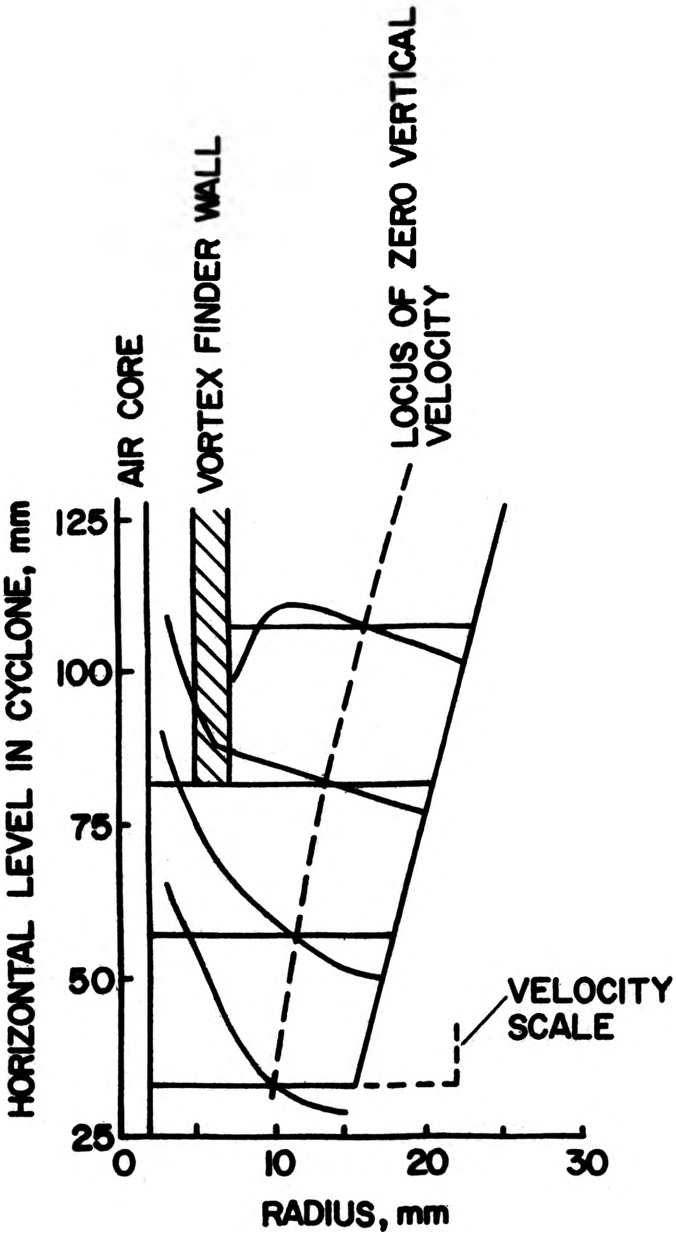


Fig. 5 Vertical Velocity Distribution in Cyclone (After Bradley[7])

of the three velocity components but is considered here because of the critical function of deciding whether a particle will end up at the overflo or the underflow. The gneeral form of the velocity is shown in Fig. 6. The component is normally inward with the maximum being at the cyclone wall.

c. Forces on a particle in the hydrocyclone. The classical theory of hydrocyclone action is that particles within the flow pattern are subjected to two opposing forces - an outward centrifugal force directing particles radially outwards depends on the fluid tangential velocity as well as on the size and specific gravity of the particles. This force is given by

$$F_c = \frac{mV_T^2}{r} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; (1)$$ where

$F_c$ is the centrifugal force

$V_T$ is the tangential velocity of fluid

r is the orbiting radius of the particle

m is the 'apparent' mass of the particle and is also given by

$$m = \frac{\pi d^3 (Sp - Sf)}{6} \quad \text{------------} \; (2)$$ where

Sp = specific gravity of the particle

Sf = specific gracity of the fluid

d = particle diameter.

The drag force depends on the fluid radial velocity, the viscosity of the fluid and the coefficient of drag of the particles. Assuming laminar flow[12], the drag force is given by

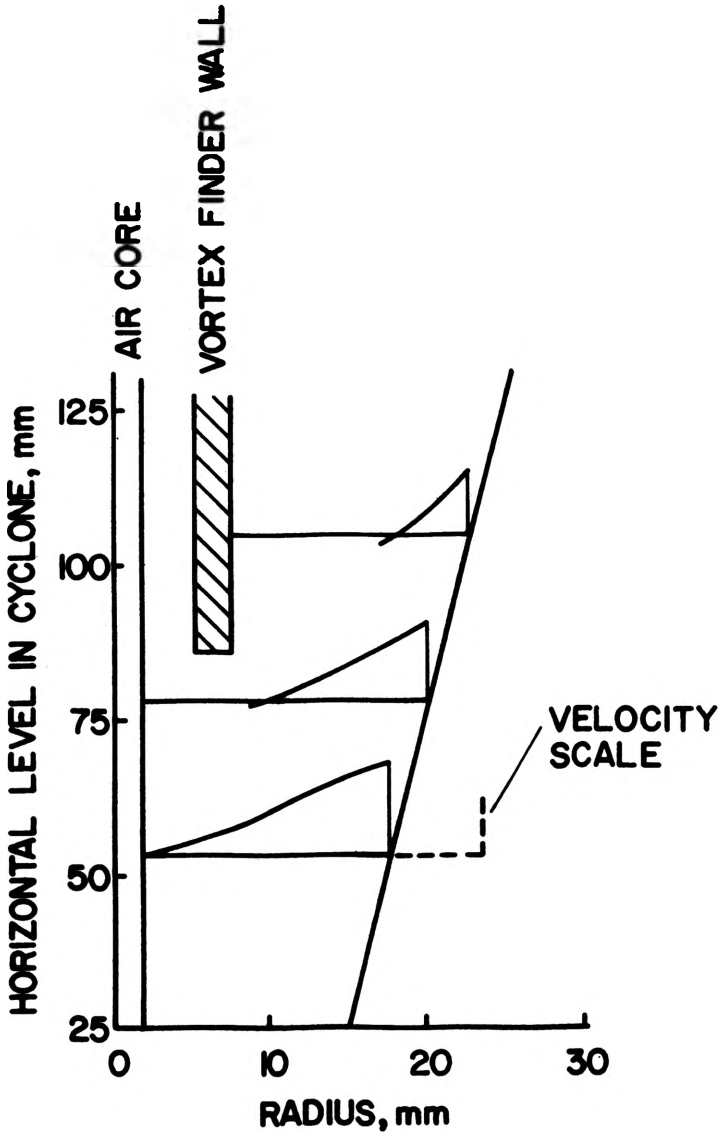


Fig. 6 Radial Velocity Distribution in Cyclone (After Bradley[7])

$Fd = 3\pi d\ nV_r$ --------- (3) where

$Fd$ = fluid drag force, $V_r$ = radial velocity

$d$ = particle diameter

$n$ = viscosity of fluid

Where Fc exceeds Fd, the particle moves outward exiting through the underflow; if Fc is less than Fd, the particle moves inward and may leave through the overflow. When Fc = Fd, the particle experiences no radial motion and has an equal chance of reporting either to the underflow or overflow.

ie. $Fc = Fd$

$$\rightarrow \quad \frac{\pi d^3(Sp-Sf)V_T^2}{6\ r} = 3\pi dnV_r$$

$$\rightarrow \quad \frac{d^2(Sp-Sf)}{18n} = \frac{V_r}{V_T}\cdot r \text{ ---------- (4)}$$

The tangential and radial velocities are both proportional to the inlet velocity. If the inlet velocity is $V_I$, then $V_T \alpha V_I$ and $V_r \alpha V_I$, and the above equation reduces to

$$d^2 \alpha \frac{18n}{Sp-Sf}\cdot \frac{r}{V_I}$$

$$\therefore d^2 \alpha \frac{r}{V_I} \text{ ----------------(5)}$$

The size of the particle at which the particle has an equal chance of reporting either to the overflow or the underflow is known as the $d_{50}$. Therefore, from above, (expression 5)

$$d_{50}^2 \alpha \frac{r}{V_I}$$

If Q= volumetric flow rate and $D_I$ = inlet diameter then $V_I = \frac{Q}{\pi D_I^2/4}$ and if $D_I = Dc/7$ and $r = Dc/4$ for a conventional cyclone

where Dc = cyclone diameter, then

$$d_{50}^{2} \alpha \frac{r}{V_I} \alpha \frac{Di^3}{Q} \alpha \frac{Dc^3}{Q} \text{------------------}(6)$$

The $d_{50}$ is also known as the separating size and from above it is shown to be governed by the cyclone size and operating conditions.

3. Performance of hydrocyclone. The most frequent method of representing cyclone efficiency is by a performance, classification, or Tromp curve (Fig. 7). This is a curve which relates the weight fraction or percentage, of each particle size in the feed which reports to the apex (underflow) or vortex finder (overflow), to the particle size. The cut point or separation size, of the cyclone is often defined as that point on the tromp curve for which 50% of the particles in the feed report to the underflow. This point correpsonds to the $d_{50}$ mentioned in the previous section.

In the cyclone, some water accompanies both the coarse and fine products. This water carries with it significant quantities of fine material. Some solids are therefore not classified but are merely divided between those streams. The performance curve is often replotted to take account of this short circuiting. The $d_{50}$ obtained from this corrected classification curve is known as the "corrected $d_{50}$." Fig. 8 shows the corrected and uncorrected performance curves. $R_f$ represents the fraction of the feed liquid which is recovered in the coarse product stream.

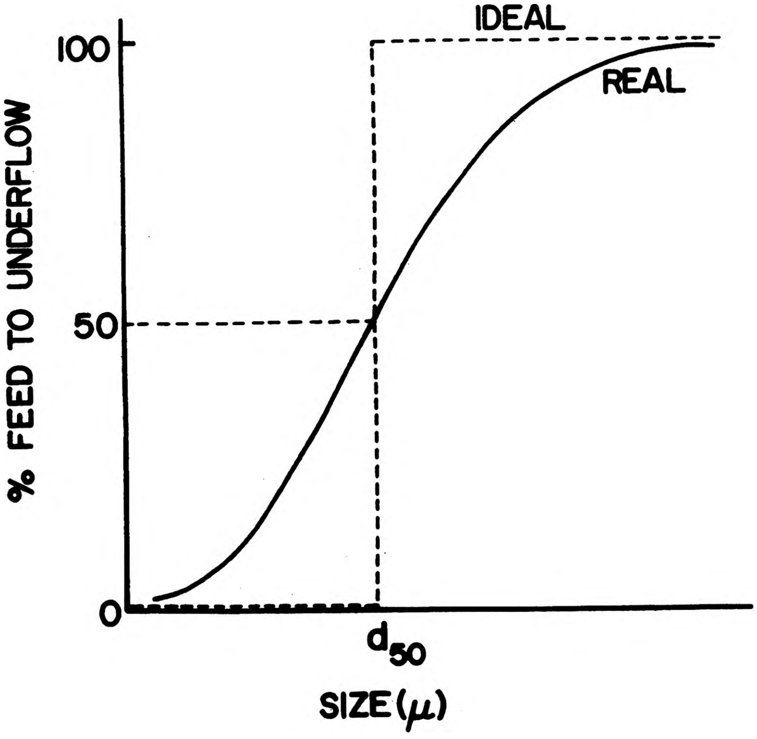
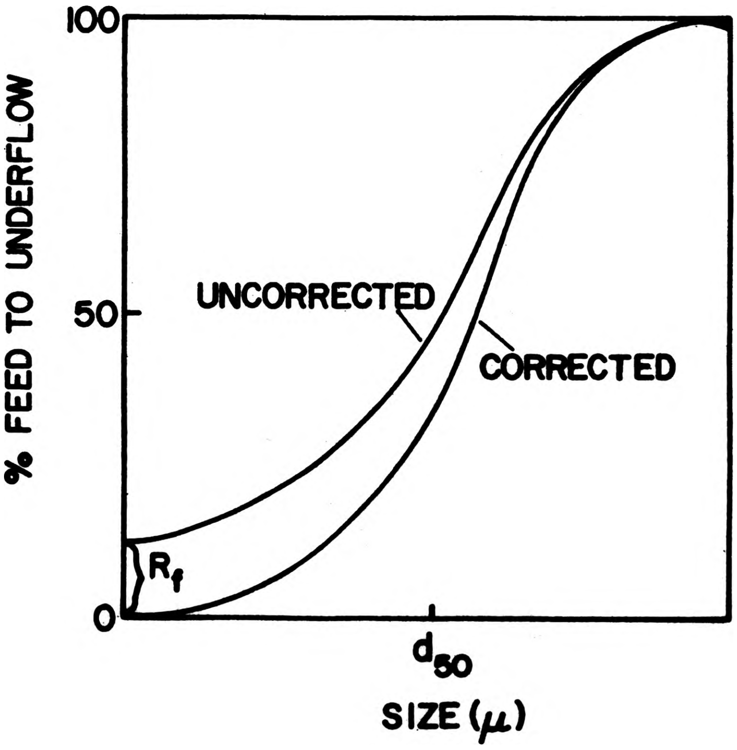


Fig. 7 Hydrocyclone Performance Curve



$$\text{Corrected \% feed to underflow} = \frac{(\text{\% Feed to U/F} - R_f)}{(1 - R_f)}$$

Fig. 8 Corrected and Uncorrected Hydrocyclone Performance Curves

Another valuable curve used in assessing cyclone performance is the reduced efficiency curve. This curve has as its abscissa the ratio of particle size to the $d_{50}$ of the cyclone (ie. $d/d_{50}$) with the weight fraction reporting to the underflow as the ordinate.

4. Factors affecting cyclone performance. The variables that affect hydrocyclone performance fall into two categories: those dependent on the cyclone size and proportions (design variables) and those independent of cyclone size and proportions (operating variables).

a. Design variables. Large cyclones tend to separate at a coarser size than smaller ones because large cyclones tend to generate much smaller accelerative forces (equation 1). For cyclones of fixed diameter and at constant pressure, the vortex finder may be altered to influence the $d_{50}$. The larger the vortex finder, the coarser the overflow. The area of the inlet determines the entrance velocity and an increase in area increases the flow rate. The size of the apex determines the underflow density and must be large enough to discharge the coarse solids that are being separated by the cyclone. The orifice must also permit the entry of air along the axis of the cyclone in order to establish the air vortex.[13]

b. Operating variables. The internal viscosity increases with increasing slurry density. An increasingly viscous overflow stream applies greater drag forces on the particles, drawing heavier and larger particles into the overflow product (ie. larger $d_{50}$). The feed flow rate and the pressure drop across the cyclone are closely related. Since increase in feed rate or pressure drop increases the centrifugal force effect, finer particles are carried to the underflow and the $d_{50}$ is decreased. However, the change has to be large to have a significant effect.

B. Magnetic Separation of Minerals. There are two kinds of classification of magnetic separation. Magnetic separation of the first kind (conventional magnetic separation) relies on the magnet susceptibility of the material to be separated. Magnetic separation of the second kind relies on the medium of separation rather the separated particles being magnetisable.[4]

1. Conventional magnetic separation. The property of a material determining its response to a magnetic field is the magnetic susceptibility. Based on magnetic susceptibility, materials may be classified as ferromagnetic for those strongly attracted, paramagnetic for materials that are weakly attracted, and diamagnetic for materials that are repelled by magnetic fields. Table I shows the relative attractabilities of some minerals.

The conventional use of magnetic separations falls into classes: the purification of feeds with magnetic components and the concentrationof magnetic materials. Table II shows the major applications of conventional magnetic separators.

2. Principles of magnetic separation. Magnetic separation

## TABLE I

## RELATIVE ATTRACTABILITIES OF DIFFERENT MINERALS

| Material | Relative attractability |
|---|---|
| Iron | 100.0 |
| Magnetite | 40.2 |
| Ilmenite | 24.7 |
| Pyrrhotite | 6.7 |
| Hematite | 1.3 |
| Quartz | 0.4 |
| Pyrite | 0.2 |
| Dolomite | 0.2 |
| Fluorite | 0.1 |

## TABLE II

## USES OF MAGNETIC SEPARATORS

A. Minerals Beneficiation

- Iron ores
- Chromite
- Rutile
- Pyrolusite
- Ilmenite
- Wolframite
- Cassiterite
- Garnet
- Clay
- Diamond
- Talc, etc.

B. Iron, Recovery

- Solid waste
- Heavy media (ferrosilicon)

C. Tramp Iron Removal

- Chemicals
- Minerals
- Scrap metals
- Food processing
- Cooling fluids
- Miscellaneous materials

is a physical separation of discrete particles based on a three-way competition between attractive magnetic forces, gravitational, frictional or inertial forces, and attractive or repulsive interparticle forces. These forces combine to act differently on particles of differing magnetic properties in the feed material.[14] The operative magnetic, competing and interparticle forces determine separator performance. These forces are dependent on both the nature of the feed to be separated as well as the character of the separation device. The nature of the feed includes its size and physical properties which may affect the various forces involved. The character of the magnetic separation device includes both the design and its variable parameters particularly the magnetic field.

a. The magnetic force. A rigorous treatment of the magnetic force on a particle is beyond the scope of this project. Basically, the magnetic force acting a particle is given by

$$F_m = VXH \frac{dH}{dr} \text{ ---------- } (7)$$

$V$ = practical volume = $\pi d^3/6$

$X$ = magnetic susceptibility

$H$ = field strength

$\frac{dH}{dr}$ = field gradient

The above relationship clearly shows that the field gradient is important in the application of a magnetic force to separate minerals. Also, the relationship will be meaningless if the particles are large enough such that the field strength and gradient change appreciably over the particle.[15]

The magnetic field and field gradient which act on particles in all magentic separation devices may be produced in a variety of ways and result in widely varying field geometries and strengths. In some cases, permanent magnets produce the fields directly while in others coils and iron magnet circuits are used to magnetize a ferromagnetic structure whose field gradients attract the magnetic particles.

b. Competing forces. Gravity, hydrodynamic drag, friction and inertia forces compete with the magnetic force in magnetic separators. Gravitational and hydrodyamic drag forces which are important in determining the characteristics of many magnetic separators will be briefly reviewed here.

For a spherical particle of diameter d and density Sp the gravitational force is given by

$$Fg = \frac{\pi d^3 (Sp-Sf)g}{6} \text{ ------- } (6)$$

$Sf$ = density of the fluid medium used in the separator

$g$ = gravitational constant.

The hydrodynamic drag force is given by

$Fd = 3\pi nvd$ where

$n$ = viscosity of the fluid medium

$v$ = velocity of the particle relative to the stream.

The dependence of the gravitational force on the third power of the particle diameter means that the gravitational force will be significant for large particles. The hydrodynamic drag force will be important for small particles. Thus, in a magnetic separator which treats large particles in dry form, the feed material might be passed through the separator under the force of gravity. The magnetic forces would have to be sufficient to hold the magnetic particles against the competing force of gravity. In a wet separator for small particles, the magnetic force would have to be larger than the hydrodynamic drag force which the slurry stream would exert on the trapped particles.

C. Theoretical Development of Magnetic Hydrocyclone. All dynamic processes of mineral separation may be conveniently divided into two general classes. The first and more common is characterised by the application of two non-coincident forces of a different nature so that particles more strongly influenced by one of the forces are separated from those more strongly influenced by the other. The second comprises processes which depend on the selective removal of one species from a mixed population of particles by acting on a distinctive characteristic.[16]

It is desired to combine the above two processes into one by the imposition of a magnetic field on a cyclone to influence the behaviour of particles in the cyclone. The magnetic force will have to perform two functions:

1. divert susceptible particles from their previous direction of motion
2. provide a force sufficient to sustain mass transport.

The location of the magnetic field is of extreme importance in the design of the magnetic cyclone. It is known that classification does not take place throughout the whole cyclone body[17], and there exists four regions that contain distinctively different size distributions (Fig. 9). Region A contains unclassified feed while region B, occupying a very lare part of the cone of the cyclone, contains classified coarse product. Region C contains fine product size distribution. The locus of active classification is the toroidal region D. This shows that for the magnetic field to have the desired effect, it must be active in region D.

The magnetic field can be produced either by an electromagnet or with permanent magnets. The first is characterised by the variability of the magnetic force and the second by its permanency. In whatever form the force is provided, the ultimate goal would have to be the enhancement of the movement of magnetic particles either to the underflow or to the overflow of the cyclone. The basis of two models would be examined: The production of a converging inwardly directed radial magnetic field to assist the migration of magnetic particles to the centre and be collected as an overflow product, and the production of an outwardly directly radial magnetic field to aid the centrifugal force in directing magnetic particles to the cyclone wall and be collected as an underflow product.

1. Inwardly directed magnetic cyclone. This model requires that the magnetic force assists the drag force to

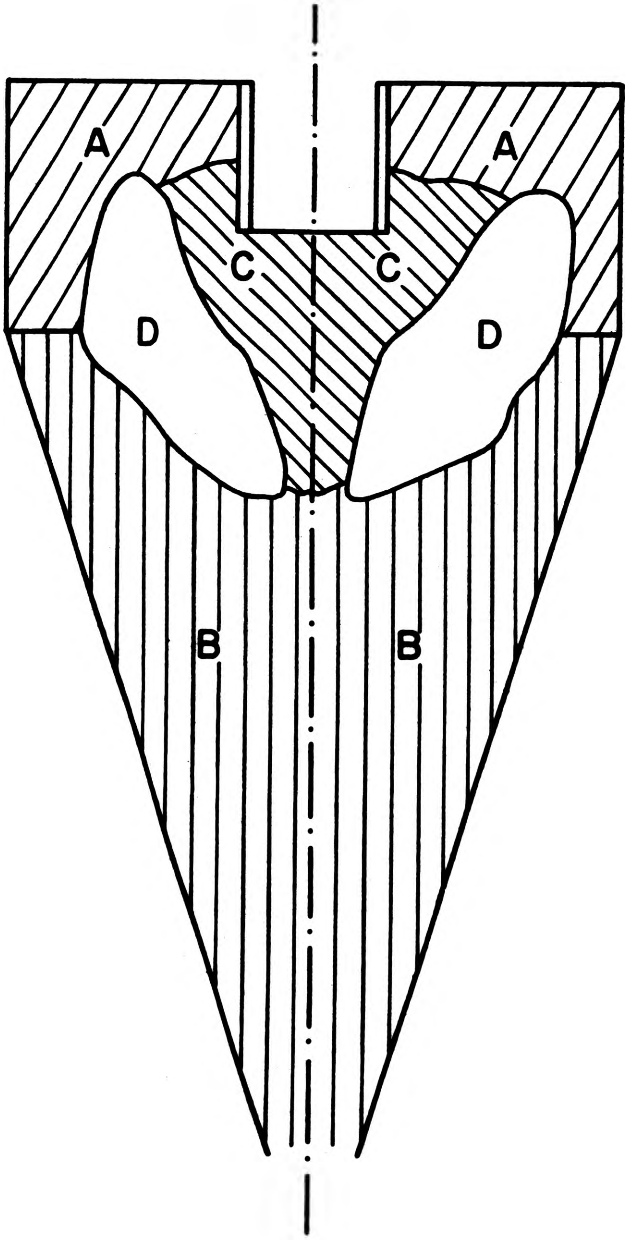


Fig. 9 Regions of Similar Size Distributions in Cyclone (After Renner & Cohen[17])

move particles to the centre of the cyclone and exit through the vortex finder. This means that the combined drag force Fd and magnetic force Fm will have to be greater than the centrifugal force Fc on the magnetic particle (Fig. 10). If the cyclone without the imposed magnetic field operates such that most of the feed (ie. magnetic and non-magnetic) material reports to the underflow, then the magnetic cyclone would result in coarser magnetic particles reporting to the overflow. The $d_{50}$ of the magnetic minerals will therefore increase. On the other hand, the non-magnetic portion of the feed will not be affected and the $d_{50}$ of these minerals will consequently remain the same.

The expected advantages of this model include the production of an overflow product high in magnetic grade and an underflow product rich in non-magnetic particles. By proper selection of cyclone operating variables therefore, a feed can be classified to produce magnetic and non-magnetic concentrates.

The main problem involved in this approach is the production of an inwardly directed radial magnetic field. As noted previously, the magnetic force on a particle depends on the magnetic field gradient. This requires that the radial magnetic field be such that the gradient decreases adequately from the axis of the cyclone to the locus of zero vertical velocity.

2. Outwardly directed magnetic cyclone. In this model, the magnetic force would be such as to combine with the

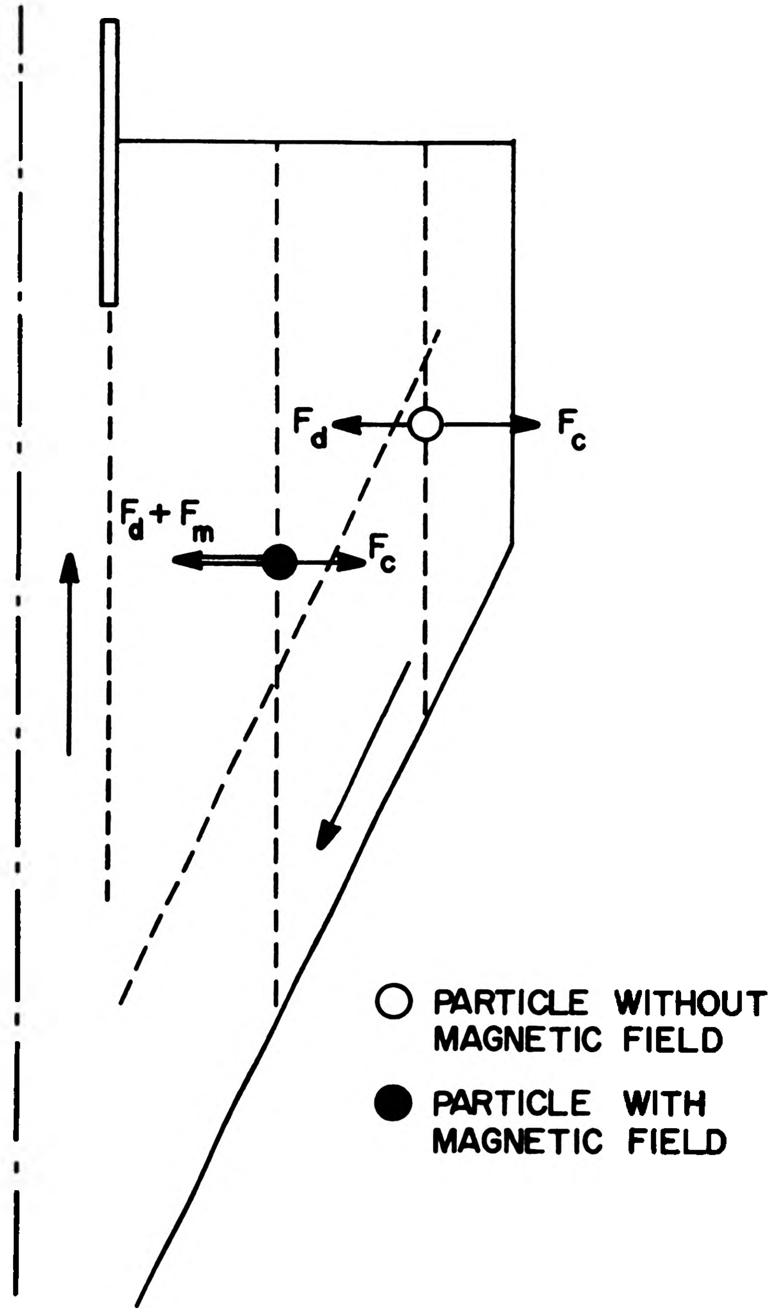


Fig. 10 Inwardly Directed Magnetic Cyclone

centrifugal force in directing particles to the cyclone wall to be collected as an underflow product. For this to be achieved, the combined magnetic and centrifugal forces will have to be greater than the drag force (Fig. 11). Fine magnetic particles which together with fine non-magnetic particles report to the overflow without the presence of the magnetic field will be made to report to the cyclone wall under this condition. The $d_{50}$ of the magnetic minerals will be smaller than the $d_{50}$ of classification for the same particles. The non-magnetic particles will not be affected and their $d_{50}$ will remain the same as in classification (ie. without the magnetic field). An increasing field gradient from the axis to the cyclone wall is required in this case.

This model has the advantage of possibly recovering most of the magnetic fraction to the underflow. The increased recovery would be made at the expense of the underflow grade. This is because the model will not be able to prevent the movement of non-magnetic particles of sufficient size reporting to the underflow. A possible way of overcoming this limitation is the use of a large cyclone with very fine feed.[18] Another limitation is the possibility of magnetic materials sticking to the sides of the cyclone wall as a result of the concentration of the magnetic field at those portions.

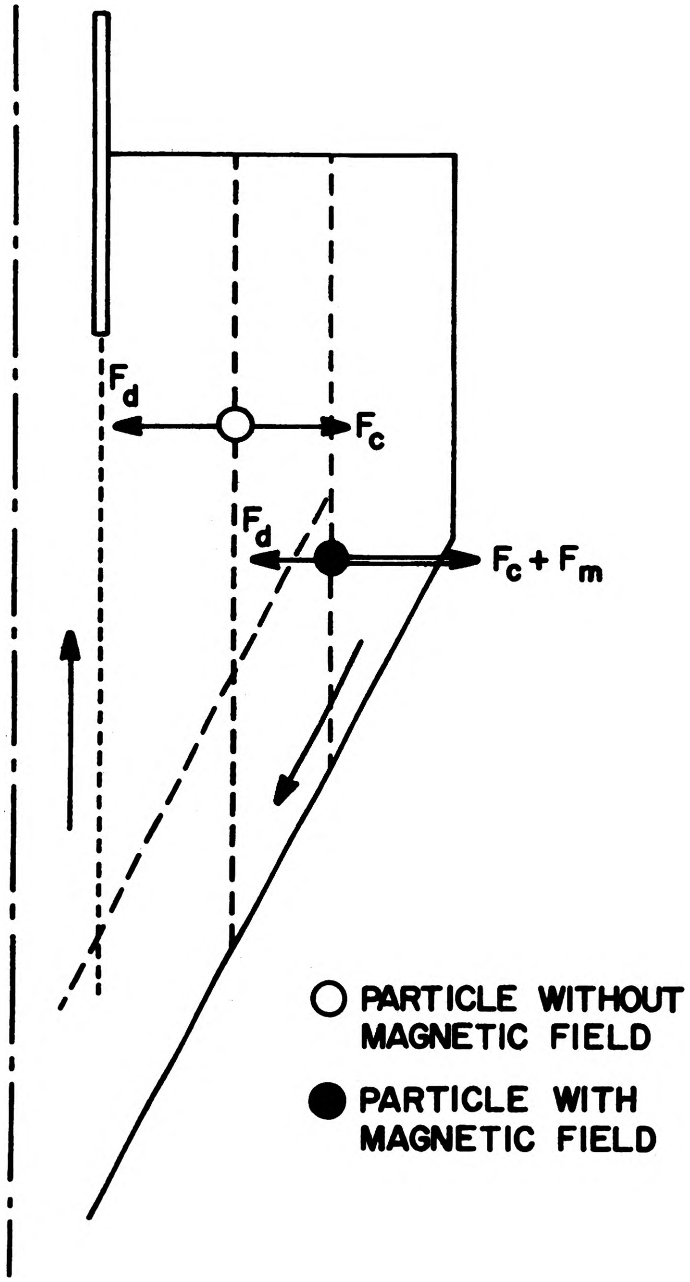


Fig. 11 Outwardly Directed Magnetic Cyclone

## III. EXPERIMENTAL DEVELOPMENT AND RESULTS

Throughout the developmental stages of this project as much use as possible were made of existing facilities in the Metallurgical Engineering department. This sometimes imposed constraints on the design and size of the test cyclones as well as the size range of the materials used in this project.

A. Materials. The test materials used in this project were dolomite and magnetite. The dolomite was obtained from the University of Missouri-Rolla experimental mine at Rolla and the magnetite from the Pea Ridge mine at Sullivan, Missouri. Table III shows the size distributions of the dolomite and magnetite. As can be noted from the size distributions, a single particle size analysis method could not be used. The samples were initially screened on a laboratory screen shaker to 100% passing a 200 Tyler screen mesh to form the feed samples which were further screened on a 270 Tyler mesh screen to produce two separations. The -270 mesh fraction were further analyzed using a Warman Cyclosizer by the kind permission of the United States Bureau of Mines at Rolla. The operation of the cyclosizer is based on Stokes law for particles settling within a fluid. This is unlike the screen analysis which measures the second largest dimension of the particle. This called for a conversion factor from the screen analysis to the cyclosizer for the -200 + 270 mesh fractions and a conversion factor of 0.94 was used.[19]

# TABLE III

## TYPICAL SIZE DISTRIBUTIONS OF FEED MATERIALS

**Dolomite**

| Stokesian Diameter (microns) | Weight % Retained | Cummulative Weight % passing |
|---|---|---|
| 69.6 | 0.0 | 100.0 |
| 49.8 | 39.3 | 60.7 |
| 42.0 | 25.5 | 35.2 |
| 31.5 | 12.6 | 22.6 |
| 22.0 | 9.4 | 13.2 |
| 14.3 | 6.4 | 6.8 |
| 10.5 | 3.4 | 3.4 |
| -10.5 | 3.4 | - |
|  | 100.0 |  |

cont.

## TABLE III

## TYPICAL SIZE DISTRIBUTIONS OF FEED MATERIALS

Magnetite

| Stokesian Diameter (microns) | Weight % Retained | Cummulative Weight % passing |
|---|---|---|
| 69.6 | 0.0 | 100.0 |
| 49.8 | 8.3 | 91.7 |
| 28.2 | 29.0 | 62.7 |
| 21.1 | 17.2 | 45.5 |
| 14.7 | 18.4 | 27.1 |
| 9.6 | 15.7 | 11.4 |
| 7.0 | 8.6 | 2.8 |
| -7.0 | 2.8 | - |
|  | 100.0 |  |

B. Assaying Equipment. The initial feed composition was made up of 10% by weight magnetite and 90% by weight dolomite. The absence of composite material in the synthetic feed meant that the magnetic percentage of samples could be obtained by directly weighing the magnetic fractions. A small hand magnet was used initially to obtain the magnetic portions of samples. For more accurate results, a Davis tube magnetic separator was used. This type of laboratory separator is commonly used in the minerals industry to determine the fraction of strongly magnetic material in a feed. A detailed description of this separator is available in most mineral processing textbooks and will not be described here. The following standard conditions were used in all the test samples in order to maintain consistency and accuracy:

| | | |
|---|---|---|
| Sample weight | : | 10.0 grams |
| Water flow rate | : | 0.50 litres/min |
| Field strength at Centre | : | 2600 gauss |
| Tube motion | : | 75 strokes/min |
| Assaying time | : | 5 mins. |

C. Experimental Procedures. The experimental test rig used throughout the project is as shown in Fig. 12. The sump was initially filled with water and the prepared composite feed was fed gradually to the sump with the pump running. The cyclone circuit was then allowed to run until a steady state condition had been attained. This was determined by noting the level of the pulp in the sump and also

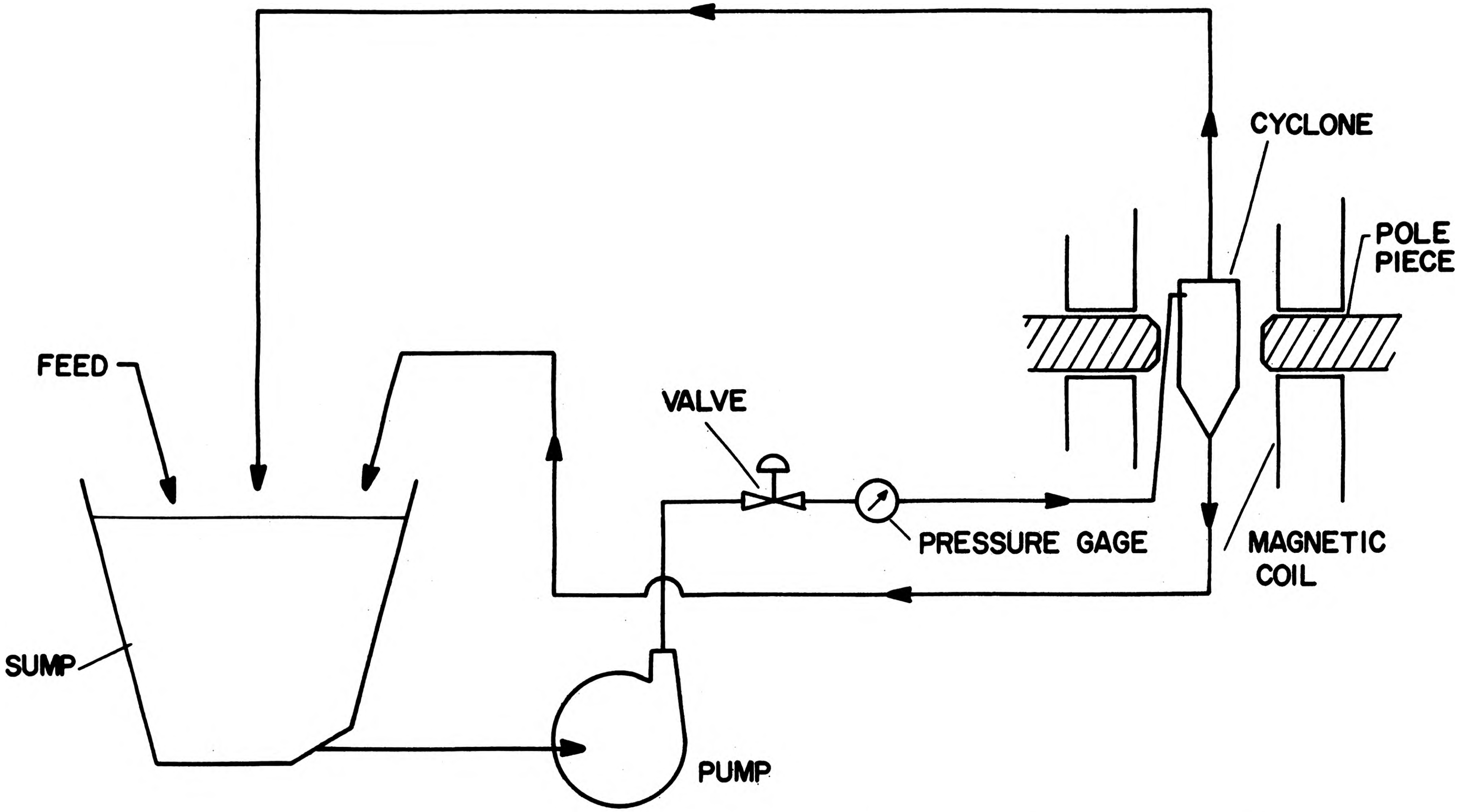


Fig. 12 Experimental Test Rig (See Appendix B)

when three consecutive pulp density measurements gave the same results. Simultaneous two second overflow and underflow samples were then cut with the cyclone operating with and without the influence of the magnetic field. The samples were then weighed, dried, reweighed and analysed (Appendix A). To assure accuracy and repeatability, two samples at five minute intervals were taken for each cyclone operating condition.

D. Developmental Work and Results. The developmental stages of this work will be presented together with partial discussions at each stage in order to facilitate comprehension by the reader. Also, each result will be presented by first giving the type of cyclone used and the conditions under which it was operated.

Direct comparisons of runs is difficult because of possible changes in the feed size distributions. To ensure justified comparisons therefore, the following common criteria were found useful: The enrichment ratio, the improvement in recovery achieved and the selectivity index.

1. Recovery of the magnetic fraction as an overflow product. The initial attempts made in this project were geared towards the recovery of the magnetic fraction of the feed as an overflow product. An electromagnet with an iron rod through the central core was so constructed and mounted such that the iron rod ran through the axis of the cyclone and terminated just below the cylindrical section of the cyclone (Fig. 13). A four inch diameter conventional brass cyclone having a cylindrical section of 3.0 inches, a

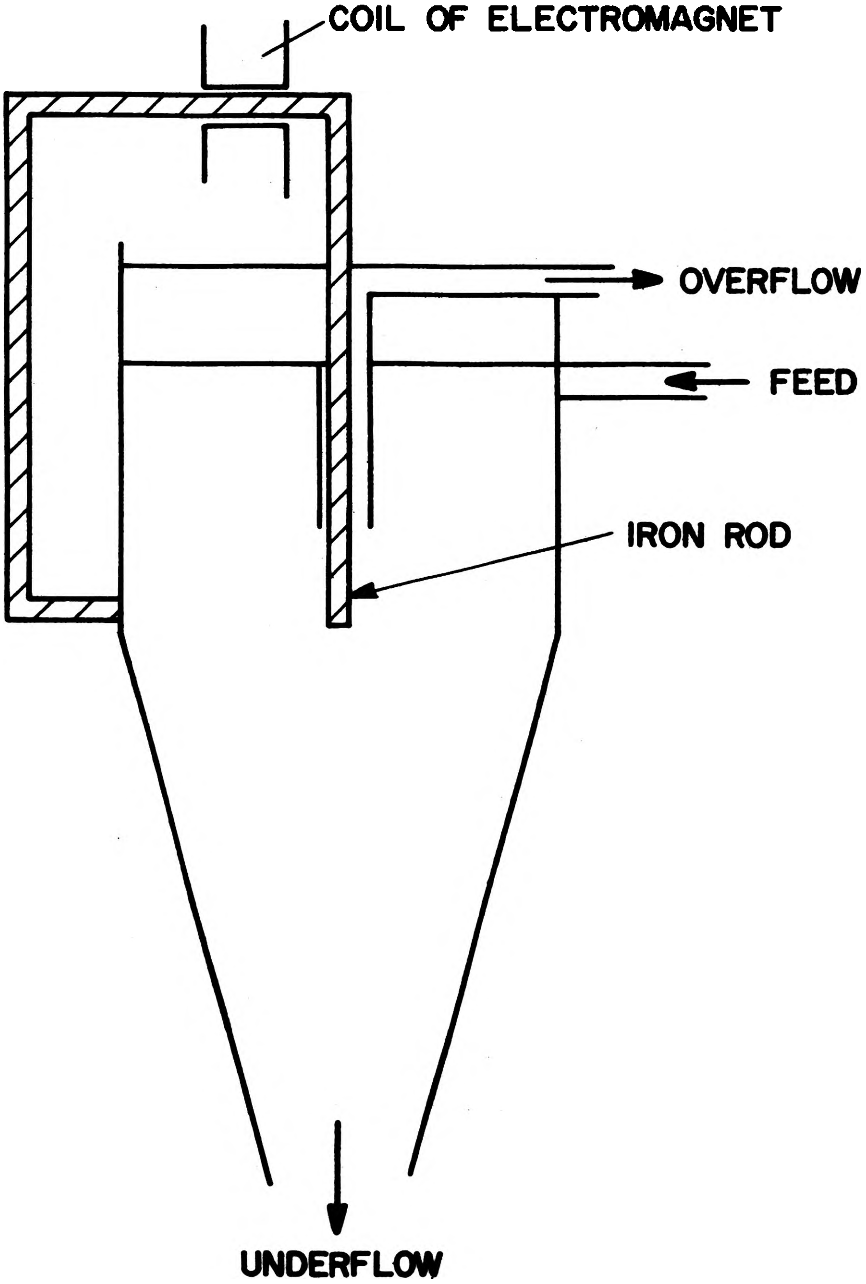


**Fig.** 13 Brass Cyclone Arrangement With Iron Rod Through The Centre conical section of 11.0 inches and a vortex finder of 1.5 inches was used in this experiment. The objective of using this arrangement was the production of an inwardly directed magnetic field sufficient to pull the magnetic particles to the centre of the cyclone and be carried to the overflow as part of the inner spiral flow. The magnetic force was to be such that the particles did not stick to the rod.

The fields produced with the passage of current through the coils of the electromagnet (less than 200 Gauss 1 in. from the rod) were not sufficiently large to produce a significant gradient towards the centre of the cyclone and results obtained by running samples through the cyclone were not encouraging. The magnetic field strength could not be increased because of the limited capacity of the DC power source used. The limited facilities did not permit the use of bigger cyclones and therefore bigger rods. In the light of the above, this approach of recovering the magnetic materials was abandoned.

2. Recovery of the magnetic fraction as an underflow product. The next strategy adopted was aimed at recovering the magnetic fraction of the feed as an underflow product. This called for an outwardly directed radial magnetic field. An electromagnetic arrangement with two cylindrical poles running through the coils was chosen for this approach. The cylindrical poles had both flat and tapered ends which could be easily manipulated to adjust the magnetic field strengths. The experimental set up of the equipment and

and other accessories is shown in Fig. 12. In this arrangement, the two poles act radially on opposite sides of the cyclone when placed between them.

The plotted magnetic field strengths with the flat ends of the poles are given in Table IV which indicates a gradual decrease in field strength towards the centre of the pole pieces. There is therefore a net attractive force towards the pole pieces on a magnetic particle in the region between the pole faces. With the cyclone in position, this net outwardly directed radial magnetic force would assist the centrifugal force in sending magnetic particles to the cyclone wall to be recovered as an underflow product.

It was also desired that the recovered underflow would be rich in magnetic particles and depleted in non-magnetic materials. This called for small feed particles and largest possible diameter cyclones such that the cyclone operating normally would recover most of the feed to the overflow. In this way, the cyclone operating under the influence of the magnetic field would lead to the recovery of mostly magnetic particles at the underflow. This idea and the fact that the distinguishing feature of a cyclone is the use of fluid pressure energy and not the vessel shape lead to the design and construction of "air-type" cyclones. The air cyclones were also chosen because they were easier to construct and could fit easily into the electromagnetic arrangement. A special feature of these cyclones is the absence of the reversal flow prevalent in conventional cyclones. They were

## TABLE IV

## MAGNETIC FIELD MAPPING USING FLAT ENDS OF POLE PIECES AT VARYING DISTANCES FROM POLE FACE AND VARYING CURRENTS

Field Strengths (gauss)* Measured
At Centre Of Pole Face

| Distance from pole face (in) | Current (amperes) | 0 | 5 | 10 | 15 | 20 | 25 |
|---|---|---|---|---|---|---|---|
| 0.0 | | 14.0 | 550 | 1070 | 1620 | 2120 | 2660 |
| 0.5 | | 13.5 | 525 | 1030 | 1580 | 2040 | 2540 |
| 1.0 | | 13.0 | 500 | 1000 | 1460 | 1950 | 2450 |
| 1.5 | | 12.0 | 495 | 960 | 1420 | 1920 | 2340 |
| 2.0 | | 11.8 | 490 | 930 | 1400 | 1880 | 2300 |

* 1 Gauss = $10^{-4}$ Tesla

constructed using ABS plastic material and the first of such referred to as the "vertical cyclone" is shown diagrammatically in Fig. 14.

a. Vertical cyclone. Experiments were carried out with the vertical cyclone by manipulating the configurations of the cylindrical poles of the electromagent as well as varying the current through the coils to achieve different field strengths. The obtained results are shown in Table V. With no current through the coils (ie. straight classification) an average concentrate grade of 10.0% magnetite with a recovery of 58.2% was obtained. The results show that the magnetic configuration having one pole face inverted produced a concentrate of 16.4% magnetite as compared to 14.7% when one pole was removed completely. The corresponding recoveries were 78.6% and 71.1%. This improvement in grade and recovery can be attributed to a higher field gradient towards the cyclone wall with one pole face inverted. A further increase in concentrate from 14.7% to 19.0% was achieved when the field strength was increased from 1900 to 2750 gauss with the passage of a higher current through the coils with one pole piece removed.

At this stage, it was thought that the process could be further improved with an improvement in the magnetic field distribution around the cyclone. Cast iron pieces were machined into semi-circular shapes to fit around the cyclone and fixed to the end faces of the poles of the electromagnet. A preliminary magnet field strength test was carried out to

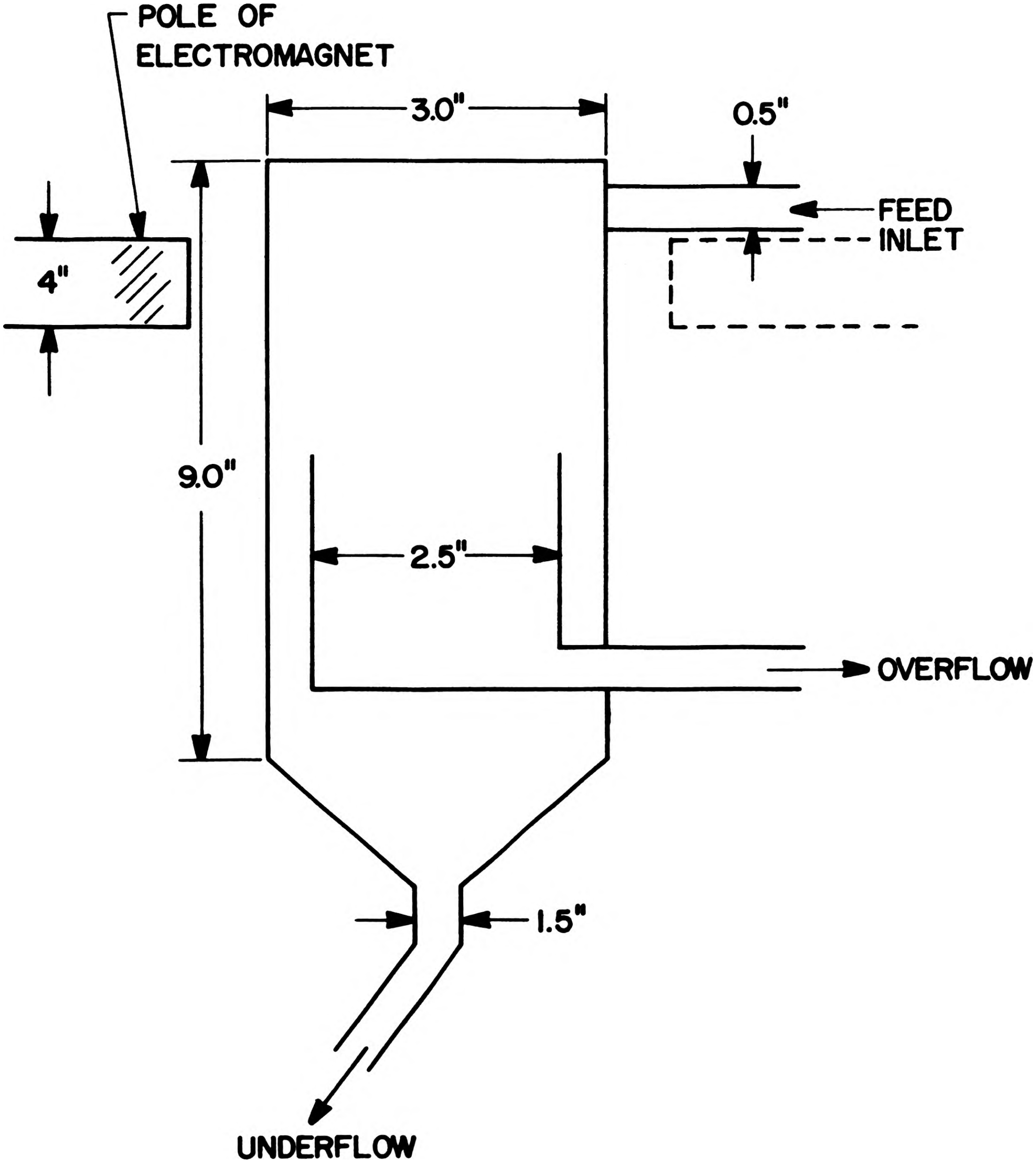


Fig. 14 Vertical Cyclone Arrangement

## TABLE V

## RESULTS OBTAINED USING VERTICAL CYCLONE WITH STRAIGHT POLE FACES TOUCHING SIDES OF CYCLONE

Cyclone diameter : 3.0 inches
% magnetite in feed : 10.0
% solids in feed : 14.0
feed inlet pressure : 6 psi

| Magnetic Configuration | Field Strength 1 in from pole face (gauss) | Concentrate grade (%) | Recovery (%) | Enrichment ratio | Improvement in recovery (%) | Selectivity index |
|---|---|---|---|---|---|---|
| One pole removed | 0 | 10.0 | 58.2 | 1.00 | - | 1.00 |
| One pole removed | 1900 | 14.7 | 71.1 | 1.47 | 12.9 | 1.60 |
| One pole face inverted | 2180 | 16.4 | 78.6 | 1.64 | 20.4 | 1.77 |
| One pole removed with higher current | 2750 | 19.0 | 72.3 | 1.90 | 14.2 | 1.95 |

find the best configuration of the cast iron pieces. Varying coil currents were then used to study the behaviour of the particles under these conditions. Table VI shows the results obtained. A comparison of Tables V and VI shows that whereas there was no substantial improvements in the magnetic concentrate grades obtained with the use of the cast iron pieces, the recoveries improved more than 20.0% at low field intensities. This improvement is thought to be due to a better distribution of the magnetic field with the use of the cast iron pieces fixed to the ends of the pole faces. This is confirmed by the fact that with the same currents through the coils, the field strengths measured at 1 in. from the pole face were less in the case where the cast iron peices were used as compared to using the straight pole faces. For example, at a current of 25 amperes through the coils, the field strength 1 in. from the pole face was 2370 gauss for the configuration with the cast iron pieces as compared to 2750 gauss at the same location for the straight pole face configuration.

b. Horizontal cyclone. It was further desired to improve the grade of the magnetic concentrate and the recovery so far achieved. The magnetic field configuration within one of the gaps of the coils of the electromagnet was studied. The study showed a decrease in magnetic field strength towards the centre and away from the edge of the coils as shown in Fig. 15. It was therefore decided to construct a cyclone that would fit into the cyclone and

## TABLE VI

## VERTICAL CYCLONE WITH CAST IRON PIECES FIXED TO POLE FACES

Cyclone diameter : 3.0 ins.
% magnetite in feed : 10.0
feed inlet pressure : 6 psi
% solids in feed : 24.0

| Field Strength 1 in from pole face (gauss) | Concentrate grade (%) | Recovery (%) | Enrichment ratio | Improvement in recovery (%) | Selectivity index |
|---|---|---|---|---|---|
| 0 | 10.0 | 50.2 | 1.00 | - | 1.00 |
| 500 | 16.0 | 75.0 | 1.60 | 24.8 | 1.59 |
| 950 | 18.0 | 71.5 | 1.80 | 21.3 | 1.85 |
| 1480 | 17.0 | 71.8 | 1.70 | 21.6 | 1.79 |
| 2370 | 16.0 | 65.7 | 1.60 | 15.7 | 1.59 |

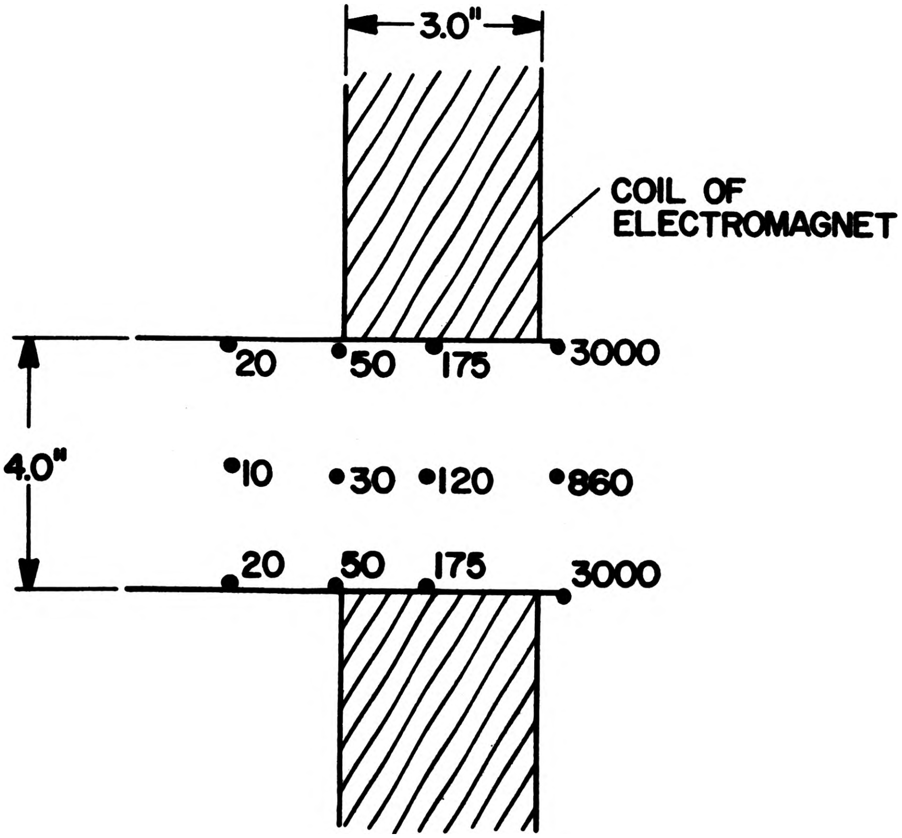


Fig. 15 Magnetic Field Mapping Within Coil of Electromagnet

operate horizontally. This air-type cyclone would be referred to as the "horizontal cyclone". The magnetic configuration in this case is fixed by the nature of the electromagnet and the experiments carried out here were to study the influence of varying field intensities on the performance of the cyclone. The results obtained are given in Table VII. Concentrate grades of 12.8 and 13.0% magnetite were obtained at field strengths of 600 and 850 gauss using a feed of 10.0% magnetite. The respective improvements in recovery were lower than 20.0% being 8.3% and 18.4% at 600 and 850 gauss. An important aspect of the results is the increment in improved recovery from 8.3% to 18.4% when the field strength was increased from 600 to 850 gauss. Further increments in the field strength could not be obtained because of the limited capacity of the DC power source and the coils.

It was decided to increase the percent solids in the feed pulp to find out if any further increase in magnetic recovery could be achieved. The results as shown in Table VIII rather indicate a slight decrease in grade from 13.0% to 12.8% magnetite with an increase in feed percent solids from 17.6% to 24.0% as well as a decrease in the recovery improvement from 16.2% to 10.7%. With increase in feed percent solids, the internal slurry viscosity increases and greater drag forces are applied on the heavier magnetic particles drawing them to the overflow. This behaviour is thought to account for the decrease in grade and recovery

## TABLE VII

## RESULTS OBTAINED WITH HORIZONTAL CYCLONE FIXED WITHIN COIL OF ELECTROMAGNET

Cyclone diameter : 3.0 in
% magnetite in feed : 10.0
% solids in feed : 15.5
feed inlet pressure : 6 psi

| Field Strength 1 in. inside coil (gauss) | Concentrate grade (%) | Recovery (%) | Enrichment ratio | Improvement in recovery (%) | Selectivity* index |
|---|---|---|---|---|---|
| 0 | 9.0 | 49.5 | 0.90 | - | 0.94 |
| 600 | 12.8 | 57.8 | 1.28 | 8.3 | 1.15 |
| 850 | 13.0 | 67.9 | 1.30 | 18.4 | 1.27 |

* Selectivity index = $\frac{cm\ tg}{cg\ tm}$

cm = % magnetite in concentrate, Cg = % magnetite in tailing
tg = % dolomite in tailing, tm = % dolomite in concentrate

## TABLE VIII

## EFFECT OF % SOLIDS IN FEED ON HORIZONTAL CYCLONE PERFORMANCE

% magnetic in feed : 10.0
feed inlet pressure : 6 psi
magnetic field strength : 850 gauss

| Solids in feed (%) | Concentrate grade (%) | Recovery (%) | Enrichment ratio | Improvement in recovery (%) | Selectivity index |
|---|---|---|---|---|---|
| 17.6 | 13.0 | 67.9 | 1.30 | 16.20 | 1.27 |
| 24.0 | 12.8 | 62.4 | 1.28 | 10.70 | 1.17 |

obtained above. At this stage, it was also thought that there could be a possible re-entrainment of magnetically classified particles after leaving the zone of concentration of the magnetic field. It was therefore decided to reconstruct the horizontal cyclone in order to minimize any possible re-entrainment of the particles. The modified cyclone is shown in Fig. 16 and the results obtained presented in Table IX and are discussed below.

c. Discussion of performance of air-type cyclones. The results so far obtained with the vertical and horizontal cyclones have indicated that the behaviour of particles within a cyclone changes when a magnetic field is imposed on the cyclone. The enrichment ratios achieved with the vertical cyclone were in the range 1.47 to 1.90. The corresponding values for the horizontal cyclone were rather low (less than 1.50) and the main reason for these low values was the inability to increase both the field strength and gradient substantially. Less than 30.0% improvements in recoveries were achieved with both the horizontal and vertical cyclones. The $d_{50}$ of the air-cyclones under various operating conditions were in the range 27-35 microns.

Three major reasons can be assigned for the low recoveries and grades:

1. The increases achieved with the use of cast iron pieces indicate that poor field distributions might have contributed to the low recoveries and grades.

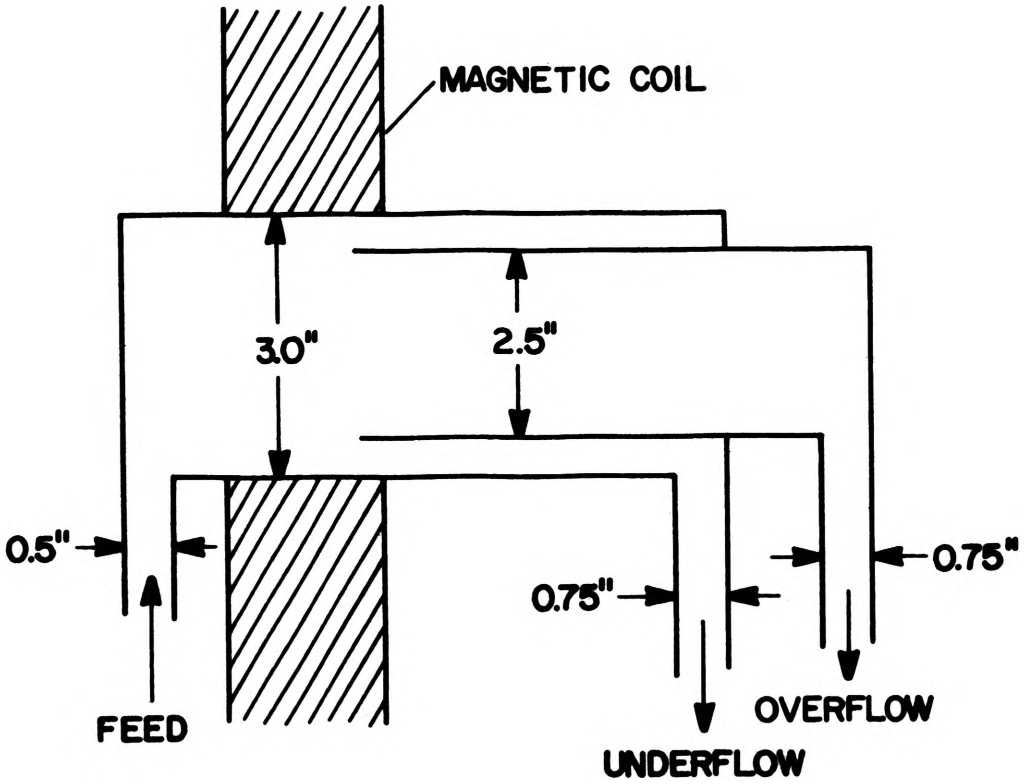


Fig. 16 Horizontal Cyclone Modified to Reduce Possible Reentrainment of Magnetically Classified Particles

## TABLE IX

## MODIFIED HORIZONTAL CYCLONE PERFORMANCE

% magnetite in feed : 10.0
feed inlet pressure : 6 psi
% solids in feed : 23.4

| Field Strength I in. inside coil (gauss) | Concentrate grade (%) | Recovery (%) | Enrichment ratio | Improvement in recovery (%) | Selectivity index |
|---|---|---|---|---|---|
| 0 | 10.0 | 60.0 | 1.00 | - | 1.00 |
| 850 | 12.8 | 69.1 | 1.28 | 9.1 | 1.20 |

2. The absence of re-entrainment as indicated by the results obtained with the modified horizontal cyclone show that there is possibly a very great degree of short circuiting occuring in the air type cyclones. This can be due to the absence of an actual vortex finder in these cyclones. The presence of short circuiting would result in some of the particles reporting directly to the overflow without being classified.
3. The use of large underflow diameters meant very dilute underflows and compounding the problem in 2 above.

Considering the results obtained and the above limitations, it was decided to construct a conventional cyclone which will have vortex finder as well as a conical section with a small spigot underflow using aluminium as the material of construction.

d. Conventional cyclone. The conventional cyclone constructed had an internal diameter of 3.0 inches with a cylindrical section of 5.0 inches a 3.5 inch conical section. A relatively long vortex finder length of 3.0 inches was used in order to increase the recovery of particles to the overflow when the cyclone was operating normally. A detailed diagram of the cyclone is shown in Fig. 17.

Several experiments were carried out under varying conditions using the conventional cyclone. Initially, different coil currents were used to vary the magnetic field

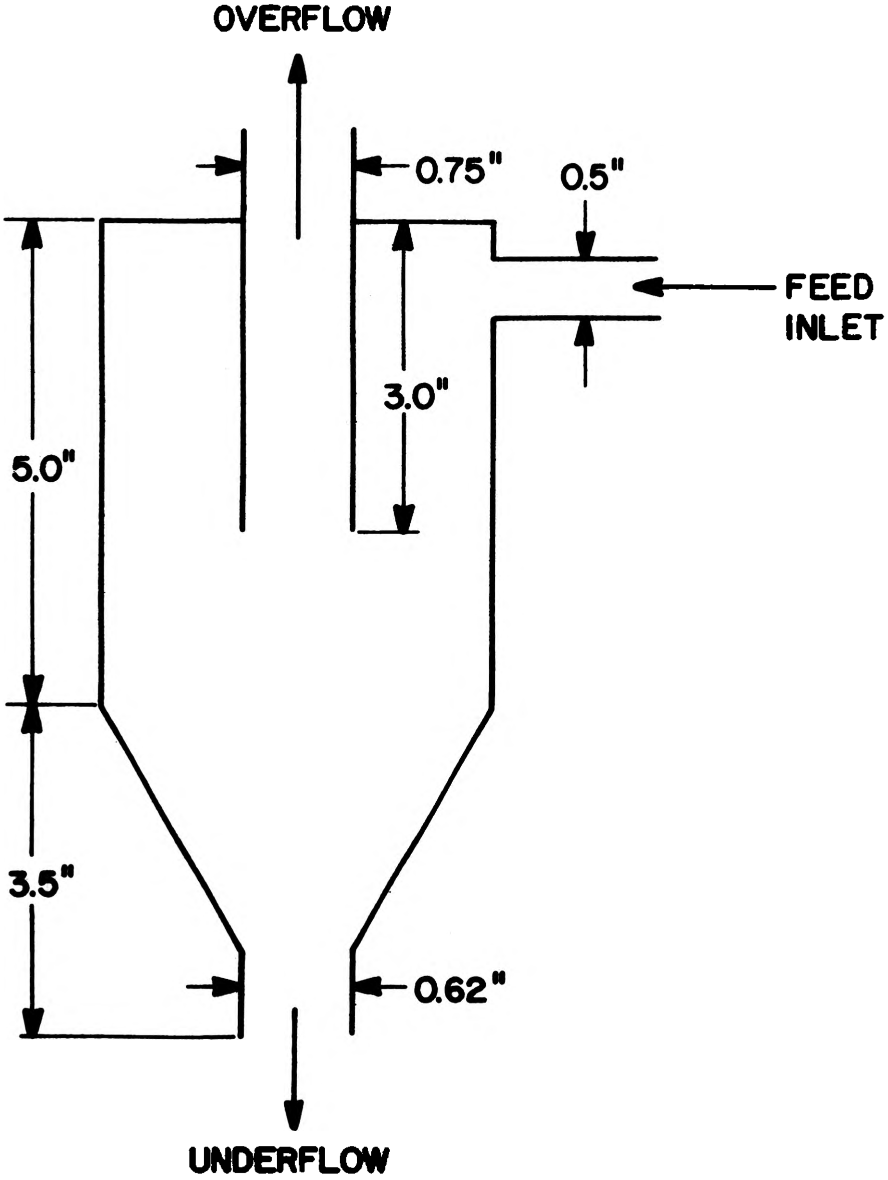


Fig. 17 A Schematic Diagram of the Conventional Cyclone

strengths with the cyclone in between the flat end faces of the poles. The results are given in Table X and the changes in grade and recovery are plotted in Fig. 18. The grade of the concentrate increased from 10.7% magnetite at zero field strength to 19.0% when the field strength was increased to 560 gauss. A further increase in field strength to 1130 gauss resulted in a grade of 21.0%. However when the field strength was increased again to 1780 gauss with the passage of a higher current through the coils, a decrease in grade to 17.0% occured. Similarly, the recovery increased from 46.8% to 88.2% with increase in field strength from zero to 1130 gauss. The recovery decreased significantly when the field strength rose to 1780 gauss. This behaviour can be attributed possibly to two reasons:

1. With increase in magnetic field strength, a slight build of magnetic particles occurs in the cyclone which increases the internal viscosity of the slurry. The resulting increase in the viscosity of the overflow stream applies greater drag forces on the particles, drawing the heavier magnetic particles to the overflow. Also this build up is thought to cause a disturbance in the flow patterns within the cyclone which alters the behaviour of the particles.
2. An increase in the magnetic field strength results in an increased attraction for the non-magnetic fraction of the feed. This second reason however is thought to play a less significant effect.

## TABLE X

## RESULTS OBTAINED USING 3.0 CONVENTIONAL CYCLONE WITH STRAIGHT POLE FACES TOUCHING SIDES OF CYCLONE

% magnetite in feed : 10.0
inlet pressure : 6 psi
% solids in feed : 19.4

| Field strength 1 in. from pole face (guass) | Concentrate grade (%) | Recovery (%) | Enrichment ratio | Improvement in recovery (%) | Selectivity index |
|---|---|---|---|---|---|
| 0 | 10.7 | 46.8 | 1.07 | - | 1.07 |
| 560 | 19.0 | 78.3 | 1.90 | 31.5 | 2.37 |
| 1130 | 21.0 | 88.2 | 2.10 | 41.4 | 3.61 |
| 1780 | 17.0 | 46.0 | 1.70 | *-0.8 | 1.59 |

* Negative sign indicates decrease in recovery.

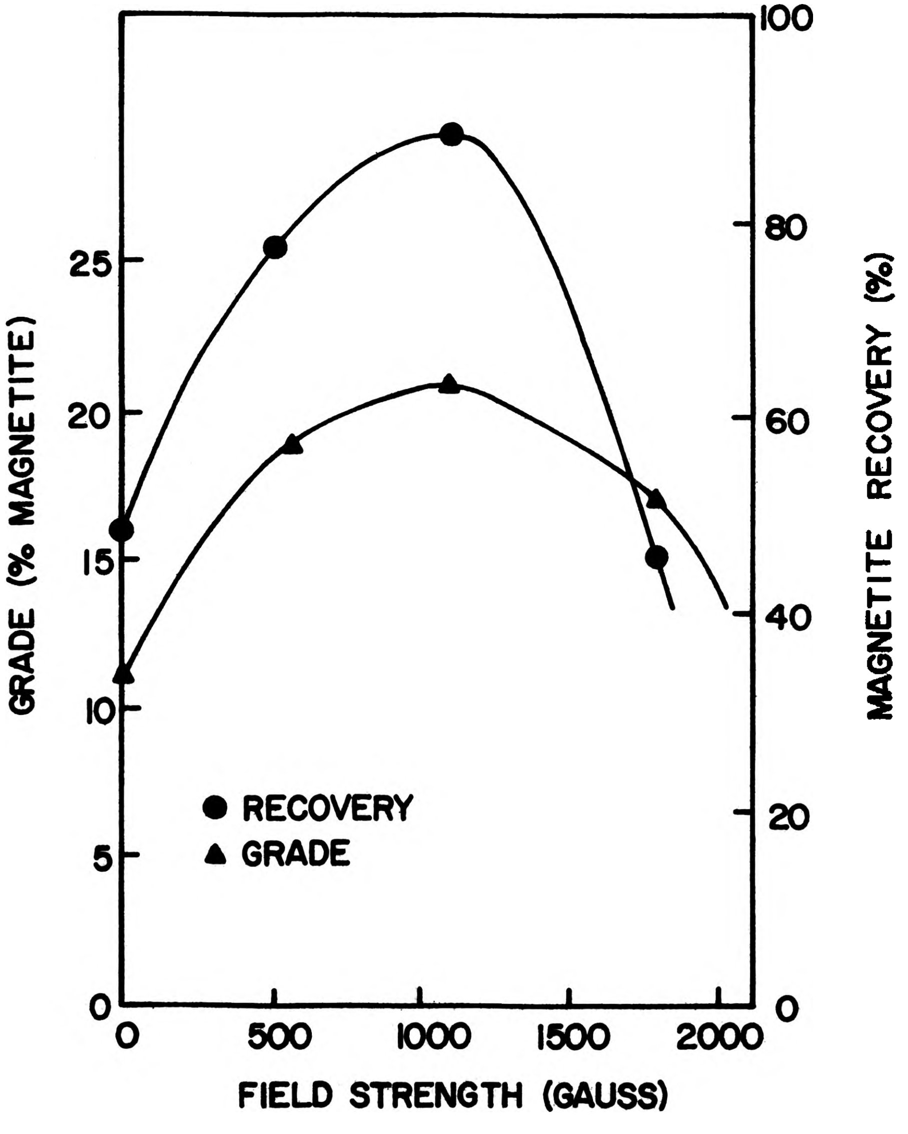


Fig. 18 Recovery and Grade for Conventional Cyclone With Straight Pole Faces

i. Effect of pressure. Using the straight pole face configuration, the changes in pressure on the cyclone performance with respect to the grade and recovery were studied. Inlet pressures of 4, 6, 9 and 12 psi were used. The operating conditions did not permit higher than 12 psi pressures to be used. Table XI gives the results and the changes in grade and recovery are plotted against the pressure in Fig. 19. The highest grade of 21.0% magnetite was achieved at a pressure of 6 psi with a corresponding recovery of 88.2%. With increasing pressures above 6 psi, the centrifugal force on the particles increases. Finer particles are therefore forced to the underflow and lead to increasing magnetite recoveries at higher pressures. The increasing recoveries of finer non-magnetic materials occuring at the same time results in the corresponding decrease in magnetic grades as depicted by Fig. 19. The changes in pressure however, have to be large for it to have any significant effect on the magnetic grades and recoveries.

ii. Variation in feed composition. The next set of experiments was designed to find the effect that changing the nature of the feed would have on the performance of the cyclone. Pulps containing 10, 20 and 30% magnetite were passed through the cyclone under varying field strengths. The results are reported in Table XII. Figs. 20 and 21 show the graphical representations of the results. The recoveries and grades increase with increasing field strength from zero to approximately 1300 gauss for the 10% magnetite

# TABLE XI

# EFFECT OF PRESSURE CHANGES ON CONVENTIONAL CYCLONE PERFORMANCE

% magnetite in feed : 10.0

field strength at 1 in.

from pole face : 1430 gauss

% solids in feed : 16.5

| Inlet Pressure (Psi) | Concentrate grade % | Recovery % | Enrichment ratio | Improvement in recovery % | Selectivity index |
|---|---|---|---|---|---|
| 12 | 17.0 | 95.6 | 1.70 | 48.8 | 4.02 |
| 9 | 18.0 | 96.8 | 1.80 | 50.0 | 4.66 |
| 6 | 21.0 | 88.2 | 2.10 | 41.4 | 3.61 |
| 4 | 19.0 | 95.8 | 1.90 | 49.0 | 4.82 |

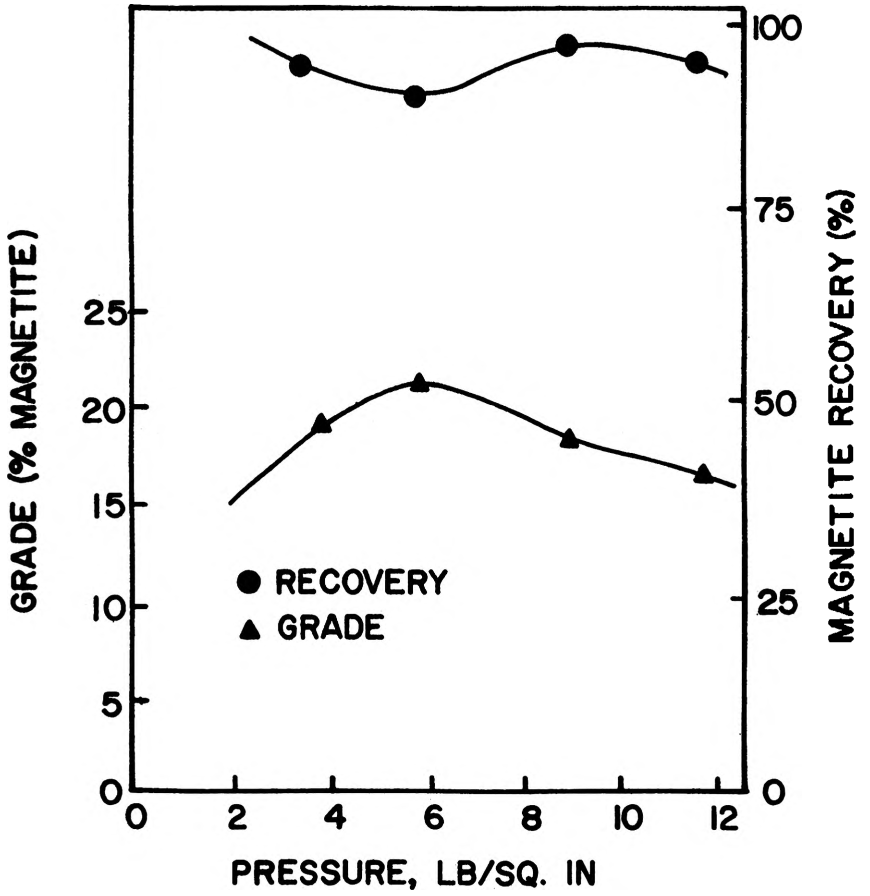


Fig. 19 Effect of Changes in Pressure on Conventional Cyclone Performance

# TABLE XII

## EFFECTS OF VARIATIONS IN PERCENT MAGNETITE IN FEED AT DIFFERENT FIELD STRENGTHS FOR CONVENTIONAL CYCLONE

% solids in all cases : 15.5

A. Field strength : 0 gauss

Inlet pressure : 6 psi

| Magnetite in feed (%) | Concentrate grade (%) | Recovery (%) | Enrichment ratio | Improvement in recovery (%) | Selectivity index |
|---|---|---|---|---|---|
| 10 | 10.7 | 46.8 | 1.07 | - | 1.07 |
| 20 | 25.0 | 67.5 | 1.25 | - | 1.43 |
| 30 | 40.0 | 64.1 | 1.33 | - | 1.58 |

B. Field strength : 560 gauss

Inlet pressure : 6 psi

| Magnetite in feed (%) | Concentrate grade (%) | Recovery (%) | Enrichment ratio | Improvement in recovery (%) | Selectivity index |
|---|---|---|---|---|---|
| 10 | 19.0 | 78.3 | 1.90 | 31.5 | 2.37 |
| 20 | 47.0 | 96.6 | 2.35 | 29.1 | 7.63 |
| 30 | 70.0 | 78.1 | 2.33 | 31.3 | 4.58 |

TABLE XII (Cont.)

C. Field strength : 1130 gauss

Inlet pressure : 6 psi

| Magnetite in feed (%) | Concentrate grade (%) | Recovery (%) | Enrichment ratio | Improvement in recovery (%) | Selectivity index |
|---|---|---|---|---|---|
| 10 | 21.0 | 88.2 | 2.10 | 41.4 | 3.61 |
| 20 | 12.0 | 9.9 | 0.60 | *-57.6 | 0.70 |
| 30 | 24.0 | 10.3 | 0.80 | *-53.8 | 0.84 |

D. Field strength : 1780 gauss

Inlet pressure : 6 psi

| Magnetite in feed (%) | Concentrage grade (%) | Recovery (%) | Enrichment ratio | Improvement in recovery (%) | Selectivity index |
|---|---|---|---|---|---|
| 10 | 17.0 | 46.0 | 1.70 | * -0.8 | 1.59 |
| 20 | 7.0 | 4.9 | 0.35 | *-62.6 | 0.50 |
| 30 | 14.0 | 5.6 | 0.47 | *-58.5 | 0.57 |

* Negative sign indicates decrease in recovery

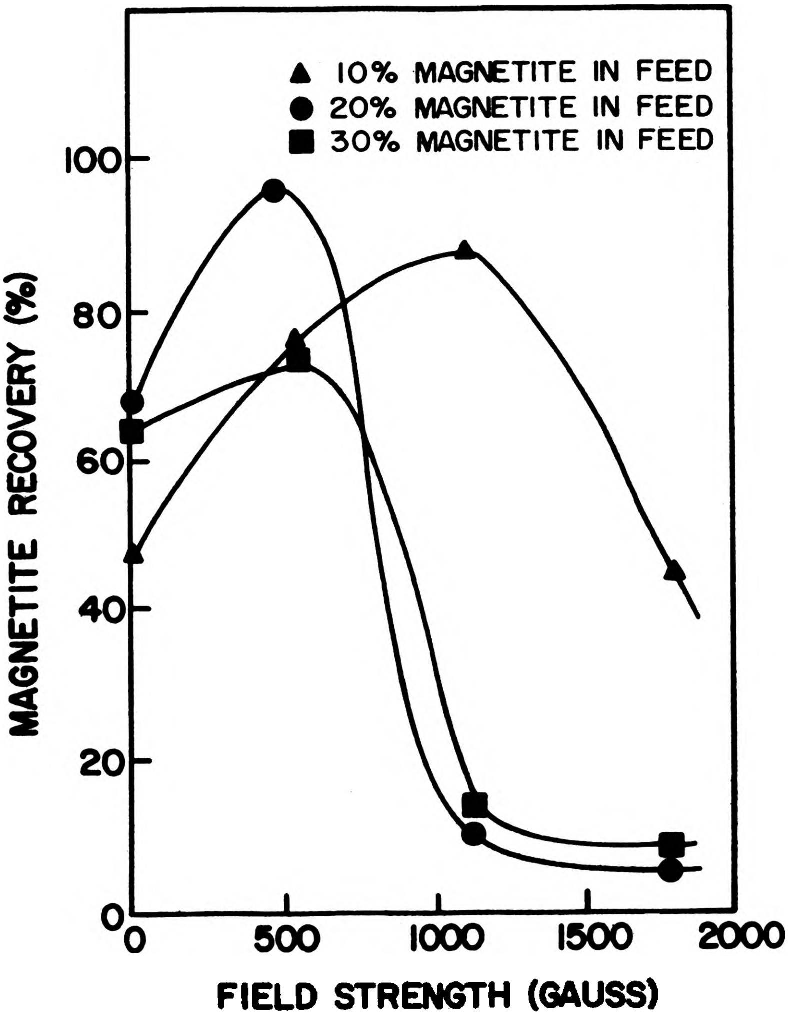


Fig. 20 Recovery-Field Strength for Varying Percent Magnetite in Feed

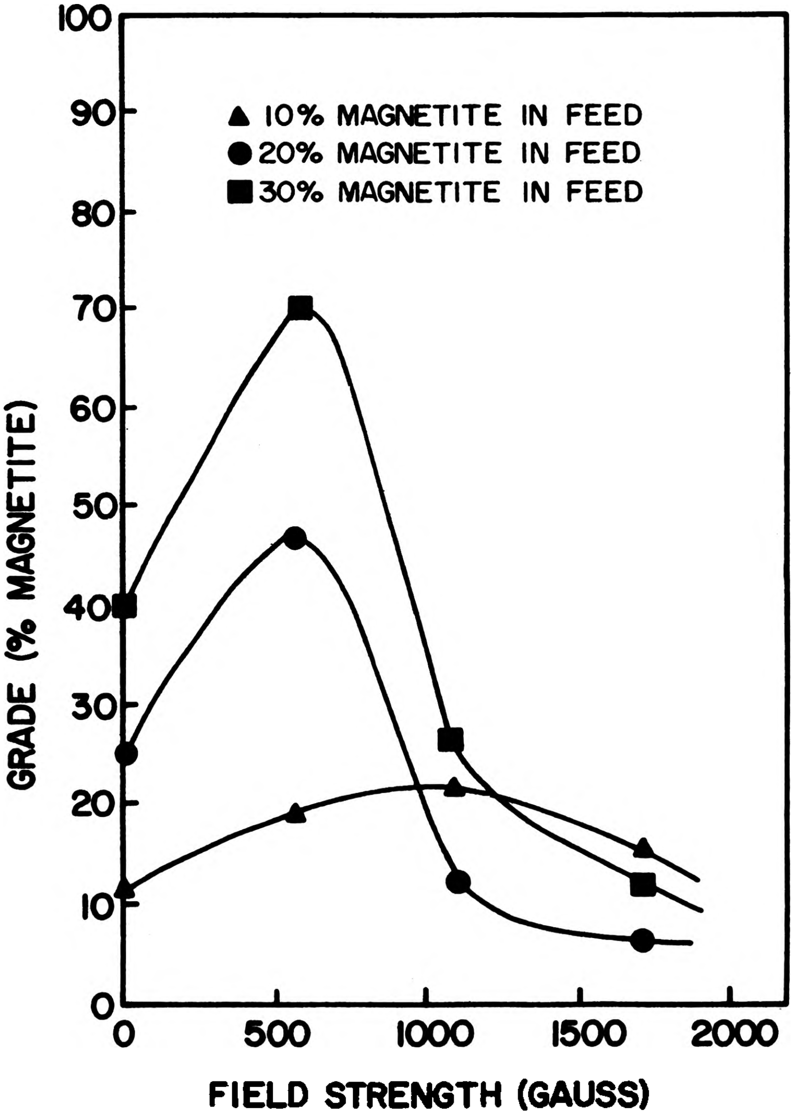


Fig. 21 Grade-Field Strength for Varying Percent Magnetite in Feed

feed and to 600 gauss for the 20 and 30% magnetite feeds. At higher field strengths, both the recovery and grade decrease substantially for all three feed becoming more significant for feeds containing 20 to 30% magnetite. As noted earlier, this unusual behaviour can probably be attributed to a build up of magnetic particles within the cyclone at high field strengths altering the flow patterns within the cyclone. The build up also increases the overflow slurry viscosity which increases the drag force on all the particles pulling them to the overflow. When the percentage magnetic material in the feed increases, this effect also increases and accounts for the greater drops in recovery and grade observed at feeds having 20 to 30% magnetite.

iii. Effect of percent solids in feed. The next operating parameter studied was the percent solids in the feed. Feed percent solids of 12.8, 17.4 and 19.4 were used in this study. Higher feed percent solids were not used because of the desire to avoid rope discharge at the underflow. Table XIII gives the results which are further presented graphically in Fig. 22. The magnetic concentrate grade increased from 42.0% to 47.0% when the percent solids in the feed was changed from 12.8 to 19.4. The recovery however dropped slightly from 96.2% to 93.8% under the same conditions. When the percent solids in the feed is increased, the resistance to the swirling motion of particles within the cyclone increases and results in slightly coarser particles reporting to the overflow and accounts for the decreasing

## TABLE XIII

## EFFECT OF PERCENT SOLIDS IN FEED ON CONVENTIONAL CYCLONE PERFORMANCE

Field strength : 560 gauss
% magnetite in feed : 20.0
Feed inlet pressure : 6 psi

| % solids in feed | Concentrate grade (%) | Recovery (%) | Enrichment ratio | Improvement in recovery (%) | Selectivity index |
|---|---|---|---|---|---|
| 12.8 | 42.0 | 96.2 | 2.10 | 28.7 | 5.96 |
| 17.4 | 46.0 | 94.4 | 2.30 | 26.9 | 6.46 |
| 19.4 | 47.0 | 93.8 | 2.35 | 26.0 | 5.35 |

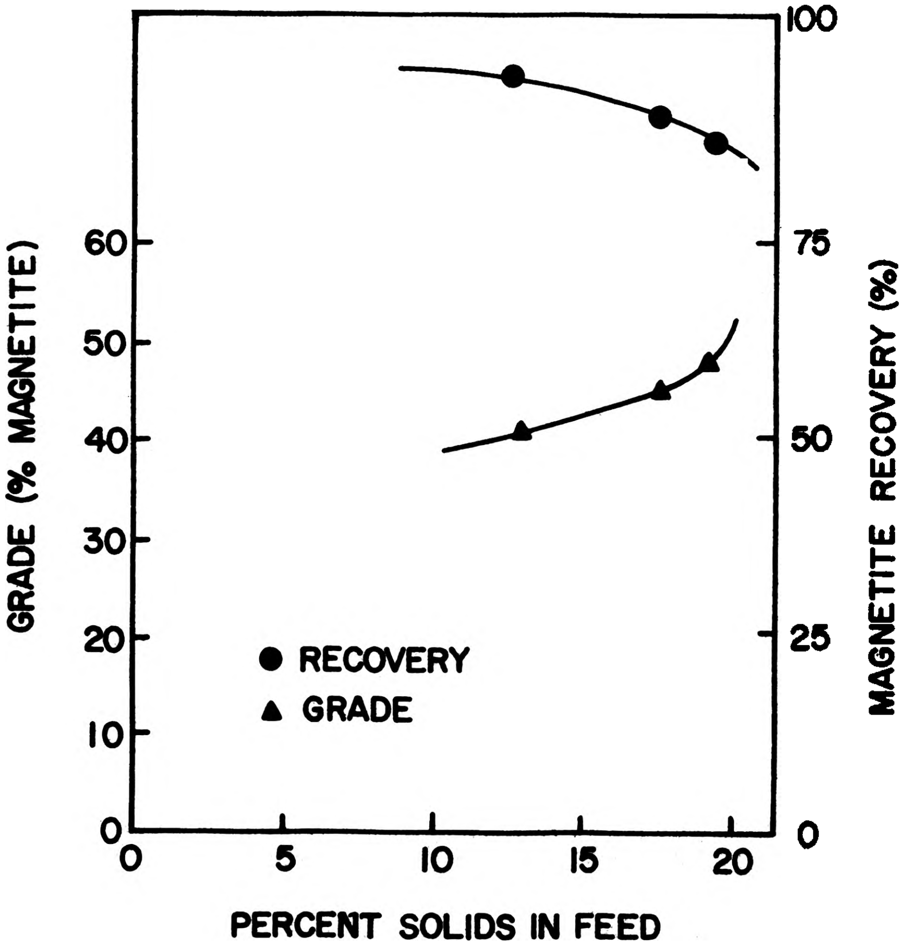


Fig. 22 Effect of Percent Solids in Feed on Grade and Recovery

magnetic recovery with increasing percent feed solids. The grade increases accordingly as a result of more non-magnetic particles reporting the overflow under these conditions.

iv. Comparison of recovery curves. Overflow and underflow samples from the cyclone operating without the magnetic field and under the influence of the magnetic field were sized using the Warman cyclosizer mentioned previously. Each size fraction was then analysed for its magnetic content. The percent magnetite in the feed was 10.0 and the inlet pressure 6 psi. The results are presented in Tables XIV and XV. The fraction of feed material in each size reporting to the underflow is plotted against the size for the combined samples and separately for the dolomite and magnetite fractions. These graphs are shown in Fig. 23 and 24. In Fig. 23, the curves obtained for the cyclone operating without the magnetic field follow the normal trend of a classification curve as mentioned in the theory. The $d_{50}$ of the composite sample was estimated to be 32 microns. That for the dolomite fraction was 34 microns and 26 microns for the magnetite fraction. Fig. 24 shows the shapes of the curves obtained with the cyclone operating under the influence of the magnetic field. The magnetite curve changes significantly from the normal classification curve. The dolomite and composite sample curves also do change though not as significantly as the magnetite curve. Considering the influence of the magnetic field, the curves shown in Fig. 24 can be appropriately referred to as "magnetic-classification" curves.

## TABLE XIV

## CALCULATIONS BASED ON SIZING ANALYSES FOR CYCLONE OPERATING WITHOUT MAGNETIC FIELD

| | | |
|---|---|---|
| % magnetic in feed | : | 10.0 |
| % solids in feed | : | 13.2 |

A. Combined Dolomite and Magnetite Fractions

| Average size (microns) | Weight % U/F | Weight % O/F | Wt. % of feed U/F | Wt. % of feed O/F | Calculated feed | Fraction of feed to U/F |
|---|---|---|---|---|---|---|
| 43.6 | 71.0 | 24.5 | 31.7 | 13.6 | 45.2 | 0.70 |
| 32.7 | 17.0 | 13.5 | 7.6 | 7.5 | 15.1 | 0.50 |
| 23.8 | 5.5 | 14.0 | 2.4 | 7.8 | 10.2 | 0.24 |
| 16.1 | 2.5 | 11.0 | 1.1 | 6.1 | 7.2 | 0.16 |
| 11.0 | 1.0 | 4.5 | 0.5 | 2.5 | 3.0 | 0.15 |
| -11.0 | 3.0 | 32.5 | 1.3 | 18.0 | 19.3 | 0.07 |
| | 100.0 | 100.0 | 44.6 | 55.4 | 100.0 | |

Table XIV (Cont.)

B. Magnetite Fraction

| Average size (microns) | Wt. % Magnetite | | Wt. % of feed | | Calculated feed | Fraction of feed to U/F |
|---|---|---|---|---|---|---|
| | U/F | O/F | U/F | O/F | | |
| 43.6 | 9.2 | 8.2 | 2.90 | 1.11 | 4.01 | .72 |
| 32.7 | 11.8 | 11.1 | 0.89 | 0.83 | 1.72 | .52 |
| 23.8 | 14.3 | 10.7 | 0.35 | 0.83 | 1.18 | .30 |
| 16.1 | 14.0 | 9.1 | 0.16 | 0.55 | 0.71 | .23 |
| 11.0 | 14.5 | 11.1 | 0.06 | 0.28 | 0.34 | .19 |
| -11.0 | 26.0 | 9.4 | 0.35 | 1.69 | 2.04 | .17 |
| | | | 4.71 | 5.29 | 10.00 | |

Table XIV (Cont.)

C. Dolomite Fraction

| Average size (microns) | Wt. % Dolomite | | Wt. % of feed | | Calculated feed | Fraction of feed to U/F |
|---|---|---|---|---|---|---|
| | U/F | O/F | U/F | O/F | | |
| 43.6 | 90.0 | 91.8 | 28.8 | 12.5 | 41.3 | .70 |
| 32.7 | 88.2 | 88.9 | 6.7 | 6.6 | 13.3 | .50 |
| 23.8 | 85.7 | 89.3 | 2.1 | 6.9 | 9.0 | .23 |
| 16.1 | 86.0 | 90.9 | 1.0 | 5.5 | 6.5 | .15 |
| 11.0 | 85.5 | 88.9 | 0.3 | 2.2 | 2.5 | .13 |
| -11.0 | 74.0 | 81.8 | 1.0 | 14.7 | 15.7 | .06 |
| | | | 39.9 | 48.4 | 88.3 | |

# TABLE XV

# CALCULATIONS BASED ON SIZING ANALYSES FOR CYCLONE OPERATING UNDER A MAGNETIC FIELD STRENGTH OF 560 GAUSS

A. Combined Dolomite and Magnetite Fractions

| Average size | Weight % | | Wt. % of feed | | Calculated | Fraction of feed |
|---|---|---|---|---|---|---|
| (microns) | U/F | O/F | U/F | O/F | feed | to U/F |
| 43.6 | 60.4 | 33.8 | 33.2 | 15.2 | 48.4 | 0.69 |
| 32.7 | 17.0 | 9.6 | 9.3 | 4.3 | 13.6 | 0.68 |
| 23.8 | 10.4 | 11.2 | 5.7 | 5.1 | 10.8 | 0.53 |
| 16.1 | 4.7 | 9.6 | 2.6 | 4.3 | 6.9 | 0.38 |
| 11.0 | 2.1 | 4.6 | 1.1 | 2.1 | 3.2 | 0.34 |
| -11.0 | 5.4 | 31.2 | 3.0 | 14.1 | 17.1 | 0.18 |
| | 100.0 | 100.0 | 54.9 | 45.1 | 100.0 | |

Table XV (Cont.)

B. Magnetite Fraction

| Average size (microns) | Wt. % Magnetite U/F | Wt. % Magnetite O/F | Wt. % of feed U/F | Wt. % of feed O/F | Calculated feed | Fraction of feed to U/F |
|---|---|---|---|---|---|---|
| 43.6 | 12.1 | 1.1 | 4.00 | 0.17 | 4.17 | 0.96 |
| 32.7 | 20.9 | 4.0 | 1.90 | 0.17 | 2.07 | 0.92 |
| 23.8 | 26.1 | 3.4 | 1.50 | 0.17 | 1.67 | 0.90 |
| 16.1 | 40.0 | 4.0 | 1.00 | 0.17 | 1.17 | 0.85 |
| 11.0 | 44.0 | 8.0 | 0.50 | 0.17 | 0.66 | 0.76 |
| -11.0 | 10.0 | 1.0 | 0.30 | 0.17 | 0.44 | 0.68 |
|  |  |  | 9.20 | 0.98 | 10.18 |  |

Table XV (Cont.)

C. Dolomite Fraction

| Average size (microns) | Wt. % Dolomite | | Wt. % of feed | | Calculated feed | Fraction of feed to U/F |
|---|---|---|---|---|---|---|
| | U/F | O/F | U/F | O/F | | |
| 43.6 | 87.9 | 98.9 | 29.1 | 15.1 | 44.2 | .66 |
| 32.7 | 79.1 | 96.0 | 7.4 | 4.2 | 11.6 | .64 |
| 23.8 | 73.9 | 96.6 | 4.2 | 4.9 | 9.1 | .46 |
| 16.1 | 60.0 | 96.0 | 1.5 | 4.2 | 5.7 | .26 |
| 11.0 | 56.0 | 92.0 | 0.5 | 1.9 | 2.4 | .21 |
| -11.0 | 90.0 | 99.0 | 2.7 | 13.9 | 16.6 | .16 |
| | | | 45.4 | 44.2 | 89.6 | |

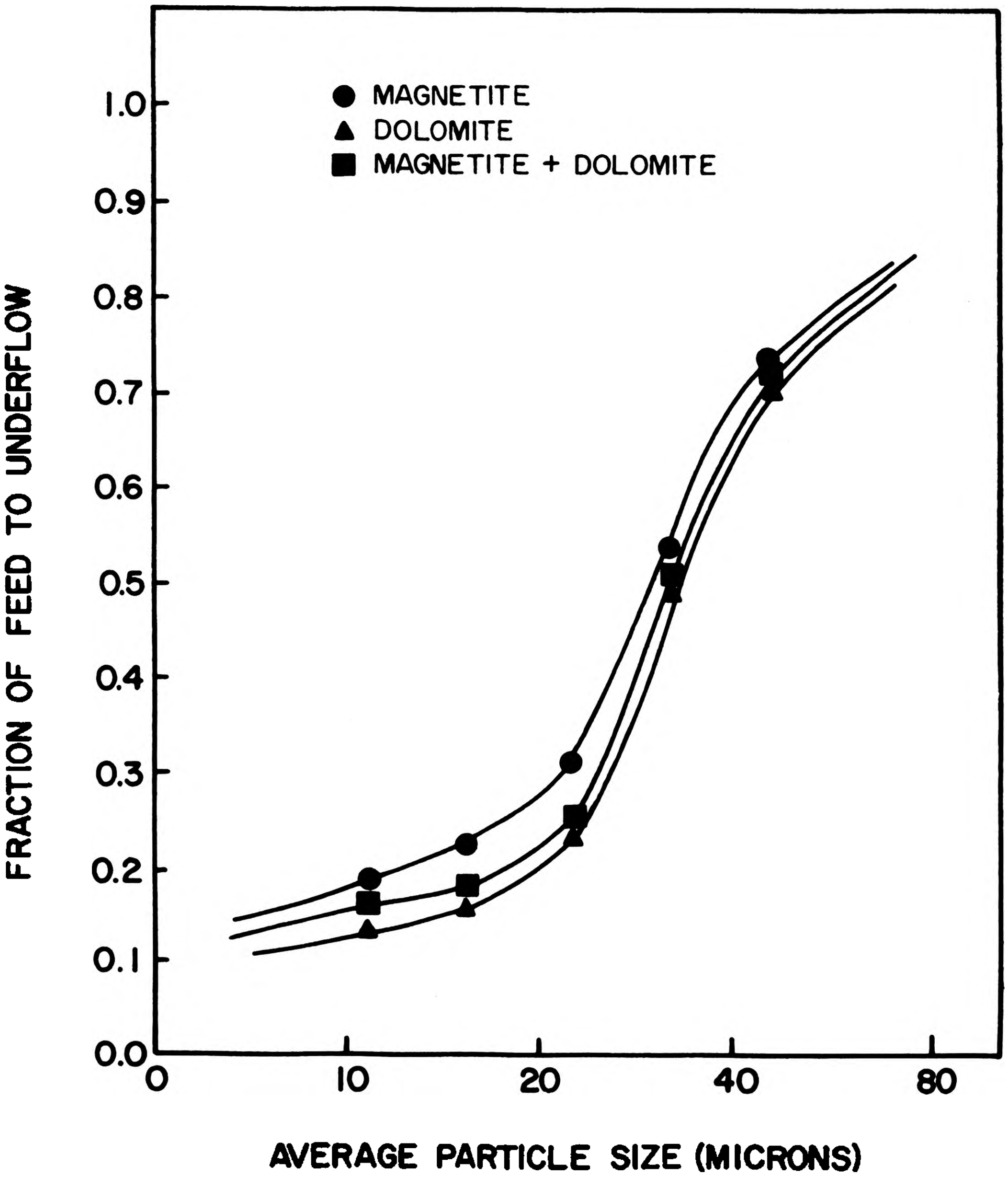


Fig. 23 Fraction to Underflow vs Particle Size for Cyclone Operating Without Magnetic Field

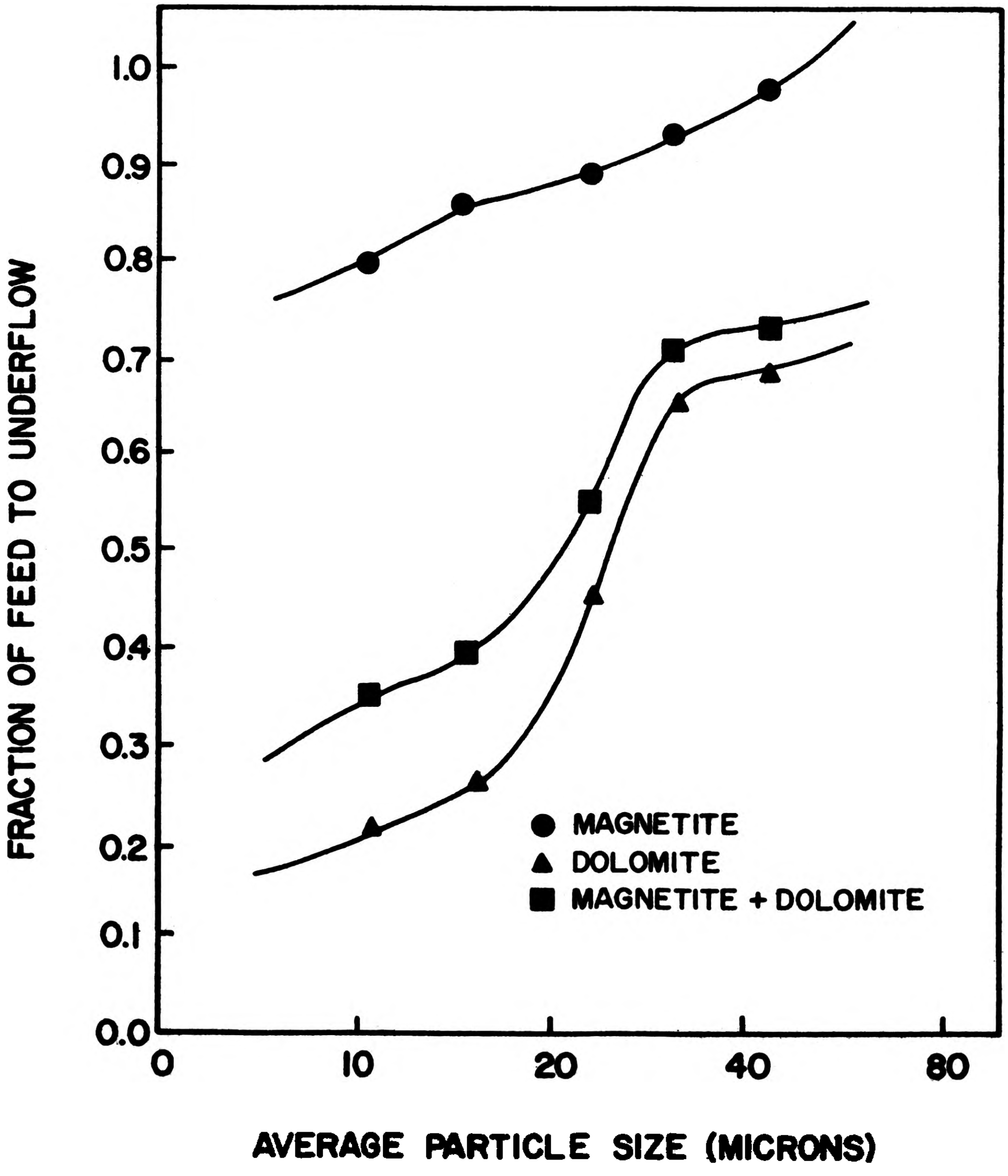


Fig. 24 Fraction to Underflow vs Particle Size for Cyclone Operating Under Influence of Magnetic Field

The magnetic $d_{50}$ of the composite sample was 20 microns whilst that of the dolomite was 24 microns. The corresponding $d_{50}$ for the magnetite fraction could not be estimated from the graph being so small as expected from the theory. It is proposed that, apart from its effect on the combined force on a particle in the cylone, the magnetic field also affects the fluid flow patterns within the cyclone altering the classification curves as evidenced in Figs. 23 and 24.

v. Use of cast iron pieces to alter field distribution. Based on the improvements achieved in magnetic recovery when cast iron pieces were used with the vertical cyclone similar cast iron pieces were machined into semi-circular shapes to fit around the conventional cyclone and fixed to the flat ends of the pole faces of the electromagnet. Coil currents of 5, 10 and 15 amperes were used to vary the field strengths and the performance of the cyclone studied. The results are shown in Table XVI and plotted in Fig. 25.

The recovery increases from 59.0% with the cyclone operating without the magnetic field to 95.5% when a field strength of 1480 gauss is applied. A comparison of Figs. 18 and 25 shows that whereas the recovery decreases substantially at very high field strength with the straight pole face configuration, the use of cast iron peices results in recoveries above 90.0% even at high field strength. The high recoveries can be attributed to the good field distributions achieved with the use of the cast iron pieces. Here again, evidence of this better field distribution is indicated by

## TABLE XVI

## CONVENTIONAL CYCLONE WITH CAST IRON PIECES AT POLE FACES

% magnetite in feed : 10.0

Inlet pressure : 6 psi

| Field strength 1 in. from pole face(gauss) | Concentrate grade (%) | Recovery (%) | Enrichment ratio | Improvement in recovery (%) | Selectivity index |
|---|---|---|---|---|---|
| 0 | 10.0 | 59.2 | 1.00 | - | 1.00 |
| 500 | 18.0 | 92.0 | 1.80 | 32.8 | 3.28 |
| 970 | 17.0 | 92.4 | 1.70 | 33.2 | 3.17 |
| 1480 | 17.5 | 95.5 | 1.75 | 36.3 | 4.50 |

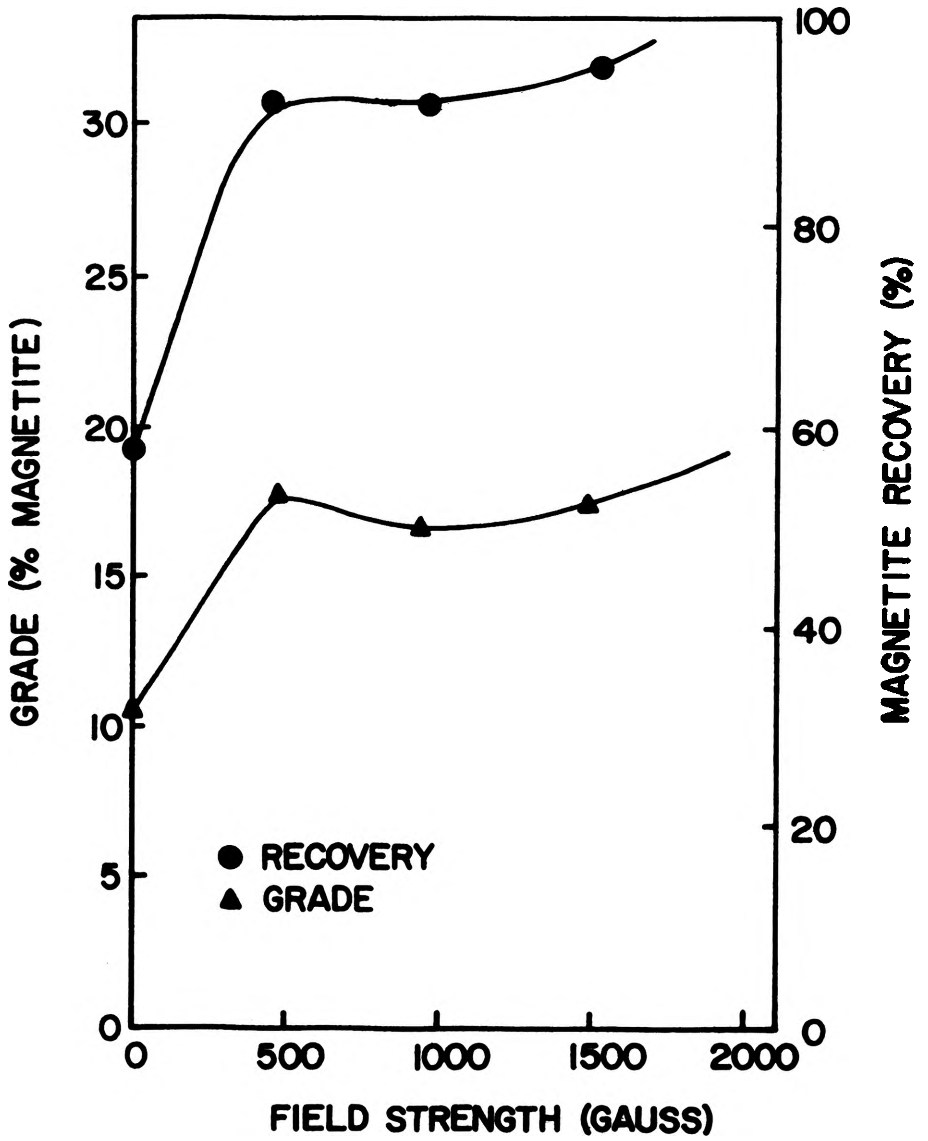


Fig. 25 Recovery and Grade for Conventional Cyclone With Cast Iron Pieces at Pole Faces

the lower values of field strengths obtained at the same positions when using the cast iron pieces as compared to the straight pole faces. The highest grade obtained with the cast iron arrangement was 18.0% as compared to 21.0% for the straight pole face arrangement. This decrease in grade is due to the fact that the improved field distribution also results in slightly more recovery of non-magnetic material due to entrapment and decreases the grade accordingly.

vi. Discussion of performance of conventional cyclone. The enrichment ratios obtained using the conventional cyclone were in the range 1.70-2.35 and improvements in recovery up to 50% were achieved. The recoveries over 90% obtained with the use of the cast iron pieces at the pole faces is attributable to the better distribution of the magnetic field around the cyclone under these conditions. The slight variations in the concentrate grades with increasing field strengths are due to increasing recovery of non-magnetic materials.

The better concentrate grades and recoveries achieved with the conventional cyclone as compared to the air-type cyclones operating under the same conditions is due mainly to the greater degree of classifying action occuring in the conventional cyclone. Also the short circuiting is thought to be less.

The effect of pressure changes on the cyclone indicate that the combined magnetic and classifying action is better at lower pressures. Since a minimum amount of pressure drop is needed to establish the vortex in a cyclone, it is proposed that the 3.0 inch cyclone is best operated at a feed inlet pressure of 6 psi.

Increasing the percent solids in the feed gave increasing concentrate grades. However, the recoveries decreased; though not very significantly. The decreases in recovery are due to the increase in the internal slurry viscosity and resulting in more particles being pulled to the overflow.

The optimum field strength needed to obtain the best grades and recoveries depends to some extent on the percent magnetic material in the feed. As noted from the results, the magnetic field strength needed to obtain the highest grades and recoveries when using a feed containing 10% magnetite was approximately 1300 gauss as compared to 560 gauss when the feed contained 20 to 30% magnetite. Apart from the build up in the cyclone and the consequent changes in flow patterns with increasing field strength, the degree of entrapment of non-magnetic and magnetic materials increases and contributes to the drops in recoveries and grades at high field strengths. It is projected that the use of cast iron to improve the field distribution when using 20 and 30% magnetite in the feed would reduce the possible build in the cyclone and increase the recoveries accordingly.

# IV. SUMMARY AND CONCLUSIONS

Air-type cyclones were constructed and successfully used in classifying solids. The use of 3.0 inch diameter air-type cyclones permitted the separation of feeds containing magnetite of size 90% passing 50 microns into equal overflow and underflow fractions. The separation of mineral particles in these cyclones under the influence of a magnetic field yielded magnetic concentrates with enrichment ratios up to 1.9 and between 10 to 25% improvements in recoveries were achieved. The limitations in the use of these air-type cyclones include the production of very dilute underflow pulps which increases the degree of short circuiting as well as the reporting of unclassified material to the underflow. For these cyclones to be more effective, they would have to be constructed to incorporate a tapering section in order to increasing their thickening effect at the underflow and reduce the amount of water reporting to the underflow. A very high percent solids in the feed might also help to improve the recovery of magnetic materials when the cylone is operated under the influence of the magnetic field.

The conventional aluminium cyclone produced magnetic concentrate grades and recoveries higher than the air-type cyclones when operated under the same magnetic field conditions. Enrichment ratios up to 2.35 were achieved and recoveries over 88% obtained. The use of cast iron pieces at the electromagnet pole faces to improve the field distributions around the cyclone led to recoveries of 92% or better. The cyclone gave the best grades and recoveries at inlet pressures around 6 psi with higher pressures producing no better results. A practical advantage of this low pressure is saving in pumping costs.

The magnetic cyclone is best operated at lower field strengths especially with increasing percent magnetic material in the feed. Practically, this is of great value because the coils get heated up with increasing coil current requiring cooling. A low current operation would therefore reduce the heating and the degree of cooling needed.

The high recoveries obtained under various conditions indicate the ability of the magnetic cyclone in recovering the magnetic materials. However the grades obtained show that a lot of non-magnetic material is obtained as well. To improve the grades, the feed to the cyclone should contain particles of sizes less than the $d_{50}$ of the cylone. When the cyclone operates with this feed, all the materials should be recovered at the overflow. The imposition of the magnetic field would then result in only magnetic materials reporting to the underflow. This could not be done in this study because of the limited facilities available.

In this project, a basis has been established for the potential use of magnetic fields to influence the behaviour of particles within the cyclone. The potential practical applications include the treatment of ores containing magnetic materials where the magnetic fraction is the desired concentrate or where the magnetic fraction is to be removed. In both cases the use of the combined magnetic and classification operations would lead to potential savings in cost in terms of:

1. less processing times
2. increased throughput
3. simplicity in process flow and hence less manpower requirement
4. less floor space requirement.

The disadvantages of this process will include the grinding costs arising from the fine grinding required even for large cyclones. Another limitation will be heating up of the coils of the electromagnet which will require continuous cooling for prolonged applications.

# BIBILIOGRAPHY

1. Edmiston, K. J., "Sizing Operations Are Key To Communition Circuits," World Mining, October 1982, 82-83.
2. Miller, J. D., "The Concept Of An Air Sparged Hydrocyclone," paper presented at the SME-AIME Chicago, February 1981.
3. Miller, J. D. and Van Camp, M. C., "Fine Coal Flotation In A Centrifugal Field With An Air Spanged Hydrocyclone," Mining Engineering, November 1982, 1575-1580
4. Khalafalla, S. E., "Magnetic Separation of The Second Kind," IEEE Transactions on Magnetics, Vol. MAG-12, No. 5, 1976.
5. Wills, B. A., "Factors Affecting Hydrocyclone Performance," Mining Magazine, February 1981, 142-146.
6. Draeger, E. A. and Collins, J. W., "Efficient Use of Water Only Cyclones," Mining Engineering, Vol. 32, 1980 1215.
7. Bradley, D., "The Hydrocyclone," Pergamon Press, 1965.
8. Mular, A. L. and Jull, N. A., "The Selection of Cyclone Classifiers, Pumps and Pump Boxes For Grinding Circuits," Mineral Processing Plant Design, Mular and Bhappu, editors, 376-403.
9. Fontein, F. J., et. al., "The Influence of Some Variables Upon Hydrocyclone Performance," British Chemical Engineering 7, 1962, 410.

## BIBILIOGRAPHY (Cont.)

10. Bradley, D., *Int. J. Mineral Porcessing Congress,* London, April, 1960.

11. Kelsall, D. F., "A Study of The Motion of Solid Particles in a Hydraulic Cyclone," *Trans. Inst. Chem. Eng.*, 30, 87-104.

12. Kelly, E., and Spottiswood, D., "Intorduction to Mineral Processing," Wiley Publications, 1982, chapter 10.

13. Wills, B. A., "Mineral Processing Technology," Pergamon Press, 1981, chapter 9.

14. Oberteuffer, J. A., "Magnetic Separation: A Review of Principles, Devices and Application," *IEEE Trans. on Magnetics*, Vol. MAG-10, No. 2, 1974.

15. Brown, J. H., "Unit Operations in Mineral Engineering," International Academics Services Ltd., 1979, chapter 9.

16. Cohen, E. and Good, J. A., "The Application of a Superconducting Magnet System to the Cleaning and Desulfirization of Coal," *IEEE Trans. on Magnetics*, Vol-MAG-12, No. 5, 1976.

17. Renner, V. G. and Cohen, E., "Measurement and Interpretation of Size Distribution of Particles Within a Hydrocyclone," *Trans. IMM. Sec. C*, 87, 1978, 139.

18. Hiew, M., "Beneficiation of Magnetic Minerals With Magnetic Hydrocyclones," M. Min. Tech Thesis, University of Otago, 1981.

19. Wills, B. A., "Mineral Processing Technology,' Pergamon Press, 1981, chapter 4.

# VITA

Kwasi Amoako-Gyampah was born on June 27, 1954 in Bekwai, Ghana. He received his secondary education at Adisadel College in Cape Coast, Ghana. He attended the University of Science and Technology in Kumasi, Ghana, from where he received a Bachelor of Science degree in Metallurgical Engineering in August 1979. Upon graduation he worked as a Trainee Metallurgist/Metallurgist at the Volta Aluminium Company in Tema, Ghana for two years.

He has been enrolled in the Graduate School of the University of Missouri-Rolla since August 1982 and he is presently a candidate for the Master of Science degree in Metallurgical Engineering. He is a member of TMS-AIME.

# APPENDIX A

## SAMPLE DATA COLLECTION

Conventional cyclone

% magnetite in feed : 30.0

Feed inlet pressure : 6 psi

| | Sample | Wet Weight (g) | Dry Weight (g) | % Solids | Flow Rate (g/sec) | % Magnetite |
|---|---|---|---|---|---|---|
| No Field | OF | 2025.5 | 157.4 | 7.8 | 1012.8 | 21.0 |
| | UF | 241.1 | 147.6 | 61.2 | 120.6 | 40.0 |
| 560 Gauss | OF | 1809.8 | 189.5 | 10.5 | 904.9 | 10.0 |
| Field Strength | UF | 203.3 | 96.5 | 47.5 | 101.6 | 70.0 |
| 1130 Gauss | OF | 1954.6 | 292.6 | 15.0 | 977.3 | 31.0 |
| Field Strength | UF | 279.0 | 43.4 | 15.6 | 139.5 | 24.0 |
| 1780 Guass | OF | 2079.6 | 301.1 | 14.5 | 1039.8 | 33.0 |
| Field Strength | UF | 379.1 | 48.7 | 12.9 | 189.6 | 14.0 |

# APPENDIX B

## OPERATING CHARACTERISTICS OF ELECTROMAGNET AND PUMP

### A. ELECTROMAGNET

Shape of poles : cylindrical

Air gap between pole faces : 4 in

Source of power : DC

Fall capacity of DC source : 20,000 gauss.

### B. PUMP

Type of pump : centrifugal

Size : 3 in

Power provision : 5 hp

Speed : 3450 rpm