MAGNETIC SEPARATION OF IRON ORES

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1. INTRODUCTION

The testing of iron ores for beneficiation by magnetic separation is normally done in laboratory separators of various types, and the results are reported in terms of the variables, such as magnet coil current, rotor speed and gap width, of the instruments used. Such testing is empirical, and the results can be reproduced only in a machine precisely similar to the test machine. A less empirical method of testing is clearly desirable, and a project was therefore initiated to develop such a method.

The basic physical property of minerals on which their magnetic separation depends is the magnetic susceptibility. The magnetic investigation of an iron ore should therefore aim to characterise the ore in terms of the susceptibilities of its components or of the fractions into which it is desired to separate the ore. In addition, it is necessary to show how a knowledge of these susceptibilities can be applied to the treatment of the ore in industrial separators.

2. SUMMARY

From a consideration of the forces acting on a particle in the magnetic field of an induced-rotor dry magnetic separator, a method is worked out for the determination of the susceptibility of paramagnetic substances by means of a laboratory separator of this type. The method is applied to a suite of South Australian iron ore samples representing a wide range of ore types. The application of the results to the separation of these samples is discussed and illustrated.

3. MATERIAL EXAMINED

The following samples were received from Mr G. F. Whitten:

1. Copper King (ochre) mine, 15 miles south of Leigh Creek. The "ironstone" outcrop on the south bank of the creek was sampled (65 lb).
2. Nicols Nob (copper) mine, 22 miles north east of Leigh Creek. The sample was taken from the dump of the central shaft (85 lb).
3. North field workings, Leigh Creek (85 lb).
4. Nairne Pyrite Limited, Grassfire Hill (i.e., northern workings), 1 bag of plus 3 inch material from the quarry floor and 1 bag of minus 3 inch material from the belt at the primary crusher (total 125 lb).

5. Nairne Pyrite Ltd., hand specimen said to be pyrrhotite (20 lb).
6. Hick's quarry, 4 miles north east of Gladstone. Magnetite altered to martite and with minor goethite (118 lb).
7. Devils Chimney. Micacous hematite (168 lb).
8. Iron Prince, 940 ft bench. Soft hematite, very friable, low in phosphorus (159 lb).
9. Iron Monarch, bench H. Hard glassy limonite, minor hematite as scree (139 lb).
10. Iron Monarch, hard hematite (116 lb).
11. Iron Monarch, bench G1. Hard manganiferous hematite (Mn up to 14%) (82 lb).
12. Iron Monarch, bench G. Blue foundry ore, low phosphorus (88 lb).
13. Iron Monarch, bench G1. Red basic (low manganese) ore (101 lb).
14. Corunna area, Co-ords 1075ON 98OW, goethite (100 lb).

Samples 7, 8, 9 and 14 were stated to represent extreme types, probably very simple mineralogically. Samples 1, 2 and 3 were thought to be siderite, but a mineralogical examination showed that only No. 3 can be so described; No. 1 and 2 are mixtures of dolomite and calcite, the grains of which are coated with goethite. A mineralogical report on Samples 1, 2 and 3 is given in an appendix to this report.

The samples were crushed in a jaw crusher and ground in stages using rolls to minus 36-mesh. The minus 36-mesh material was screened into 4 fractions:

- 36 + 52 mesh
- 52 + 72 "
- 72 + 100 "
- 100 "

The proportions by weight of these fractions, and the iron assay of the first and last of them, are shown in Table 1. The assay results show that there is very little difference in iron content between the fractions.

TABLE 1: WEIGHT AND ASSAY OF SIZED FRACTIONS

Sample No.	Weight of Sized Fractions, %				Iron Assay, % Fe	
	-36+52 mesh	-52+72 mesh	-72+100 mesh	-100 mesh	-36 +52 mesh	-100 mesh
1	57.5	23.4	14.1	5.0	16.7	16.7
2	52.5	20.4	16.8	10.3	11.3	11.6
3	61.7	11.5	15.5	11.3	45.5	44.0
4	61.0	9.8	16.6	12.6	9.65	9.75
5	57.3	8.8	19.9	14.0	59.8	58.4
6	51.4	10.0	17.9	20.7	64.9	64.9
7	44.1	15.2	20.1	20.6	62.8	62.8
8	24.4	6.6	16.0	53.0	69.2	69.2
9	63.0	11.1	17.4	8.5	58.1	57.6
10	48.5	10.7	12.2	28.6	68.8	68.5
11	53.2	12.0	21.6	13.2	54.1	54.1
12	39.9	10.4	18.0	31.7	69.0	69.0
13	45.4	11.4	24.9	18.3	67.8	67.5
14	48.3	16.4	14.6	20.7	58.4	58.4

4. EQUIPMENT

A Carpco laboratory high-intensity induced-rotor dry magnetic separator was used in all the experimental work. This instrument consisted of a rotor which could be made to rotate with variable speed between the pole pieces of an electromagnet, one of which was fixed and the other movable. The sample was fed from a hopper to the rotor from above, and passed into the gap between rotor and movable pole piece. The size of the gap could be adjusted by moving the pole piece, but throughout the experimental work the pole piece was set to give the minimum gap width of 3 mm. The power supply to the magnet coils could be varied from 0 to 1.5 amp, but the magnet became saturated at 1.2 to 1.3 amp. Below the rotor were two chutes, separated by an adjustable splitter.

British standard sieves were used, and all screen sizes quoted refer to them.

5. THEORY

A particle on the surface of the rotor at P (see Figure 1) is acted upon by a magnetic force Fm and a gravitational force Fg given by

$$Fm = \chi m H \frac{dH}{ds} \qquad \text{(1)}$$

$$Fg = mg \qquad \text{(2)}$$

where χ = the specific or mass susceptibility of the particle
m = the mass of the particle
H = the magnetic field strength
dH/ds = the gradient of magnetic field strength in the direction of the force Fm
g = the acceleration due to gravity.

The instantaneous velocity v of the particle is $2\pi rn$ in the direction PQ, where PQ is the tangent to the rotor at P, r is the radius of the rotor, and n is the number of revolutions per second. The angular acceleration of the particle is $v^2/r = 4\pi^2 n^2 r$, and the centripetal force required to maintain the particle on its circular path is $4\pi^2 n^2 rm$. This centripetal force is provided by the magnetic and gravitational forces. The gravitational force may be resolved into 2 components, mg $\sin\theta$ in the direction of the centre of rotation O, and mg $\cos\theta$ in the direction PQ. The particle will leave the rotor when the value of

$$4\pi^2 n^2 rm \text{ exceeds } \chi m H \frac{dH}{ds} + mg\sin\theta.$$

If PQ represents the splitter, the particle will be just as likely to fall into the left hand chute as into the right when

$$\chi m H \frac{dH}{ds} + mg\sin\theta = 4\pi^2 n^2 rm \qquad \text{(3)}$$

or

$$\chi H \frac{dH}{ds} + g\sin\theta = 4\pi^2 n^2 r \qquad \text{(4)}$$

PQ makes an angle ψ with the horizontal. If the splitter is set so that its edge lies in a vertical plane tangent to the rotor, $\psi = 90^0$, $\theta = 0^0$, and, for particles of the same susceptibility, the ratio of the weight of particles delivered by the left hand chute to the weight delivered by the right hand chute (= L/R) will be unity when

$$\chi H \frac{dH}{ds} = 4\pi^2 n^2 r \qquad \text{(5)}$$

Rearrangement of (5) gives

$$n^2 = \frac{\chi H}{4\pi^2 r} \quad \frac{dH}{ds} \qquad \text{(6)}$$

The value of n determined by (6) will be called the "critical rotor speed". The function $H\frac{dH}{ds}$, which (and not the field strength) determines the intensity of a separator, will be referred to as the "field characteristic".

Equation (5) is of course an idealised formula and neglects a number of factors, such as the distortion of the original magnetic field by the presence of the particles, the shape of the particles, which introduces a form factor called the "demagnetising effect", and the interaction of the particles on one another.

6. DETERMINATION OF MAGNETIC SUSCEPTIBILITY

Consideration of equation (5) suggested the possibility of using the Carpco separator for the determination of magnetic susceptibility. For a given coil current and gap setting, $H\,dH/ds$ should be constant, so that the susceptibility χ should be directly proportional to n^2, the square of the critical rotor speed, that is, the speed for which the ratio L/R is unity. Since the value of $H\,dH/ds$ cannot be directly determined, it is necessary to calibrate the separator with compounds of known susceptibility.

6.1 Calibration of Separator

The following salts were used for calibration, since their susceptibilities have been accurately determined[1]

	χ at 20°C	
$Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$	32.4×10^{-6}	cgs units
$NiSO_4 \cdot 6\text{-}7H_2O$	15.8×10^{-6}	ditto
$CuSO_4 \cdot 5H_2O$	5.88×10^{-6}	"

The salts were sized to minus 36- plus 52-mesh, since at this size they flowed readily through the feed hopper. The splitter was set by means of a plumb line so that its edge lay in a vertical plane tangent to the rotor. At each setting of the magnet coil current 20 to 30 g of salt were passed through the separator at various rotor speeds. The portion delivered by each chute was weighed, and the ratio of the weight delivered by the left hand chute to that delivered by the right hand chute (=L/R) was calculated. The speed of the rotor at each pass was determined by a revolution counter.

The rotor speed required to give a weight ratio of 1.00 (i.e. the critical rotor speed) was determined graphically by plotting rotor speed against weight ratio (the relation is not linear). Four points, or

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[1] See J. McAndrew, Proc. Aust. I.M.M. No.181, 59 (1957).

three sufficiently close to the unit ratio, were found sufficient. The results are shown in Table 2.

TABLE 2: CALIBRATION OF SEPARATOR
Particle size: -36 +52-mesh

Magnet Current amp	Critical Rotor Speed, rps		
	Copper Sulphate	Nickel Sulphate	Ferrous Ammonium Sulphate
0.3	-	2.27	3.92
0.4	-	3.12	4.88
0.5	1.85	3.83	5.68
0.6	2.24	4.40	6.50
0.7	2.58	4.90	7.13
0.8	2.82	5.25	7.63
0.9	3.00	5.45	8.12
1.0	3.12	5.73	8.37
1.1	3.24	5.90	8.58
1.2	3.33	6.00	8.78
1.3	3.49	6.08	-

Equation (5) shows that, for a fixed gap setting and a fixed current in the electromagnet, a log-log plot of χ against n should give a straight line of slope 2. Such a plot is shown in Figure 2, the values of n being taken from Table 2. The lines joining the corresponding points for ferrous ammonium sulphate and nickel sulphate have the following slopes:

Current amp	Slope
0.3	1.33
0.4	1.63
0.5 - 0.6	1.86
0.7 - 1.2	1.90

As the current increases, the slope approaches the theoretical value of 2. The points for copper sulphate do not lie on this series of straight lines, and if the points for copper sulphate and nickel sulphate are joined, a line of smaller slope than that of the line joining the corresponding points for nickel sulphate and ferrous ammonium sulphate is obtained. The magnetic force acting on a particle increases both with the susceptibility of the particle and with the current in the magnet coils, and it may be concluded that as the factors neglected in the derivation of (5) become small in relation to the magnetic force, so the behaviour of the particle approaches that predicted by the ideal equation.

The value of n corresponding to any value of χ within the range of the figure may be found from Figure 2, and from values so obtained Figure 3 has been constructed, in which critical rotor speed in revolutions per minute is plotted against $\chi \times 10^6$ for magnet currents ranging from 0.3 to 1.2 amp. These are the calibration curves for the instrument.

6.2 Effect of Particle Size

The mass of the particles does not enter into equation (5), and hence the weight ratio L/R should be independent of particle size. The 3 salts used for calibration were tested in 3 size ranges,

Mesh			
-	36	+	52
-	52	+	72
-	72	+	100

and the critical rotor speeds are shown in Table 3. The results for minus 36- to plus 52-mesh are independent of those given in Table 2, and serve as a check on reproducibility. Susceptibilities corresponding to these rotor speeds were read off from the calibration chart (Figure 3), and are shown in Table 4.

These results show that if the sample is ground to a particle size smaller than that for which the calibration curve has been constructed, high results will be obtained by use of the calibration curve, and these will become higher as the particle size is reduced. As the susceptibility decreases, the error will become greater. A mixture of particle sizes gives a result intermediate between the extremes. Thus for a mixture of equal parts by weight of the 3 ferrous ammonium sulphate grades the critical rotor speed at 0.5 amp was 365 rpm, equivalent to a susceptibility of 36.7 by 10^{-6} according to the calibration curve. The average of the 3 sets of values in Table 4 is 36.3 by 10^{-6} (each set itself being averaged). It is clear from this that to determine the susceptibility of a sample it must be screened to the same range of particle sizes as the standards used to calibrate the instrument, unless a correction factor can be applied.

TABLE 3: EFFECT OF PARTICLE SIZE

Magnet Current amp	Critical Rotor Speed, rpm -36 +52 mesh	-52 +72 mesh	-72 +100 mesh
	Ferrous Ammonium Sulphate		
0.3	234	276	296
0.5	350	370	405
0.7	432	465	505
0.9	481	513	537
	Nickel Sulphate		
0.4	184	193	236
0.6	262	288	310
0.8	314	343	360
1.0	341	377	392
	Copper Sulphate		
0.6	124	160	170
0.8	158	201	240
1.0	178	215	265
1.2	198	222	279

TABLE 4: SUSCEPTIBILITIES CORRESPONDING TO ROTOR SPEEDS IN TABLE 3
From Figure 3.

Magnet Current amp	χ by 10^6, cgs units		
	-36 +52 mesh	-52 + 72 mesh	-72 +100 mesh
	Ferrous Ammonium Sulphate		
0.3	32.4	-	-
0.5	34.0	37.6	-
0.7	32.8	38.0	-
0.9	31.7	35.8	39.0
Average	32.7	37.1	-
	Nickel Sulphate		
0.4	15.3	16.9	22.8
0.6	15.5	18.4	21.1
0.8	15.4	18.3	20.0
1.0	15.3	18.5	20.0
Average	15.4	18.0	21.0
	Copper Sulphate		
0.6	5.5	7.1	7.7
0.8	5.5	7.3	9.7
1.0	5.6	7.0	9.7
1.2	5.8	6.8	9.7
Average	5.6	7.1	9.2

6.3 Correction for Particle Size

The mean aperture of the limiting screens has been taken as a measure of the particle size, and is as follows:

Mesh	Mean Aperture μ
- 36 + 52	358
- 52 + 72	253
- 72 + 100	181

A plot of mean aperture against the average value of χ by 10^6 taken from Table 4 is shown in Figure 4. The relationship is approximately linear, and by the intrapolation of additional lines a correction chart has been formed. By taking lines parallel to these, any apparent value of χ (determined from the calibration chart) at any mean aperture within the limits of the correction chart can be corrected to the value at minus 36-plus 52-mesh, for which the calibration chart has been prepared.

6.4 Method of Test and Examples

The method of test consists in selecting a suitable magnet current and determining the critical rotor speed at this current. The critical speed is found graphically by plotting weight ratio (L/R) against rotor speed. The susceptibility corresponding to the critical rotor speed is then read off from the calibration chart (Figure 3) and corrected if necessary for particle size by means of the correction chart (Figure 4). Although this method is based on theoretical considerations, it is empirical, since the form of the calibration curves cannot be accurately predicted, and they vary for different particle sizes. An indication of the accuracy to be expected is given by the second column of Table 4, from which it appears that, if low rotor speeds (less than 170 rpm) are avoided, susceptibilities can be determined with an error of not more than 5 per cent. The method was tested by using it to determine the susceptibilities of cobalt sulphate and potassium ferricyanide.

Cobalt Sulphate. A sample of crude cobaltous sulphate was dissolved in boiling water. The solution was filtered and allowed to crystallise. The crystals were dried by suction and by pressing between filter paper and were ground and screened to obtain a minus 36 plus 52-mesh fraction. This fraction had the composition $CoSO_4 . 7H_2O$, and when it was treated in the separator at 0.5 amp a critical rotor speed of 366 rpm was found, corresponding to $\chi = 37.0 \times 10^{-6}$. The value given in Hodgman's Handbook of Chemistry and Physics for $CoSO_4 . 7H_2O$ is 37.0×10^{-6} at 19.9°C.

Potassium Ferricyanide. This salt was used to check the correction chart as well as the calibration chart. The results for a magnet current of 0.9 amp were as given in Table 5. The value given by Hodgman is 7.08 x 10^{-6} at 21°C.

TABLE 5: SUSCEPTIBILITY OF POTASSIUM FERRICYANIDE

Particle Size Mesh				Critical Rotor Speed rpm	χ x 10^6 (from Figure 3)	Corrected Value of χ x 10^6 (from Figure 4)
-	36	+	52	201	6.8	6.8
-	52	+	72	236	8.6	6.5
-	72	+	100	273	10.6	7.0

7. APPLICATION OF THE CALIBRATION CURVES TO THE SEPARATION OF MIXTURES

A mixture was prepared containing equal weights of ferrous ammonium sulphate, nickel sulphate and copper sulphate, all sized to minus 36- plus 52-mesh. At 0.9 amp the critical rotor speeds corresponding to the susceptibilities of these salts are, from Figure 3:

486 rpm for ferrous ammonium sulphate
336 rpm for nickel sulphate
180 rpm for copper sulphate

As the speed is reduced from 486 rpm, more of the iron salt will be held to the rotor; as it is increased from 336 rpm, more of the nickel salt will be thrown from the rotor. Optimum separation of the iron and nickel salts should therefore occur at a speed midway between these two speeds, i.e., at 411 rpm. Similarly, optimum separation of the nickel and copper salts should occur at 258 rpm.

The mixture was separated at 0.9 amp and 411 rpm into an iron and a nickel-copper product, using a cleaning process consisting of 9 cycles, each of 3 stages. The arrangement of cycles and stages is shown in Figure 5. The same arrangement is referred to subsequently in this report, and it should be noted that, however many cycles were used, the L or R fractions remaining after the last cycle were always added to the L or R products respectively. The nickel-copper product was separated at 0.9 amp and 258 rpm into a nickel and a copper product, using 7 cleaning cycles. The final products were examined under the microscope. The ferrous ammonium sulphate fraction was of high purity; it was virtually free from copper and contained only an occasional crystal of nickel sulphate. The nickel sulphate fraction contained some iron and very little copper. No iron was detected in the copper sulphate fraction, which however contained a small amount of nickel sulphate. The percentage composition of the separated fractions was estimated to be approximately as follows:

Fraction	Ferrous Ammonium Sulphate	Nickel Sulphate	Copper Sulphate
1	100	-	-
2	5	95	-
3	-	4	96

8. DETERMINATION OF THE FIELD CHARACTERISTIC OF THE SEPARATOR

The field characteristic may be calculated from equation (5) as follows:

$$H \frac{dH}{ds} = \frac{4 \Pi^2 n^2 r}{\chi} = \frac{122.2\ n^2}{\chi} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

and should be a constant for a given coil current and gap setting. Values of 122.2 n^2/χ have been calculated from corresponding values of n and χ taken from the calibration curves (Figure 3 – it should be noted that n is the critical speed in revolutions per second). These values, though not constant for a given current, appear to approach a constant value as the rotor speed increases. The maximum deviations occur at low speeds, and in the range 300 to 550 rmp all the values lie within 3 per cent of the mean value, which is very close to the value at 400 rpm. As an example, the values at 0.8 amp may be quoted:

rpm	122.2 n^2/χ
200	1.94×10^8
250	2.04×10^8
300	2.14×10^8
350	2.19×10^8
400	2.20×10^8
450	2.21×10^8
500	2.21×10^8

The values of the field characteristic given in Table 6 have been calculated from (7) for a critical speed of 400 rpm. Below 0.6 amp, the calibration curves of Figure 3 do not extend to 400 rpm, and the values given in the table for 0.3, 0.4 and 0.5 amp have been obtained by graphical extrapolation to 400 rpm. The field strength is also shown in Table 6. This was measured directly by inserting the probe of a gaussmeter into the gap. The field was explored as far as possible with the probe, and the maximum reading observed is given in the table. The field gradient may be calculated by dividing the field characteristic by the field strength, and this is also shown in Table 6.

TABLE 6: MAGNETIC FIELD OF LABORATORY SEPARATOR

Magnet Current amp	Field Strength H gauss	Field Gradient $\frac{dH}{ds}$	Field Characteristic $H \frac{dH}{ds}$
0.3	3900	1.69×10^4	0.66×10^8
0.4	4700	2.00×10^4	0.94×10^8
0.5	5400	2.31×10^4	1.25×10^8
0.6	6000	2.67×10^4	1.60×10^8
0.7	6600	2.89×10^4	1.91×10^8
0.8	7000	3.14×10^4	2.20×10^8
0.9	7350	3.32×10^4	2.44×10^8
1.0	7600	3.45×10^4	2.62×10^8
1.1	7750	3.51×10^4	2.72×10^8
1.2	7800	3.65×10^4	2.85×10^8

9. EXAMINATION OF IRON ORE SAMPLES

The bulk susceptibility of the iron ore samples was determined by the method described in Section 6.4, using the minus 36- plus 52-mesh fraction. The results are shown in Table 7.

Susceptibility values above 40×10^{-6} cgs units were obtained by extrapolation, since they lie above the calibrated range of the instrument, and are less accurate than values below 40×10^{-6}. More accurate values could be obtained by calibration of the instrument with compounds such as $CoSO_4$, $CoSO_4 . H_2O$, $Fe_2(SO_4)_3$, $MnSO_4$, NiO, CoO, MnO, Mn_3O_4 and Mn_2O_3, which would enable the range to be extended to about 90×10^{-6}. These compounds however would probably have to be prepared specially for the purpose, since they are less readily available in a pure form than the compounds listed in Section 6.1. The susceptibilities of samples 6 and 11 were far too high to be measured by the method described in Section 6.4, and the values shown in Table 7 are those obtained by the Geophysical Laboratories of the Department of Mines from susceptibility bridge balance measurements, using plus 10- minus 16-mesh material.

The results given in Table 7 enable the samples to be classified as follows:

a. Sample 4 (Nairne Pyrite). The susceptibility of this lay far below the calibration curves prepared for the instrument. It is certainly less than 5×10^{-6}, and probably less than 0.5×10^{-6}. At 1.2 amp and the lowest rotor speeds (14-175 rpm) the L:R ratio was less than 0.1, i.e., less than 10 per cent of the sample could be obtained in the L or magnetic fraction at the highest intensity and lowest rotor speed available. Useful beneficiation of this sample by magnetic means is therefore impossible with field characteristics of the order shown in Table 6.

b. Samples 1 and 2. Dolomite-calcite mixtures containing goethite, of low susceptibility and low iron content.

c. Samples 5 (pyrrhotite), 9 (limonite) and 14 (goethite) These have moderate susceptibility and high iron content. The iron content is close to the theoretical value for the pure mineral, so that the question of beneficiating these samples does not arise.

d. Sample 3 (siderite) and the hematite samples 7, 8, 10, 12 and 13. These have high susceptibility and high iron content. Here again the iron content is close to the theoretical value for the pure mineral.

e. Samples 6 (altered magnetite) and 11 (manganiferous hematite). These are ferromagnetic and their separation from gangue minerals in low intensity separators would present no difficulty, provided the iron mineral were liberated at a suitable particle size.

TABLE 7: BULK SPECIFIC SUSCEPTIBILITY OF IRON ORE SAMPLES

Sample No.	Brief Description	% Fe	Bulk Specific Susceptibility x 10^6 (cgs units)
1	Dolomite-calcite	16.7	8.5
2	Dolomite-calcite	11.3	8.1
3	Siderite	45.5	75
4	Pyrite	9.65	< 5
5	Pyrrhotite	59.8	32.6
6	Altered magnetite	64.9	3,300(a)
7	Micaceous hematite	62.8	76
8	Soft hematite	69.2	91
9	Hard limonite	58.1	25.3
10	Hard hematite	68.8	77
11	Hard manganiferous hematite	54.1	24,600(a)
12	Blue foundry ore	69.0	75
13	Red basic (low Mn) ore	67.8	100
14	Goethite	58.4	27.6

(a) Results from Geophysical Laboratories, Department of Mines.

10. BENEFICIATION AND SEPARATION OF SAMPLES

It has been shown in Section 9 that of the 14 samples only 3, No. 1, 2 and 4 require beneficiation, and that beneficiation of No. 4 (pyrite) is not possible with the inducted-rotor separator used. Beneficiation experiments were therefore confined to Samples 1 and 2 (carbonate minerals containing goethite).

Separation from gangue was studied by taking Samples 3, 12 and 13 to represent minerals of high susceptibility, Samples 5 and 9 to represent minerals of medium susceptibility, and Sample 1 to represent minerals of low susceptibility. The ferromagnetic minerals No. 6 and 11 were not further investigated.

10.1 Beneficiation of Sample 2

The sample (minus 36- plus 52-mesh) was separated into 2 equal portions (L_1 and R_1) using the induced-rotor separator at 0.9 amp and 227 rpm, the critical rotor speed being determined from the bulk susceptibility by means of Figure 3. The bulk susceptibility of each portion was then determined, and the more magnetic portion (L_1) was separated at 0.9 amp into 2 equal portions (L_2 and R_2), the rotor speed required for this having already been found in the susceptibility determination. The process was repeated 3 more times. Each fraction was analysed for iron content and the results are shown in Table 8.

TABLE 8: SEPARATION OF SAMPLE 2 AT 0.9 AMP

Fraction	Critical Rotor Speed rpm	$\chi \times 10^6$	Weight %	Iron %
R1	175	5.7	50	10.3
R2	228	8.2	25	11.2
R3	300	12.8	12.5	14.2
R4	328	15.2	6.25	16.8
L1	287	11.8	50	14.9
L2	324	14.8	25	16.3
L3	353	17.5	12.5	24.2
L4	380	20.2	6.25	28.2

The critical rotor speed shown in the table for each left fraction is of course the speed at which that fraction was separated into the next 2 fractions. Thus fraction L1 was separated at 287 rpm to give L2 and

R2, L2 was separated at 324 rpm into L3 and R3, etc. An indication of the accuracy of the results is given by averaging the susceptibility values for corresponding L and R fractions and comparing the results with the value for the L fraction from which they were derived. Thus, the average for L4 and R4 is 17.2 x 10^6, to be compared with 17.5 x 10^6 for L3.

By this process, a product containing 28.2 per cent Fe was obtained, but the recovery of iron in this product was only about 16 per cent. In an attempt to improve the recovery of iron, the first right hand fraction (R1), containing 50 per cent of the original sample, was treated at 0.9 amp and 227 rpm in a 24 stage process, in which left and right hand fractions were successively combined and recleaned, to yield finally 2 fractions as follows:

Fraction	χ x 10^6	Weight, g	% Fe
Right	4.3	300	10.0
Left	10.0	94	12.5

A weighted average of these results gives for the original fraction

$$\chi = 5.7 \times 10^{-6},\ \mathrm{Fe} = 10.6 \text{ per cent}$$

(compare the results for R1 in Table 8, 5.7 x 10^{-6} and 10.3 per cent).

Let us suppose that the sample consists essentially of 2 fractions having the following characteristics:

% Fe	χ x 10^6	Critical Rotor Speed at 0.9 amp
10.0	4.3	148
28.2	20.2	380

Optimum separation of such a mixture at 0.9 amp should take place at a rotor speed of 264 rpm. The sample (-36 +52-mesh) was separated under these conditions using an 8 cycle process (see Figure 5). The final products had the following characteristics:

Fraction	χ x 10^6	Weight, g	% Fe
Right	5.5	203	10.1
Left	14.6	103	17.1

These figures represent an iron recovery of 46 per cent in a grade of 17.1 per cent.

This result is very different from that which should be obtained for the separation of 2 fractions of susceptibility 4.3 x 10^{-6} and 20.2 x 10^{-6} (cf 7). The supposition that the sample consists of 2 such fractions is therefore false. Rather, the experimental results indicate that the particles cover a wide spectrum of susceptibilities (and hence of composition), so that no cut, however sharp, can give a satisfactory grade and recovery. To obtain a useful grade it would be necessary to make a cut near the upper limit of the susceptibility spectrum, and this would necessarily entail a very low recovery.

Since finer grinding might produce a product in which the particles were more sharply differentiated in respect of susceptibility, the experiment described above was repeated with a sample sized to minus 72- plus 100-mesh (iron content 11.6%). The object proposed was to separate the sample into 2 fractions having susceptibilities of 5×10^{-6} and 20×10^{-6}. The mean particle size for minus 72- plus 100-mesh material is 181 microns and from Figure 4 the apparent susceptibility values at 181 microns corresponding to actual values at 358 microns (minus 36- plus 52-mesh) of 5×10^{-6} and 20×10^{-6} are 8.4×10^{-6} and 26.2×10^{-6}. From Figure 3 the critical rotor speeds at 0.9 amp for susceptibilities of 8.4×10^{-6} and 26.2×10^{-6} are 234 and 435 rpm respectively. The average of these values is 335 rpm, so that for minus 72- plus 100-mesh material optimum separation into the postulated fractions at 0.9 amp should occur at a rotor speed of 335 rpm, and the sample was therefore treated under these conditions in an 8 cycle process with the following results:

Fraction	$\chi \times 10^6$	Weight, g	% Fe
Right	5.2	147	10.0
Left	13.5	112	16.0

These figures represent an iron recovery of 55 per cent in a grade of 16 per cent. This result is no better than that achieved before with minus 36- plus 52-mesh material, and it is evident that Sample 2 cannot be usefully beneficiated by magnetic separation, at least at particle sizes above 100-mesh.

10.2 Beneficiation of Sample 1

The sample, sized to minus 36- plus 52-mesh, was split into 2 equal portions (L1 and R1) at 0.9 amp and 235 rpm. The more magnetic fraction (L1) was then split at the same amperage and the appropriate rotor speed into 2 equal fractions, and the process was repeated 4 more times, as described in 10.1 for Sample 2. The results are shown in Table 9.

These results are similar to those obtained with Sample 2. The sample can be divided into a series of fractions of increasing susceptibility; the fraction with the highest susceptibility contained 32 per cent of iron, but the recovery of iron in this fraction was only 6 per cent. The same conclusion may be drawn for Sample 1 as for Sample 2; there is no point at which a cut can be made to give an iron product of high grade and reasonable recovery. This conclusion was confirmed by a subsequent mineralogical examination (see Appendix), which showed that the samples, originally thought to be siderite, were mixtures of dolomite and calcite, the grains of which were coated with goethite. The composition and susceptibility of each particle will therefore depend on the size of the particle and the thickness of the goethite coating, and this accounts for the wide susceptibility spectrum.

TABLE 9: SEPARATION OF SAMPLE 1 AT 0.9 AMP

Fraction	Critical Rotor Speed rpm	$\chi \times 10^6$	Weight %	Iron %
R1	178	5.8	50	13.5
R2	252	9.5	25	18.5
R3	298	12.7	12.5	21.8
R4	344	16.5	6.25	25.3
R5	381	20.2	3.12	28.2
L1	280	11.3	50	21.6
L2	333	15.6	25	25.4
L3	375	19.6	12.5	27.5
L4	408	23.2	6.25	29.7
L5	436	26.3	3.12	31.9

10.3 Separation from Gangue

10.3.1 Minerals of High Susceptibility

Samples 3, 12 and 13, sized to minis 36- plus 52-mesh, were mixed with equal weights of acid-washed silica sand, also sized to minus 36- plus 52-mesh. The mixtures were separated at 0.5 amp and a rotor speed equal to half the critical speed for the unmixed iron sample (pure silica has a susceptibility of minus 0.493×10^{-6}). Separation was made in a number of 3-stage cycles (see Figure 5). The quantity of material left after the second cycle was small, and after the third cycle very small, so that 2 cycles would probably have given much the same results. The results are given in Table 10.

Sample 3 was mixed with an equal weight of Sample 2, both samples being sized to minus 36- plus 52-mesh. Sample 2 was selected as an example of a paramagnetic gangue of low susceptibility. At 0.5 amp the critical rotor speed for Sample 2 is 145 rpm and for Sample 3 548 rpm. The mixture was therefore separated at a point midway between these speeds, i.e. at 346 rpm. In the first test 9 cycles were used, but the quantity of mixture remaining after the 4th cycle was very small. The experiment was then repeated without any cleaning at all, i.e., only one division of the mixture into L and R fractions was made. The results are given in Table 10.

The results given in Table 10 show that material having susceptibility of the order $50\text{-}100 \times 10^{-6}$ can easily be separated from siliceous gangue or other material of low susceptibility (say less than 10×10^{-6}), provided of course that the iron mineral is liberated at a convenient particle size.

TABLE 10: SEPARATION OF 1:1 MIXTURES
Samples 3, 12 and 13

Mixture	Head Assay of Components % Fe		Separation		Number of Cleaning Cycles	Weight, %		Iron, %		Iron Recovery %
			amp	rpm		Tail	Conc	Tail	Conc	
No. 3+sand	No. 3	45.5	0.5	270	5	51.6	48.4	-	43.9	93.4
No. 12+ sand	No. 12	69.0	0.5	270	5	50.7	49.3	-	68.5	97.9
No. 13+ sand	No. 13	67.8	0.5	300	5	52.0	48.0	-	67.7	95.9
No. 2+ No. 3	No. 2 No. 3	11.3 45.5	0.5	346	9	50.6	49.4	12.6	43.6	94.7(a)
No. 2+ No. 3	No. 2 No. 3	11.3 45.5	0.5	346	0	54.7	45.3	14.8	43.2	86.0(a)

(a) These figures represent the ratio, expressed as a percentage, of the iron recovered in the magnetic fraction to the iron that would have been recovered if the separation had been perfect.

10.3.2 Minerals of Medium and Low Susceptibility

Samples 1, 5 and 9, sized to minus 36- plus 52-mesh, were mixed with equal weights of acid-washed silica sand sized to the same limits. The mixtures were separated under the conditions and with the results shown in Table 11.

Equal weights of Samples 4 and 5 (pyrite and pyrrhotite), each sized to minus 36- plus 52-mesh, were also mixed and separated as indicated in Table 11.

The results in Table 11 show that material having a magnetic susceptibility as low as 8×10^{-6} may be readily separated from siliceous gangue or other material of similar susceptibility, and the conclusions reached for the separation of material in the susceptibility range $50\text{-}100 \times 10^{-6}$ are valid for values down to 8×10^{-6}. The clean separations achieved indicate that the limit has not been reached, and effective separation can probably be achieved for any value above 5×10^{-6}.

TABLE 11: SEPARATION OF 1:1 MIXTURES
Samples 1, 5 and 9

Mixture	Head Assay of Components % Fe		Separation		Number of Cleaning Cycles	Weight, %		Iron, %		Iron Recovery %
			amp	rpm		Tail	Conc	Tail	Conc	
No. 1 + sand	No. 1	16.7	1.05	122	1	49.2	50.8	-	15.9	96.7
No. 1 + sand	No. 1	16.7	1.1	122	1	48.4	51.6	-	16.2	100
No. 5 + sand	No. 5	59.8	0.5	170	1	49.2	50.8	-	58.4	99.2
No. 5 + sand	No. 5	59.8	0.5	170	2	50.7	49.3	-	59.7	98.4
No. 9 + sand	No. 9	58.1	0.5	145	3	49.5	50.5	-	57.0	99.1
No. 4 + No. 5	No. 4 No. 5	9.65 59.8	0.5	170	3	48.9	51.1	11.7	57.7	98.6[(a)]

(a) These figures represent the ratio, expressed as a percentage, of the iron recovered in the magnetic fraction to the iron that would have been recovered if the separation had been perfect.

11. PRACTICAL APPLICATION OF SUSCEPTIBILITY MEASUREMENTS

Runolinna[1] describes an induced rotor magnetic separator with a field strength of 900 gauss, a field gradient of 50 gauss per mm and a radius of rotor of 20 cm. This separator will be distinguished as "Runolinna's machine". Palasvirta[2] discusses the design of high-intensity induced rotor separators and illustrates such a separator used by him. Details of the separator used are not given, but he seems to contemplate a 4 inch diameter rotor, an average field strength in the separation gap of 20,000 gauss and a field gradient of 5000 gauss per cm. A separator having these characteristics will therefore be referred to a "Palasvirta's machine".

Suppose that the following minerals can be liberated from gangue by grinding:

Sample No.	Mineral	$\chi \times 10^6$
14	Goethite	27.6
3	Siderite	75
6	Altered magnetite	3,300
11	Manganiferous hematite	24,600

The question to be determined is whether these minerals can be effectively separated from the gangue in either of the above separators.

For Runolinna's machine

$$\frac{H}{4\pi^2 r} \quad \frac{dH}{ds} = \frac{900 \times 500}{4 \times 9.87 \times 20} = 570,$$

and for Palasvirta's,

$$\frac{H}{4\pi^2 r} \quad \frac{dH}{ds} = \frac{20,000 \times 5000}{4 \times 9.87 \times 5.08} = 4.99 \times 10^5.$$

The critical rotor speed for each mineral may be calculated from these values by means of equation (6). The results, expressed in revolutions per minute, are:

Sample	Critical Rotor Speed, rpm	
	Runolinna's machine	Palasvirta's machine
Goethite	7.5	223
Siderite	12.4	367
Altered magnetite	82.3	2440
Manganiferous hematite	225	6650

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[1] "Progress in Mineral Dressing", Almqvist and Wiksell, Stockholm, p 255, (1958).

[2] Mining Engineering II, 1244 (1959).

These results show that the goethite and siderite samples could be separated by Palasvirta's machine, but not by Runolinna's. The very low speeds indicated for the latter are quite impracticable, and at such speeds the principles of separation do not apply: very little separation takes place, since frictional forces and the interaction of the particles on one another, factors neglected in the theoretical treatment, become of major importance. Even if separation were possible at such speeds, it would still not be practicable, since the capacity of a dry magnetic separator is, as Runolinna observes, directly proportional to the peripheral speed of the rotor.

The manganiferous hematite could be separated with Runolinna's machine, but neither machine is suitable for treating the altered magnetite. The low speed indicated for this sample in Runolinna's machine is probably too small for effective separation - and it must be remembered that for effective separation the rotor speed must be below the critical speed. The very high critical speed indicated for Palasvirta's machine shows that this sample is much too strongly magnetic for treatment in a separator of such high intensity, and this applies with even greater force to the manganiferous hematite. The attempt to treat such samples would result in clogging of the high intensity gap by bridging of the sample.

To sum up, the goethite and siderite could be separated in Palasvirta's machine, the manganiferous hematite in Runolinna's, and the altered magnetite in neither. For separation of the altered magnetite, the field characteristic of Runolinna's machine would have to be increased, and that of Palasvirta's diminished.

It should be noted that the performance of a magnetic separator is determined by the field characteristic, not the field strength. The field characteristic of Runolinna's machine is 4.5×10^5, and of Palasvirta's 1.0×10^8. Comparison of these figures with those given in Table 6 shows that, although Palasvirta's machine has a much greater field strength than the laboratory separator, the laboratory separator has a higher field characteristic, and is thus a machine of higher intensity.

12. CONCLUSIONS

Minerals having a magnetic susceptibility greater than 5×10^{-6} cgs units may be separated from siliceous gangue or other diamagnetic material, provided that the feed is suitably sized and the mineral is free.

The type of magnetic separator to be used may be determined from the magnetic susceptibility of the mineral to be separated and the particle size to which the ore must be ground to liberate the mineral.

Examination of ores to assess the possibility of magnetic recovery of minerals should take the following form:

a. Mineralogical examination to determine the particle size for liberation.

b. Grinding of the ore to the required size and determination of the bulk susceptibility of the ground material.

c. Separation of the ore into fractions, based on the susceptibility found in (b), and determination of the susceptibility of the fractions.

d. Assay of the fractions obtained in (c).

e. Application of the data obtained in (c) and (d) to determine the separator characteristics necessary to effect optimum separation.

13. RECOMMENDATIONS

The following recommendations for further work are made:

1. Extension of the upper limit of the calibration range of the instrument from about 35×10^{-6} to about 100×10^{-6} by the use of standard compounds such as those mentioned in Section 9.

2. Improvement of the accuracy of susceptibility measurements by modifications of the Carpco instrument as follows:

   a. addition of a vibratory feeder to give a more regular feed supply and to permit the use of smaller particle sizes,

   b. elimination of draughts by enclosing the rotor in perspex,

   c. incorporation of a revolution counter.

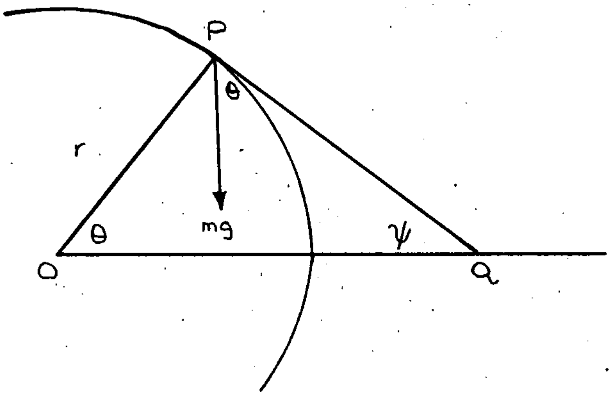
3. Determination of the field characteristics of other laboratory magnetic separators, so that their potentialities can be accurately assessed.

4. Investigation by the method outlined in Section 12 of ores that appear to have reserves of industrial value. Most of the samples tested were of high iron content, approaching the composition of pure minerals, and so offered less scope for the investigation of separation technique than ores of lower grade.

5. Test of the efficacy of the method by combining the results of (3) and (4), that is, by selecting one of the larger laboratory separators characterised under (3) for the separation of natural ores examined under (4), and comparing the predicted with the actual results.

FIGURE 1

TO ILLUSTRATE THE DYNAMICS OF A PARTICLE ON THE ROTOR SURFACE



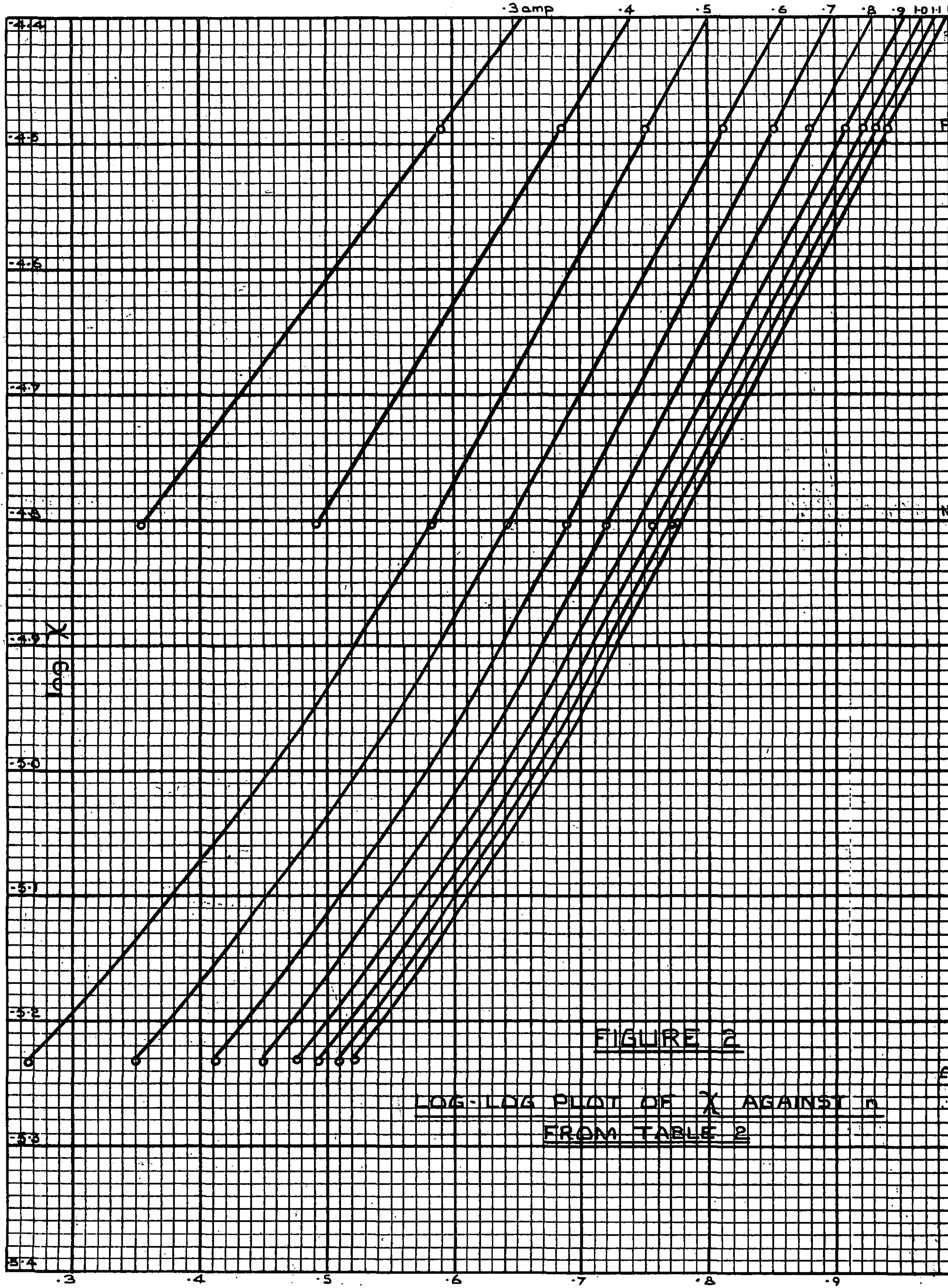


FIGURE 2

LOG-LOG PLOT OF λ AGAINST n FROM TABLE 2

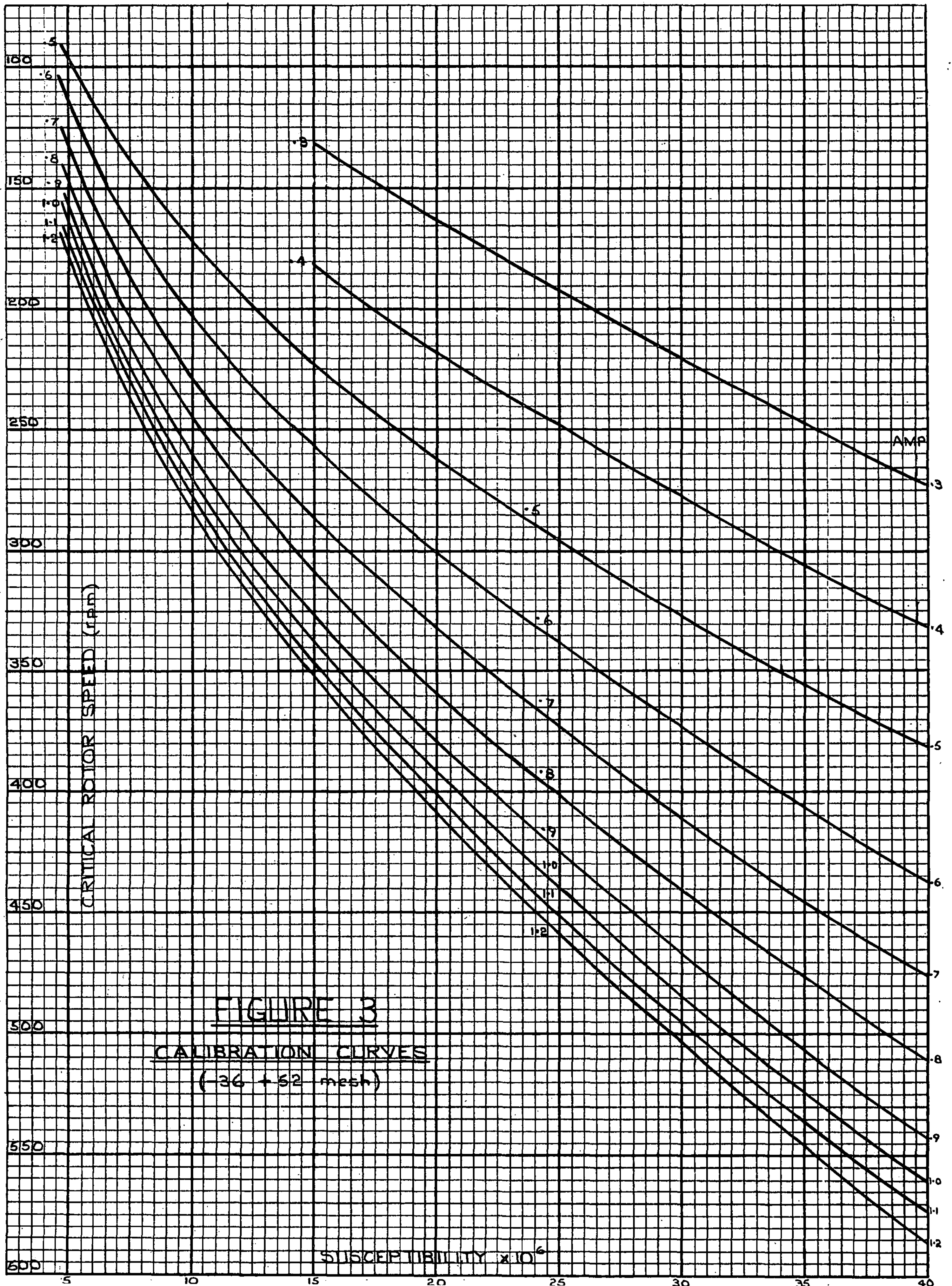


FIGURE 3

CALIBRATION CURVES

(-36 +52 mesh)

FIGURE 4

CORRECTION FOR PARTICLE SIZE

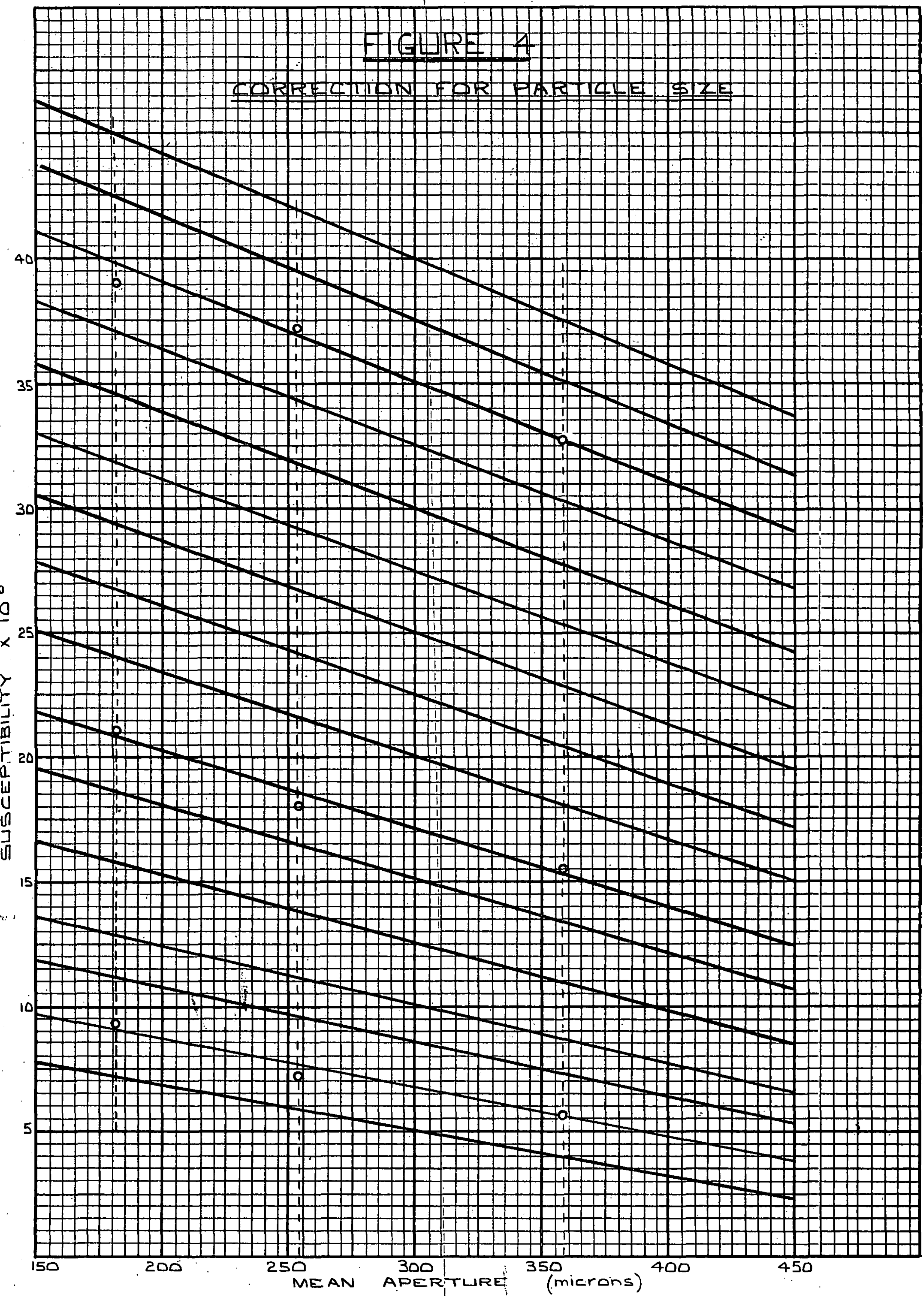
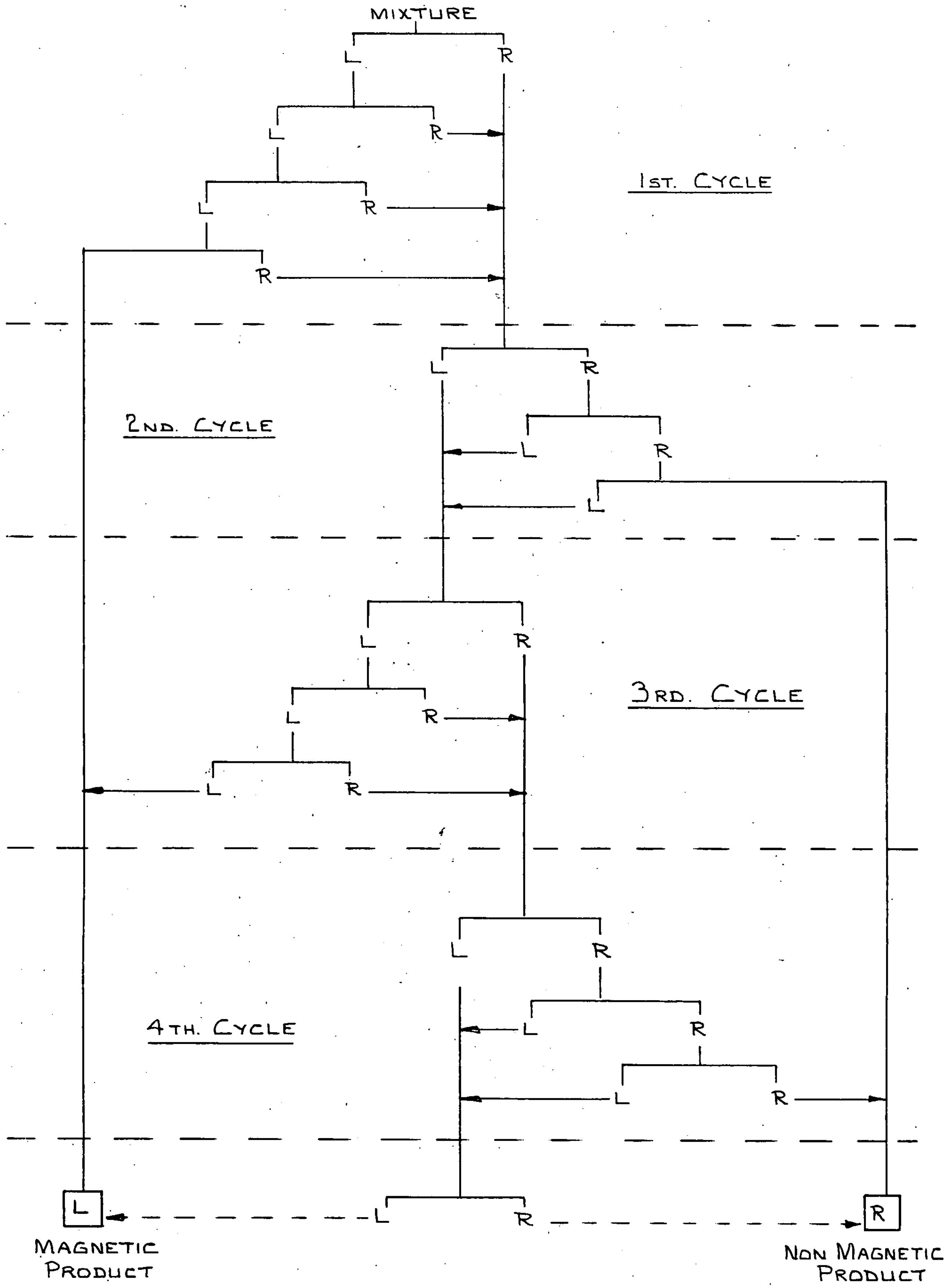


FIGURE 5

FLOW SHEET SHOWING CLEANING CYCLES AND STAGES



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APPENDIX

MINERALOGICAL REPORT ON SAMPLES 1, 2, AND 3

Sample 1

The grains are heavily coated with goethite, so that they are impossible to examine optically. However, x-ray diffraction shows that dolomite and calcite are present in approximately equal amounts; the quantity of $FeCO_3$ molecule present in these minerals would probably be too small to account for the goethite coatings. Some quartz is also present.

Sample 2

This sample is not as dark as the others, and goethite coatings on the grains are less pronounced. X-ray diffractographs show dolomite and subordinate calcite.

Sample 3

The grains are very heavily coated with goethite. X-ray diffractographs show that this sample consists mainly of siderite.

Investigation and Report by: H. W. Fander

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