

DISCUSSION OF THIS PAPER IS INVITED. It should preferably be presented by the contributor in person at the New York Meeting, February 1943, when an abstract of the paper will be read. If this is impossible, discussion in writing (2 copies) may be sent to the Secretary, American Institute of Mining and Metallurgical Engineers, 29 West 39th Street, New York, N. Y. Unless special arrangement is made, discussion of this paper will close April 1, 1943. Any discussion offered thereafter should preferably be in the form of a new paper.

## Magnetic Separation of Sulphide Minerals

By A. M. GAUDIN,\* MEMBER, AND H. RUSH SPEDDEN,† JUNIOR MEMBER A.I.M.E.

(New York Meeting, February 1943)

ALTHOUGH the number of minerals that are ferromagnetic‡ or highly paramagnetic is strictly limited, it has been known for some time that many minerals have slight but supposedly characteristic magnetic susceptibilities. With the exception of pyrrhotite, however, sulphides have been thought nonmagnetic.

A new magnetic separator has been made available recently in limited quantity to research laboratories. This device, the Frantz Isodynamic Separator, has been used for the separation of various non-sulphides from each other. Its application to the separation of sulphides, however, does not seem to have been reported.

In the Richards Mineral Dressing laboratories, the success achieved through the use of this device in separating associated sulphides has been so startling as to lead us to believe that it constitutes a magnificent adjunct to heavy-liquid separation and to quantitative mineragraphy as a tool for the mineral investigator.

---

Manuscript received at the office of the Institute Aug. 25, 1942.

\* Richards Professor of Mineral Dressing, Massachusetts Institute of Technology, Cambridge, Mass.

† Instructor in Mineral Dressing, Massachusetts Institute of Technology.

‡ A *paramagnetic* substance is one that, when placed in a magnetic field, becomes magnetized in the same direction as the field, and in proportion to it.

A *diamagnetic* substance, on the contrary, becomes magnetized in a direction opposed to that of the field but in proportion to it.

A *ferromagnetic* substance resembles a paramagnetic substance, except that it is magnetized much more strongly, and not in proportion to the field. For strong fields the susceptibility decreases with increasing field; in other words, saturation takes place.

### THE SEPARATOR

The separator (Fig. 1) consists of:

1. A powerful magnet, the strength of which can be adjusted by means of a rheostat;
2. A vibrating chute of nonmagnetic metal on which the mineral to be separated is made to flow (Fig. 2);
3. A feed bin and adjustable feeder;
4. Receptacles for the collection of products;
5. Means for changing, setting, and accurately reading the two slopes of the chute; viz., the cross slope and longitudinal slope.

The separator is made operative by the special shape of its pole pieces, which ensures a strongly converging field. It is said by the makers of the machine that the pole pieces apply a constant mechanical force to a particle of given susceptibility, regardless of its position in the operating space of the separators.\* Susceptible particles, therefore, behave as though of lower specific gravity than under ordinary circumstances. This effect, combined with the slopes of the chute and the action of the vibrator, causes a stratification not unlike that obtainable on a shaking table.

The chute is of rectangular cross section, and shallow; it is broadened toward the discharge end and divided longitudinally by a partition into two compartments that lead to the collecting receptacles.

Although the separator probably can be used to make separations at fairly coarse

---

\* A description of the separator is given in the Appendix, page 12.

sizes, we have used it only in the size range from 35 mesh to 600 mesh and particularly from 100 to 400 mesh.

Ferromagnetic minerals are somewhat

represent the type of mineral associations on which the separator could be employed to advantage. A series of mill products was available in the laboratory, collected in

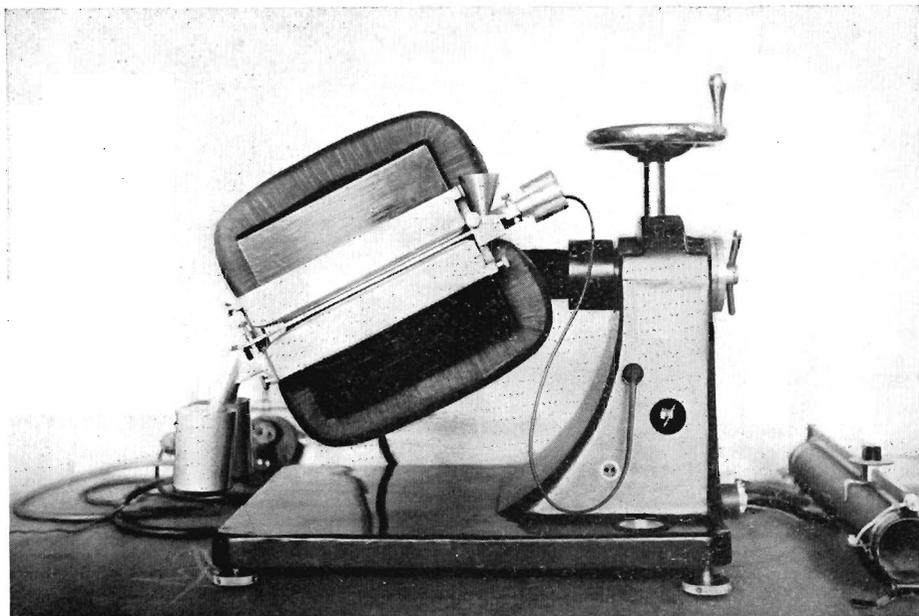


FIG. 1.—FRANTZ ISODYNAMIC SEPARATOR.

troublesome in that they "hang up" in the separator instead of flowing out into the compartment designed to receive the more magnetic fraction. It is desirable, therefore, first to remove metallic iron, magnetite, franklinite, and perhaps pyrrhotite, by means of a hand magnet.

Control of the path taken by any one mineral is obtained by varying the intensity of the current in the separator and the cross slope of the chute. Variations in the longitudinal slope are required essentially in relation to the sizes of the particles, a steeper slope being useful for finer particles.

#### MATERIALS STUDIED

For this study it was deemed desirable to utilize actual mill products, since they

1939-1940 by a number of leading metallurgists. Our thanks go out to them for their hearty cooperation.

The samples were taken wet and shipped to the laboratory under water in glass jars. When received, the sample bottles were sealed with melted paraffin, to keep oxidation to a minimum. Two years later the concentrates and tailings were still in satisfactory condition and showed no visible sign of change during storage.

The samples were wet-and-dry screened, dispersing agents being added if necessary to ensure sparkingly clean grains. Drying of the wet-screened products was done in a low-temperature oven (*ca.* 75°C.) to prevent oxidation and the corresponding possible change in magnetic properties.

## SEPARATOR PRACTICE

A sample of some 3 to 5 grams of granular material is passed through the separator at very low intensity. The ammeter attached to the magnet allows readings to the nearest 0.02 amp., from 0.00 amp. to about 1.45 amp. The first separation at 0.10 amp. and a cross slope of  $10^{\circ}$  to  $15^{\circ}$  gives a preliminary indication as to the presence or absence of ferromagnetic particles. The latter adhere to the upper magnet pole; they must be brushed aside with the magnetizing current off and the vibrator on, by working a few bristles from an ordinary paint brush in the clearance between the chute and the upper pole.

Later, higher intensities, and eventually lower cross slopes, are employed to crudely fractionate the sample into a number of products, which are examined under the binocular microscope to get a general idea of what is being accomplished. From this preliminary fractionation it is then possible to pass to an accurate fractionation producing a limited number of cuts at carefully chosen magnet intensities and chute slopes.

For a quick appraisal of the separation made in the machine, a binocular microscope is helpful; indeed, it might well be said that the separator and the binocular are a team. But the binocular can give only a crude estimate of what the separator is doing; it is worthless in regard to locked particles, and even in regard to the determination of free particles of many minerals.

To assess accurately the Frantz separator, briquettes were prepared of many separated fractions. For convenience in referring from one fraction to another, and for economy in polishing, several small briquettes were mounted together, by a second briquetting operation, to form one large briquette.

All polishing was done on the Graton-Vanderwilt machine and the quantitative mineragraphic technique followed was that

described in "Flotation" and in "Principles of Mineral Dressing."

The results of our study are presented under three headings: copper-flotation

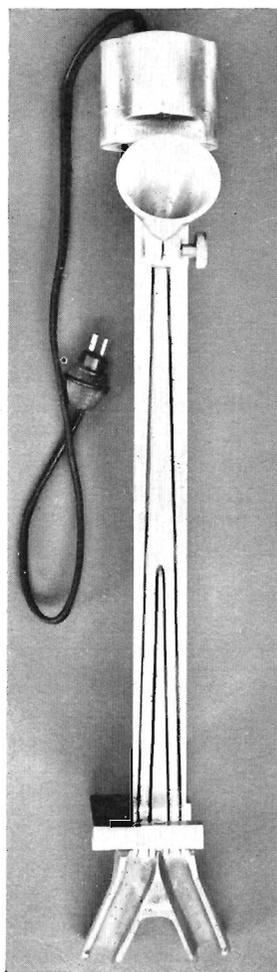


FIG. 2.—VIBRATING CHUTE.

plants, lead-zinc-flotation plants, silver-flotation plants. These data are necessarily incomplete and extremely condensed. Their main purpose is not only to substantiate the statement that the Frantz separator is particularly useful, but also to outline the qualitative scale of magnetic susceptibility of common sulphide minerals, as well as the

range of variation in susceptibility demonstrated by the various sulphides.

### COPPER-FLOTATION PLANTS

#### *Macuchi, Ecuador*

At the mill of the Cotopaxi Exploration Co., Macuchi, Ecuador, the principal minerals are chalcopyrite, pyrite, barite, and quartz. The ore contains considerable gold, which occurs largely, if not wholly, as the native metal, the characteristic occurrence being at the chalcopyrite-pyrite grain boundary. Minor constituents are bornite, sphalerite, and chalcocite.

The 200 to 270-mesh fraction of the flotation concentrate was fractionated with a cross slope of  $10^\circ$  and a longitudinal slope of  $20^\circ$  at the following intensities: 0.50 amp., 0.90 amp., and 1.40 amp. This gave four fractions, in order of decreasing magnetic response A, B, C, D. Table 1 shows the composition of the various products, as determined by quantitative mineralography.

TABLE 1.—*Fractionation of the Macuchi Concentrate*  
(200 TO 270-MESH)

Mineral	Mineralogical Assay of Each Fraction, Per Cent by Weight			
	A Mag- netic at 0.5 Amp.	B Mag- netic at 0.5 to 0.9 Amp.	C Mag- netic at 0.9 to 1.4 Amp.	D Non- mag- netic at 1.4 Amp.
Bornite.....	28.1	2.2	2.1	0.4
Chalcocite.....	3.0	0.2	1.6	0.7
Chalcopyrite.....	40.9	92.5	55.1	7.2
Sphalerite.....	4.8	1.3	5.2	4.4
Pyrite.....	6.5	2.7	26.1	81.2
Gangue.....	16.7	1.2	9.9	6.1

In Table 2, the data of Table 1 are rearranged and expressed in terms of the free or locked character of the various particles. This table brings out that there is no free pyrite in fractions A, B or C, no free chalcopyrite in fraction D, and virtually no free particles of any kind in fraction C.

Gold was seen only in sections of products C and D, but the number of particles

counted was too small to provide statistical grounds for estimating its behavior in the separator. Since no free bornite, chalcocite, or sphalerite was seen in any product, and

TABLE 2.—*Fractionation of Macuchi Concentrate*

Mineral	Mineralogical Assay of Each Fraction, Per Cent by Weight			
	A Mag- netic at 0.5 Amp.	B Mag- netic at 0.5 to 0.9 Amp.	C Mag- netic at 0.9 to 1.4 Amp.	D Non- mag- netic at 1.4 Amp.
Free particles:				
Bornite.....	0	0	0	0
Chalcocite.....	0	0	0	0
Chalcopyrite.....	13.6	68.6	0.5	0
Sphalerite.....	0	0	0	0
Pyrite.....	0	0	0	32.9
Gangue.....	3.6	0	0.4	0.4
Locked particles.....	82.8	31.4	99.1	66.7

since "gangue" is a collective term, these data provide little information concerning these minerals. On the contrary, a clear-cut separation of chalcopyrite was obtained, with a tendency for bornite to respond to a weaker field than chalcopyrite.

#### *New Cornelia, Arizona*

The 270 to 400-mesh fraction of the concentrate from the New Cornelia mill was fractionated at 0.6, at 0.85, and at 1.4 amp., and the fractions were briquetted and counted with the results shown in Table 3.

TABLE 3.—*Fractionation of New Cornelia Concentrate*  
(270 TO 400-MESH)

Mineral	Mineralogical Assay of Each Fraction, Per Cent by Weight			
	A Most Mag- netic	B	C	D Least Mag- netic
Bornite.....	17.9	9.3	1.0	0.1
Chalcopyrite.....	61.0	75.5	18.1	3.5
Pyrite.....	2.9	4.2	34.9	53.3
Gray sulphides <sup>a</sup> .....	8.0	0.8	3.2	2.2
Gangue.....	10.2	10.2	42.8	40.9

<sup>a</sup> Chalcocite, tetrahedrite, tennantite, enargite, molybdenite, sphalerite.

Table 3 shows that bornite is more susceptible than chalcopyrite, and the latter than pyrite, thus confirming the observations made on the Macuchi prod-

with tetrabromomethane (sp. gr. 2.96) to remove the gangue. The sediment was fractionated magnetically at 0.77 amp., 0.92 amp. and 1.0 amp., all with a cross

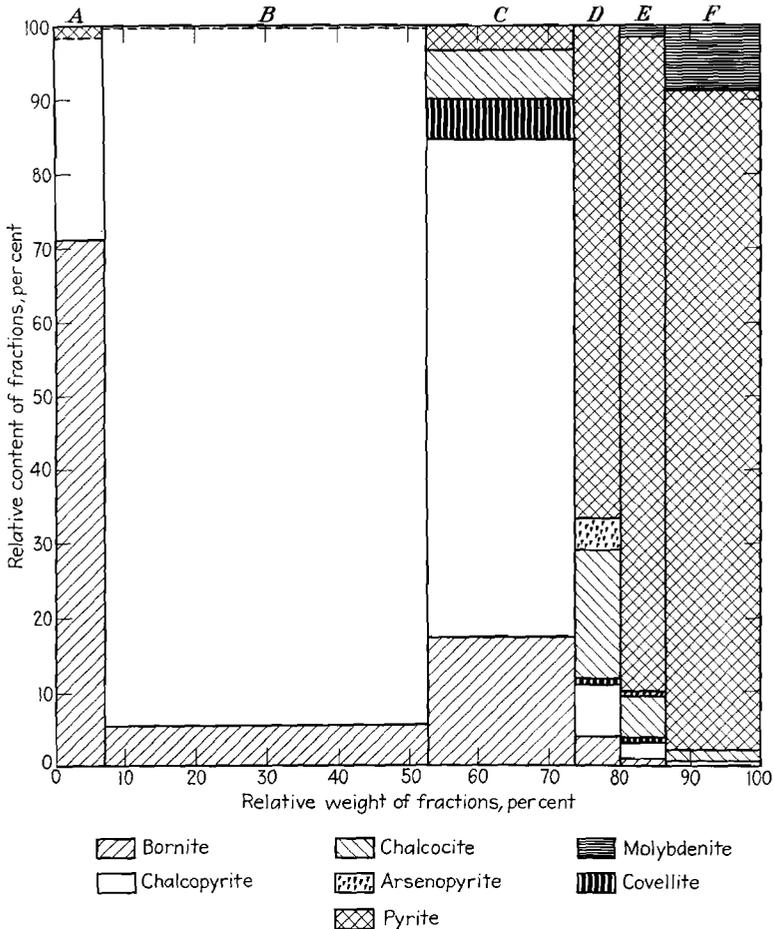


FIG. 3.—FRACTIONATION OF UTAH COPPER CONCENTRATE.

ucts. The gray sulphides were in small quantity and largely locked; their identification was not attempted. However, it seemed as though tennantite-tetrahedrite were present, particularly in A, sphalerite in C and D, and molybdenite in D.

#### Arthur, Utah

The 150 to 200-mesh fraction of the Utah Copper concentrate was first fractionated

slope of 13°, and at 1.4 amp. with cross slopes of 3° and of 30'. Close control of the amperage was made necessary by the large quantity of chalcopyrite and its evidently consistent response in the range of a few hundredths of an ampere on either side of 0.85 ampere.

The results obtained confirm that bornite is more susceptible than chalcopyrite, and the latter than pyrite, but they add further

information, as may be seen in Fig. 3. This chart shows clearly that chalcocite is slightly, if faintly, magnetic; that covellite is slightly more magnetic than chalcocite, and that molybdenite is less susceptible than pyrite. We believe that molybdenite may even be diamagnetic. Furthermore, arsenopyrite can be spotted definitely in only two of the fractions, D and E.

#### Anaconda, Montana

The greater complexity of the Anaconda concentrate and the more intimate intergrowth of the minerals did not prevent a fairly clean-cut separation.

The fractionation was made at 0.77, 0.83, 0.93, and 1.05 amp., with cross slope of 12° and longitudinal slope of 25°, and at 1.40 amp. with cross slopes of 8° and of 2°. The results are presented in Table 4. This brings out the relative positions of certain additional minerals, notably tennantite-tetrahedrite and enargite. The first of these

TABLE 4.—*Fractionation of Anaconda Concentrate*  
(200 TO 270-MESH)

Mineral	Mineralogical Assay of Each Fraction, Per Cent by Weight. Fractions Arranged in Order of Decreasing Magnetic Susceptibility						
	A	B	C	D	E	F	G
Bornite.....	85.6	40.6	7.7	12.8	14.4	4.3	0.9
Tennantite....	3.9	20.3	8.7	19.0	9.5	6.1	0.7
Chalcocopyrite..	6.8	34.1	78.1	55.6	19.7	6.7	0.5
Chalcocite.....	2.1	1.8	1.1	4.1	16.8	18.2	6.1
Enargite.....	0.1	2.0	2.2	3.9	6.7	5.0	4.3
Sphalerite.....	0.1	0.4	0.1	0.9	2.2	0.6	3.7
Pyrite.....	0.9	0.5	2.1	4.5	30.2	53.4	80.2

is distinctly susceptible, but the latter, like pyrite, is either not paramagnetic at all or very faintly so.

It was observed in the course of the microscope counts that the tennantite-tetrahedrite is not of uniform composition, but that the grains more susceptible to filming fast by selective iridescent filming\*

\* A. M. Gaudin: Identification of Sulphide Minerals by Selective Iridescent Filming. A.I.M.E. Tech. Pub. 912 (*Min. Tech.*, March 1938).

are more likely to be paramagnetic than those filming slowly. It was also observed that certain grains prone to look now like bornite, then like chalcocite, are really colloidal dispersions of one of these phases in the other, and that the separator sorts out dispersions high in bornite from those low in bornite.

Since well over three-fourths of the concentrate particles in the size range studied are locked, it is not surprising that the separation is not perfect. We feel that it is about as good as could be expected. This is reflected in the average composition of locked particles. As an example, Table 5 gives the average bornite content of chalcocopyrite-bornite and pyrite-bornite locked particles.

TABLE 5.—*Percentage of Bornite Content in Two Types of Locked Particles in Fractions from Anaconda Concentrate*

Mineral	Fractions Arranged in Order of Decreasing Magnetic Susceptibility						
	A	B	C	D	E	F	G
Chalcocopyrite-bornite.....	84	34	12	a	a	a	a
Pyrite-bornite.....	a	a	50	35	25	11	7

a The number of grains of this type was insufficient for statistical analysis.

#### LEAD-ZINC FLOTATION PLANTS

##### Midvale, Utah

Perhaps because the samples were taken at an unusual time, the Midvale lead concentrate was found to contain an exceptionally large quantity of copper as chalcocopyrite. To an extent, therefore, the data on this plant provide a measure of the behavior of minerals from a lead-zinc-copper ore.

A portion of 270 to 400-mesh lead concentrate was fractionated at 1.4 amp. with a longitudinal slope of 20° and a cross slope of 10°, giving two products that are essentially a lead concentrate and a copper-zinc

concentrate (Table 6). Detail fractionation of the copper-zinc product was carried out qualitatively but not quantitatively. The chalcopyrite seemed to concentrate in the range provided by magnet amperage of 0.85 to 0.90, with sphalerite occurring abundantly in both the more magnetic and the less magnetic fractions.

TABLE 6.—*Fractionation of Midvale Lead Concentrate (270 TO 400-MESH)*

Mineral	Mineralogical Assay, Per Cent	
	Magnetic Fraction	Nonmagnetic Fraction
Galena.....	8.5	69.2
Sphalerite.....	32.6	3.9
Chalcopyrite.....	42.9	1.2
Tetrahedrite and other gray coppers.....	7.7	1.7
Bornite, chalcocite, co- vellite.....	0.5	0.0
Pyrite.....	5.2	20.3
Gangue.....	2.6	3.7

When allowance is made for locked particles, the separation is all the more striking, the magnetic fraction consisting mostly of free chalcopyrite and tetrahedrite and of locked particles and the nonmagnetic fraction mostly of free galena and free pyrite.

In this case it may be said that the separator has clearly sorted sphalerite-bearing locked particles, tetrahedrite, and chalcopyrite on the one hand from galena and pyrite on the other. Actually, if such a separation could be carried out on a practical scale, it might have commercial value, not only because of removal of zinc from the lead concentrate, but also because of segregation of copper from lead minerals. Chemical analyses for lead, copper, and zinc are as follows: in the magnetic fraction, 7.4 per cent Pb, 18.8 Cu, 21.2 Zn; and in the nonmagnetic fraction 60 per cent Pb, 1.23 Cu, 2.5 Zn. The lead-copper and lead-zinc selectivity indices are 11.2 and 8.2, respectively.

In the Midvale products the sphalerite is largely contaminated by inclusions of chalcopyrite. These inclusions, although in minor volume (about one-twentieth of the volume of the sphalerite), might conceivably be the cause of the magnetic response exhibited by the sphalerite.

In order to obtain a more accurate appraisal of the influence of the chalcopyrite inclusions on the magnetic susceptibility of the sphalerite, the zinc concentrate was fractionated at 0.65, 0.8, 1.0, and 1.4 amp., with slopes of  $10^\circ$  and  $25^\circ$ . Table 7 presents the composition of the various fractions as determined microscopically. The startling fact is that there is so little difference between the fractions. Except for the occurrences of a few grains of free chalcopyrite in fraction C and for the occurrence of appreciably more galena and pyrite in fractions D and E, the fractions are not distinguishable. This leads to the thought that the differences in susceptibility of the sphalerite particles are not due to their chalcopyrite inclusions, but to some other reason. Actually, when the particles are viewed with polarized light, crossed nicols, and an oil-immersion objective of medium power (8 or 16 mm.), the internal reflections are deep red or orange for the sphalerite from A, but pale yellow to white for that from E. This suggests that the differences in magnetic susceptibility may be related to the color in transmitted light. Naked-eye comparison of heaps of A and E particles confirms this correlation. Generally speaking, the sphalerite is chocolate colored, but the intensity of the coloration decreases from A to E. Since there is no corresponding decrease in either the quantity of inclusions or the dispersion of the inclusions, the brown color cannot be caused by the inclusions. Actually, similar inclusions in the sphalerite from the Morning mill, whenever present, give it a terne grayish luster, rather than the familiar resinous or honeyed luster of blende.

It is tempting to believe that the color and magnetic variations are due to an iron content in solid solution, and no doubt this can be ascertained if desired, but because of the pyrite content of fraction E, analyti-

TABLE 7.—*Fractionation of Midvale Zinc Concentrate (270 TO 400-MESH)*

Minerals	Mineralogical Assay of Each Fraction, Per Cent by Weight				
	A	B	C	D	E
	Most Mag-netic				Non-mag-netic
Sphalerite.....	98.2	98.6	96.7	88.8	70.6
Chalcopyrite....	1.4	1.0	2.1	2.3	1.3
Pyrite.....	0.1		0.7	4.3	16.7
Galena.....	0.2		0.5	4.5	11.4
Miscellaneous..	0.1	0.4		0.1	

cal verification would require much painstaking microscopy, supplemented by heavy-liquid fractionation.

#### *Morning, Idaho*

The zinc concentrate from the Morning mill, size 150 to 200-mesh, was first washed in acetone, to remove adhering slime particles. Then the sparkingly clear particles were fractionated at 0.32 amp., with cross slope of  $15^\circ$  and longitudinal slope of  $25^\circ$ ; at 0.52 amp. and 1.0 amp. with the same slopes, and at 1.4 amp., with slopes of  $6^\circ$  and  $25^\circ$ . The five fractions were then viewed under the binocular microscope, with the Ultropak microscope, and in polished section.

The binocular indicated the presence of two kinds of sphalerite occurring *simultaneously in each cut*, one black and opaque and the other translucent in various shades of brown, ranging from medium brown in B to pale yellow in E. In addition, much siderite was seen in A; it is easily revealed by immersion in an oil of suitable index of refraction (e.g., methylene iodide). The Ultropak makes the distinction between sphalerite and siderite very clear;

the latter is clear to very pale yellow, while the first glows with fiery internal reflections.

The two kinds of sphalerite seen under the binocular are probably particles devoid of inclusions (translucent) and peppered by inclusions (opaque), respectively. The inclusions are commonly galena, pyrite and chalcopyrite; they occur frequently in tremendously fine state of dispersion, so fine, indeed, as to challenge identification of the dispersed phase.

Table 8 shows that, in spite of the intimate locking, the magnet first removes the siderite, then the sphalerite.

TABLE 8.—*Fractionation of Morning Zinc Concentrate (150 TO 200-MESH)*

Mineral	Mineralogical Assay of Each Fraction, Per Cent by Weight				
	A	B	C	D	E
	Most Mag-netic				Non-mag-netic
Siderite.....	47.0	9.6	0.7	0.0	0.0
Sphalerite.....	44.0	81.5	96.2	84.7	58.8
Galena.....	6.2	5.9	1.4	4.7	5.4
Pyrite.....	0.7	1.5	0.8	6.6	33.1
Silicates.....	1.7	1.1	0.8	1.9	2.3
Others.....	0.4	0.4	0.1	2.1	0.4

The pyrite is clearly concentrated in fraction E. Galena presents a curious case of a mineral concentrated in fractions A, B, and E, not because it is sometimes magnetic and sometimes nonmagnetic but because most of it is locked, some being attached

TABLE 9.—*Percentage Distribution of Galena in Morning Zinc Fractions*

Galena Attached to	Fraction				
	A	B	C	D	E
Siderite.....	30	29	0	0	0
Sphalerite.....	5	13	66	30	42
Pyrite.....	0	0	0	3	7
One of several others.	0	0	0	30	14
Several minerals.....	65	58	34	37	37
Total.....	100	100	100	100	100

to siderite (goes to A and B), some to pyrite (goes to E), some to sphalerite (goes to C, D, and E), and some to several of these minerals together (Table 9).

### *Sullivan, British Columbia*

Two sizes of the lead concentrate from Sullivan, B. C., were fractionated, the 200 to 400-mesh size and the size retained in the wet state by a 400-mesh sieve but passing it after drying.

The 200 to 400-mesh size contained some

the marmatite and the galena is just what would have been expected. Actually, products A and B consist almost wholly of locked particles (they each contain about 10 per cent assorted free particles and 90 per cent locked), while C contains 54 per cent free galena and D, 95 per cent free galena. If magnetic separation could be made cheap enough to become a practical tool in the size range and susceptibility range of interest in connection with sulphides, it would provide a means to segregate for regrinding locked particles not

TABLE 10.—*Fractionation of Sullivan Lead Concentrate*

Mineral	Mineralogical Assay of Each Fraction, Per Cent by Weight						
	A	B	C	D	E	F	G
	Most Magnetic			Least Magnetic			
	Size 200 to 400-mesh				Size 400 Wet to 400 Dry Mesh		
Pyrrhotite.....	58.0	17.0	1.0	0.0	64.5	13.8	0.3
Marmatite.....	8.5	32.6	15.4	0.6	4.8	30.8	2.9
Galena.....	27.0	41.6	76.9	97.0	27.4	50.9	95.4
Chalcopyrite.....	4.0	7.6	1.7	0.0	1.9	2.4	0.2
Other minerals <sup>a</sup> .....	2.5	1.2	5.0	2.4	1.4	2.1	1.2

<sup>a</sup> Largely pyrite, arsenopyrite, jamesonite, and tetrahedrite; silicate gangue is inconsequential.

white mica, which, because of its shape and peculiar magnetic response, caused difficulty in the separator. Accordingly, the mica was removed by settling the sample in tetrabromethane (sp. gr. 2.94). The sediment was washed, dried, and passed over the separator at 0.2 amp., 0.5 amp. and 1.4 amp., with a cross slope of 12° and a longitudinal slope of 20°.

The finer size contained very little mica and was separated directly at 0.5 amp. and at 1.4 amp., with slopes at 12° and 20°. Passage through the separator was disappointingly slow in this fine size.

Table 10 shows great similarity in the results obtained on the two sizes, thus confirming the qualitative observation that while close sizing ahead of separation is desirable, it is not entirely necessary.

The separation of the pyrrhotite from

segregable by flotation. But such a development is, of course, not yet at hand.

### *Tooele, Utah*

The Tooele sphalerite is much paler in color than that from either Midvale or Sullivan. Nearly pure fractions are readily

TABLE 11.—*Fractionation of Tooele Zinc Concentrate*  
(150 TO 200-MESH)

Mineral	Mineralogical Assay of Each Fraction, Per Cent by Weight				
	A	B	C	D	E
	Most Magnetic				Least Magnetic
Sphalerite.....	98.1	98.5	99.0	98.9	81.5
Chalcopyrite...	1.3	0.3	0.3	0.2	0.5
Pyrite.....	0.1	0.2	0.2	0.2	11.1
Galena.....		0.5	0.1	0.2	3.0
Miscellaneous..	0.5	0.5	0.4	0.5	3.9

obtainable by magnetic fractionation at 0.05 amp., 1.1 amp., 1.4 amp., with slopes of  $13^\circ$  and  $25^\circ$ , and at 1.4 amp. with slopes of  $6^\circ$  and  $20^\circ$ . Table 11 presents the quanti-

tative mineralographic results obtained. Although the various fractions differ in appearance to the naked eye, there is little difference in zinc content until fraction E is

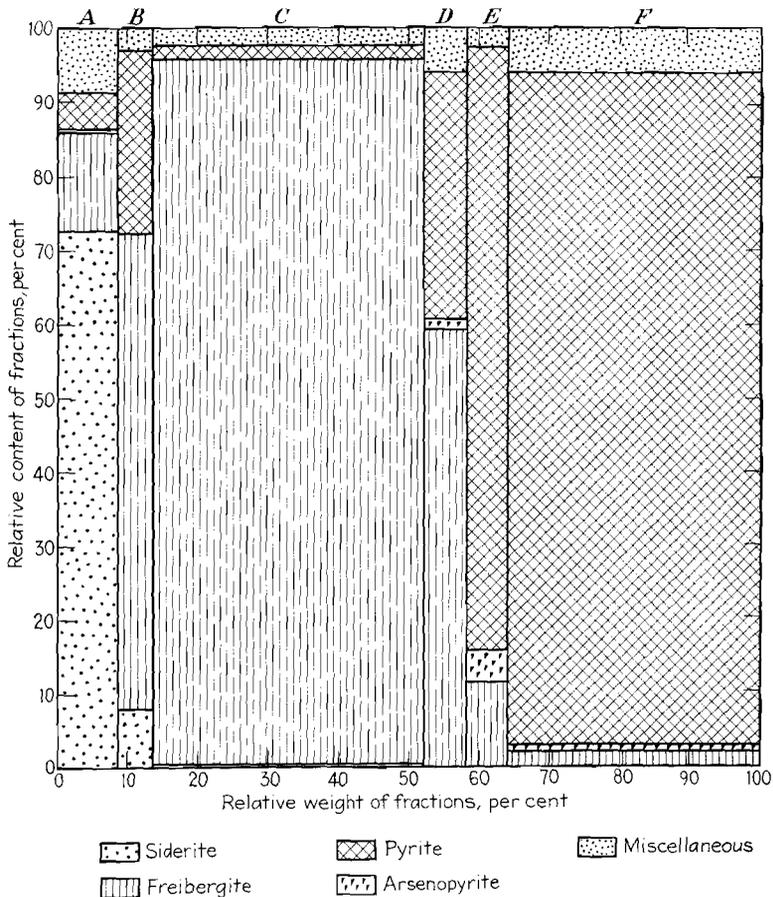


FIG. 4.—QUANTITATIVE MINERALOGRAPHIC RESULTS IN FRACTIONATION OF SUNSHINE CONCENTRATE.

TABLE 12.—Color of the Tooele Sphalerite as Seen in the Ultrapak<sup>a</sup>

Color	Percentage of Particles Viewed in Each Fraction				
	A	B	C	D	E
Red brown.....	31	2	0	0	0
Orange.....	34	16	5	0	0
Yellow.....	33	76	48	21	10
Pale yellow.....	2	5	40	62	36
Clear.....	0	1	7	17	54

<sup>a</sup> This table presents the average color perceptions of two observers.

considered. The zinc mineral must vary in composition, since it varies in both optical and magnetic properties. Table 12 shows that the variation in color is very marked.

The data from the various plants making zinc concentrates—namely, Midvale, Morning, Sullivan and Tooele—show that the sphalerite does not have a uniform susceptibility, and that this lack of uniformity is not due primarily to the occlusion of paramagnetic minerals in the

sphalerite. In fact, the occlusion of chalcopyrite, which is so common, does not account for the observed behavior of the

content. A correlation between magnetic susceptibility and color can be noted, but the agreement is imperfect; this suggests

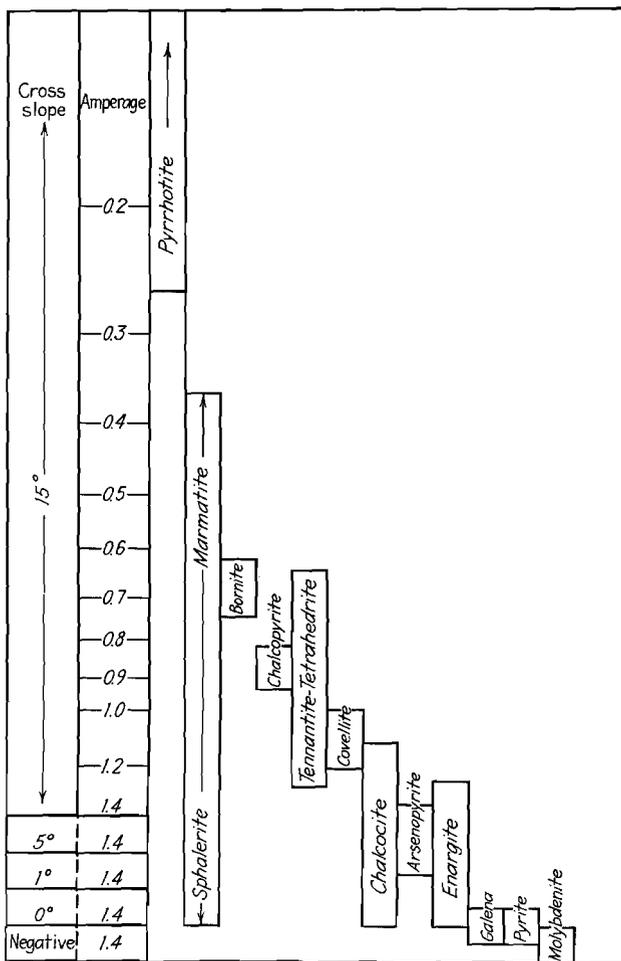


FIG. 5.—MAGNETIC RESPONSE OF SULPHIDE MINERALS.

mineral. It is our opinion that the magnetic susceptibility of the sphalerite is due to iron in solid solution, and that the brown color is caused by foreign atoms in solid solution, particularly iron, copper, and manganese. The grayish color of some otherwise pale sphalerites is due to inclusions, and the dull black color to inclusions occurring jointly with high solid-solution

that the coloring ingredient and the magnetizing ingredient are not exactly concordant.

#### SILVER-FLOTATION PLANT

##### *Sunshine, Idaho*

The Sunshine plant was selected because it features a highly argentiferous tetrahedrite (usually called freibergite). Actu-

ally, this mineral and pyrite form the bulk of the concentrate with galena, chalcopyrite, arsenopyrite and ruby silver as minor constituents.

Fractionation of the concentrate was made at 0.5 amp., 0.79 amp., 1.0 amp., and 1.4 amp., with cross slope of  $15^\circ$  and longitudinal slope of  $25^\circ$ , and at 1.4 amp. with slopes of  $5^\circ$  and  $25^\circ$ . Quantitative mineragraphic results are summarized in Fig. 4.

Clearly freibergite is magnetically susceptible to much the same extent as chalcopyrite.

#### DISCUSSION AND SUMMARY

The results presented in this paper give some measure of the magnetic susceptibility of a number of sulphide minerals. These minerals fall into three groups.

The minerals of one group, pyrite, galena, chalcopyrite, and bornite, have been found to display consistently the same susceptibility. Of these four, galena and pyrite are wholly nonsusceptible, but the other two are susceptible.

The second group consists of four sulphides, which we believe have definite, if slight, susceptibilities. They are arsenopyrite, covellite, enargite, and molybdenite. Of these we believe that molybdenite is diamagnetic, and that enargite, arsenopyrite, and covellite are faintly paramagnetic. The evidence on these minerals, however, is not yet as full as might be wished.

The third group, the most interesting, consists of chalcocite, sphalerite-marmatite, pyrrhotite and tennantite-tetrahedrite-freibergite. The minerals of this group all display paramagnetism, even perhaps ferromagnetism, as in the case of pyrrhotite. But the susceptibility varies from particle to particle within the same ore, as well as from ore to ore.

For sphalerite, it has been shown that the

magnetic property and the color are largely parallel; also that the susceptibility is not primarily due to inclusions of chalcopyrite. For tetrahedrite-tennantite, it has been shown that some correlation exists between magnetic susceptibility and iridescent filming. It is believed that the variability in the susceptibility is due to variations in composition. The minerals in this group are all notable for their tendency to form solid solutions; it would be but natural for these solid solutions to have unequal susceptibilities.

Fig. 5 summarizes our observations. The results presented in this paper also point out the great possibilities of the Frantz isodynamic separator as a research tool

#### ACKNOWLEDGMENTS

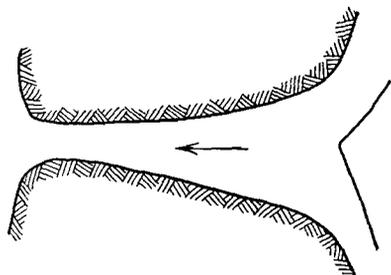
In concluding, we wish to express our appreciation to our associate, Dr. R. Schuhmann, Jr., for his helpful suggestions and to Messrs. S. C. Sun, Risto Hukki, and Frank Bowdish for their assistance.

#### APPENDIX

Concerning the construction and operation of the separator, Mr. Samuel G. Frantz, President, S. G. Frantz Co., writes as follows:

The Frantz Isodynamic Separator consists essentially of an electromagnet having two long pole pieces shaped to a special contour with a long, narrow air gap between them through which the material is continuously fed. The separating force is effective in the air gap, and a divider or interceptor directs the products into two separate containers. The laboratory separator, Model L1, weighs about 200 lb. and occupies a space about 16 by 21 in. by 20 in. high. It is equipped with hopper feed, chute and vibrator feed, ammeter, and rheostat. The current required for the magnet is about 1.6 amp. maximum at 115 volts direct current. The vibrator uses 60 cycles alternating current at 115 volts. A tube rectifier furnishes direct current for the magnet if direct current is not otherwise available. The pole pieces are 10 in. long and the gap width is about  $\frac{3}{16}$  in. at the narrowest place. The material to be separated travels parallel to the length of the pole pieces; the magnetic force urges the grain to the left

in the sketch, which shows a cross section normal to the length of the poles:



The magnetic system is carried on a universal mounting, so that it can be oriented in any direction with respect to gravity. One method of use is to set the pole pieces vertical and drop the grain stream straight through the gap from a small hopper at the top about over the base of the arrow in the sketch. The more magnetic particles are urged toward the left where the air gap is a minimum, and are intercepted by an adjustable dividing edge at the bottom of the pole pieces, which directs the two fractions into separate containers.

The separator may also be used with a vibrating feed chute  $5$  or  $10^\circ$  with the grains fed slowly down over it. This method is particularly suited to the separation of small samples of finely ground materials. The laboratory machine is regularly used with inclined chute for samples of a gram or less. When used in the vertical position on heavy minerals, it has a maximum capacity of 40 to 60 lb. per hour. It is possible to make diamagnetic separations, that is, to separate diamagnetic substances like quartz or zircon having negative mass susceptibilities of the order of  $-0.3 \times 10^{-6}$  from substances that are less strongly diamagnetic or are paramagnetic.

The selectivity of the isodynamic separator is due to the shape of the pole pieces, which gives a constant force on a particle of given susceptibility regardless of its position in the operating space; that is, the space in the magnetic field where magnetic forces are effective to cause separation. In other separators, such as the pick-up type, the force varies enormously with the distance from the surface of the pole piece, so that the separation of a given particle will depend not alone on its susceptibility but on the path along which it happens to be fed, and also even on its size.

The reason is that in other separators mag-

netic forces are exerted on the magnetic particles in the grain mixture by means of localized concentrations of magnetic flux. Typical of such arrangements are the field between a curved and a flat pole piece, and the field near a magnetized serrated or laminated rotor, and it is inherent in these designs that the operating space is very restricted in volume. For example, in a rotor-type separator, the operating space is a small volume immediately surrounding a line parallel to the rotor axis and passing through the point where the grain stream leaves the rotor. In the old Edison separator, the grain is dropped through a columnar space in which the operating spaces are small regions adjacent to the pole pieces of the magnets, and the rest of the columnar space is not usefully employed for separation. The isodynamic separator has a long operating space, measured parallel to the flow of the grain, compared with other types, and the magnetic field has a special configuration. This gives a long time of action on the particles instead of a short impulse, and the direction of motion assumed is substantially the direction of the resultant of the magnetic and gravitational forces. Because of the special configuration of the pole pieces, the ratio of magnetic force to gravity is substantially constant for any particle, that is independent of its position or path, and the resulting direction of motion is a function only of the mass susceptibility, the initial velocity, and interference between particles. The initial velocity is either made negligible or carefully controlled by properly designed feed nozzles. Interference between particles is limited by feeding a rather thin grain stream, which for maximum flow is in the form of a flat ribbon or curtain of falling grains.

When used with vertical pole pieces and free fall of grain, the isodynamic separator gives good results on free-flowing granular materials of size between about 30 and 100 mesh. Below 100 mesh capacity and efficiency begin to suffer because of grain interference and cohesive forces between particles. Above 30 mesh it is not feasible to feed a good straight stream except through large, low-power gaps. In the laboratory, samples of fines of 200-mesh size or smaller are successfully separated at very slow rates by using inclined pole pieces and the vibrating chute. In every case highly magnetic particles such as magnetite must be removed by a preliminary pass at very low power, otherwise they would stick to the pole pieces. A typical separation involves several passes at increasing intensities.