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A Laboratory-Scale Magneto-hydrostatic Separator and its Application to Mineralogic Problems

U.S. GEOLOGICAL SURVEY BULLETIN 1541



A Laboratory-Scale Magnetohydrostatic Separator and its Application to Mineralogic Problems

By HENRY V. ALMINAS, TERRI L. MARCEAU, JAMES D. HOFFMAN,
and ROBERT C. BIGELOW

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Construction plans, operational instructions, and some data on the instrument's effectiveness



UNITED STATES DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, *Secretary*

GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging in Publication Data

Main entry under title:

A Laboratory-scale magnetohydrostatic separator and its application to mineralogic problems.

(Geological Survey Bulletin ; 1541)

Includes bibliographic references.

Supt. of Docs. No.: I 19.3

1. Magnetic separation of ores. 2. Calutron.

I. Alminas, Henry V., 1938- . II. Series.

QE75.B9 no. 1541

557.3s [622'.77]

83-600204 [TN530]

For sale by the Branch of Distribution
U.S. Geological Survey
604 South Pickett Street
Alexandria, VA 22304

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A LABORATORY-SCALE MAGNETOHYDROSTATIC SEPARATOR AND ITS APPLICATION TO MINERALOGIC PROBLEMS

By HENRY V. ALMINAS, TERRI L. MARCEAU,
JAMES D. HOFFMAN, and ROBERT C. BIGELOW

ABSTRACT

Tests of a newly designed laboratory-scale magnetohydrostatic separator (MHS) indicate an alternative to the standard heavy-liquid separation techniques currently in use in the U.S. Geological Survey.

An MHS separator is based on the principle that a paramagnetic solution placed in an inhomogeneous magnetic field will exhibit an apparent specific gravity directly proportional to the magnetic field strength. An aqueous solution of $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ at a concentration of 150 g/100 mL, placed in the magnetic field, becomes an instantly variable heavy liquid, ranging in density from 1.4 to >9.0 . Nonmagnetic minerals are affected only on the basis of their specific gravity characteristics. Partially magnetic minerals are affected through a combination of their specific gravity and magnetic susceptibility characteristics and react as if the specific gravities of these minerals were higher than, in fact, they are. Magnetic minerals are pulled out of the solution by the magnet.

INTRODUCTION

This study was initiated in 1978 to determine whether methods other than the standard heavy-liquid techniques could be used to make mineral separations on the basis of specific gravity. The experimental area of MHS (magnetohydrostatic) separation techniques was chosen as showing the most promise at that time.

The authors designed, constructed, and operated an MHS separator that uses an aqueous paramagnetic solution (manganous chloride) to test the behavior of some common minerals, the rate and cleanliness of mineral separation, and the applicability of the separator to routine U.S. Geological Survey operations. Studies are currently underway to determine the applicability of ferro-fluids (a water-base suspension of miniature magnetite crystals) to this device.

The term magnetohydrostatic (MHS) was coined by U. Andres, who did much of the original experimental work in the definition of the principles of this phenomenon, as well as its applicability to industrial processes.

MHS PRINCIPLE

A magneto-hydrostatic separator is based on the principle that when a paramagnetic solution (or ferro-fluid) is placed within an inhomogeneous magnetic field, it will exhibit an apparent specific gravity directly proportional to the magnetic field strength. Thus, in a container filled with a paramagnetic solution placed within a wedge-shaped air gap between the pole pieces of an electromagnet (fig. 1), the apparent specific gravity of the solution will be highest in the zone of maximum constriction and will decrease progressively upward, as illustrated by the suspension levels of galena, barite, fluorite, and quartz (fig. 1). These nonmagnetic mineral grains were displaced to those portions of the magnetic field where the solution has an equivalent apparent specific gravity. Partially magnetic minerals will show an increase in apparent specific gravity, similar to the increase in the paramagnetic solution, and will be accordingly suspended lower than their true specific gravity would dictate. Magnetic minerals (those having a magnetic susceptibility equal to or greater than that of the solution) will simply collect at the strongest portion of the magnetic field. Andres (1976) notes that, for most purposes, the following equation can be used for the calculation of MHS separation:

$$f_0 = \frac{4}{3\pi} \cdot \frac{\mu_2 - \mu_1}{\mu_2 + 2\mu_1} \cdot H \text{ grad } H \quad (1)$$

where

- f_0 = body force;
- μ_1 = magnetic permeability of the liquid medium;
- μ_2 = magnetic permeability of the mineral particle;
- H = magnetic field strength.

Solutions of any number of soluble paramagnetic salts (table 1) could be used in an MHS separator. For practical purposes, the overriding considerations in the choice should be nontoxicity, magnetic permeability, low corrosiveness, stability, and cost. These considerations make manganese chloride one of the better choices.

The magnetic susceptibility of a salt is dependent on the amount of magnetophoretic ions in it. The magnetic susceptibility of a paramagnetic solution depends on the solubility of the paramagnetic salt in water, in addition to the salt's magnetic susceptibility. The bulk magnetic susceptibility of an aqueous paramagnetic salt solution can be calculated by the following equation:

$$X = CX_i - 0.724 \cdot 10^{-6}(1 - C) \quad (2)$$

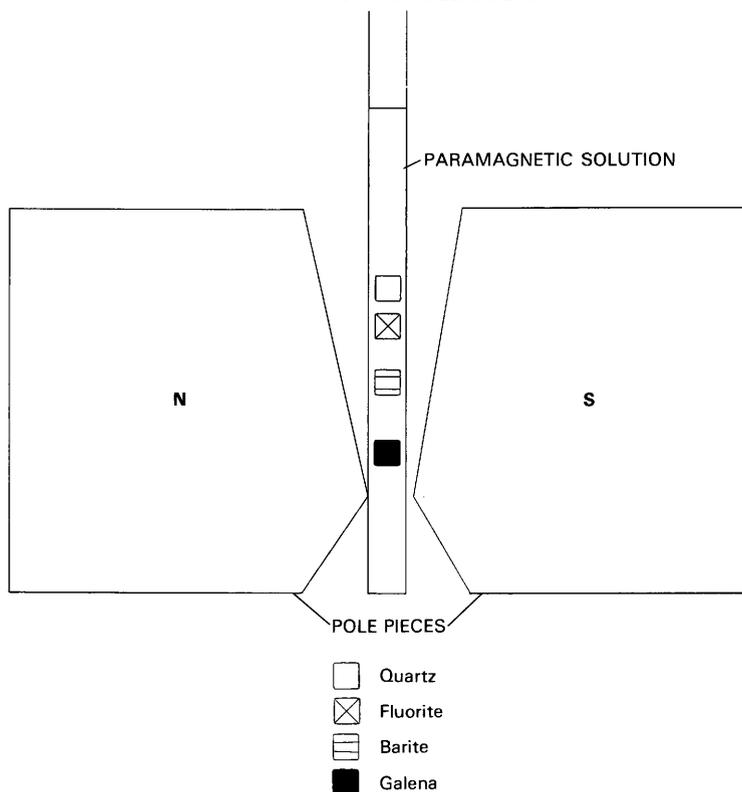


FIGURE 1.—Relative height of suspension of grains of quartz, fluorite, barite, and galena in a paramagnetic solution within a magnetic field.

where

X = bulk susceptibility of solution;

X_i = magnetic susceptibility of salt;

C = concentration of salt in water;

$(0.724 \cdot 10^{-6})$ = magnetic susceptibility of water.

Measurements by U. Andres, using the Gouy method, indicate that the highest magnetic susceptibilities at room temperature are exhibited by solutions of MnCl_2 and $\text{Mn}(\text{NO}_3)_2$. The higher specific gravity and viscosity of the $\text{Mn}(\text{NO}_3)_2$ solution make it less desirable than the MnCl_2 solution.

MHS SEPARATOR CONSTRUCTION

The MHS separator described in this report (fig. 2) was constructed around a modified Frantz Isodynamic Separator¹, which is used to provide the required magnetic field. The modifications are such that

¹Use of brand or manufacturers' names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

TABLE 1.—*Water soluble paramagnetic salts and their magnetic susceptibilities*
[From Andres (1976)]

Salt	Molar susceptibility (10^6 CGSM units)	Molar weight	Volume susceptibility (10^6 CGSM units)
CoBr ₂ -----	13,000	219	59
CoCl ₂ -----	12,600	130	98
Dy ₂ (SO ₄) ₃ -----	45,700x2	539	170
Er ₂ (SO ₄) ₃ ·8H ₂ O	37,300x2	768	97.5
EuBr ₂ -----	26,800	312	85.7
EuCl ₂ -----	26,500	223	118.5
EuI ₂ -----	26,000	406	64.0
EuSO ₄ -----	25,730	248	104.0
FeCl ₂ -----	14,750	136.8	108.0
FeCl ₃ -----	13,450	172.0	78.5
FeSO ₄ -----	10,200	152.0	67.5
GdCl ₃ -----	27,930	263.0	106.0
Gd ₂ (SO ₄) ₃ -----	27,160x2	602.0	90.0
MnBr ₂ -----	13,000	215.0	61.0
MnCl ₂ -----	14,350	126.0	114.0
MnF ₂ -----	10,700	74.0	145.0
MnI ₂ -----	14,400	309.0	46.6
MnSO ₄ -----	13,660	151.0	91.0
NiBr ₂ -----	5,600	218	25.7
NiCl ₂ -----	6,145	130	47.4
Tb ₂ (SO ₄) ₃ -----	39,160x2	706	111.0

the Frantz can be easily reconverted to its original purpose and consist of:

1. The cutting of a rectangular hole in the Frantz base plate, as shown in figure 3, and
2. The replacement of the standard Frantz pole pieces with the modified ones shown in figure 4.

Plans for a specialized table for mounting the MHS separator are also shown in figure 3.

With the new pole pieces in place, the electromagnet is oriented with the pole-piece air gap upward and the long axes of the pole pieces running front to rear. The magnet is tilted forward so that the plane formed by the tops of the pole pieces makes a 45° angle

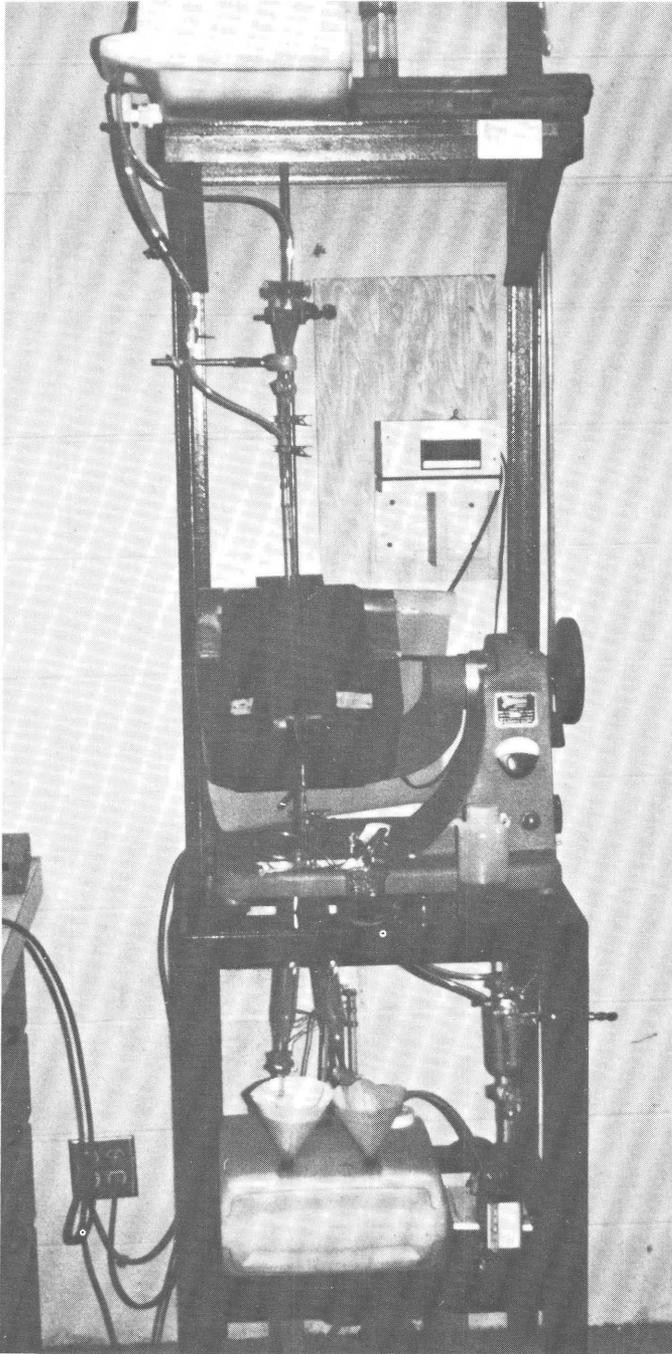


FIGURE 2.—The U.S. Geological Survey's magnetohydrostatic (MHS) separator.

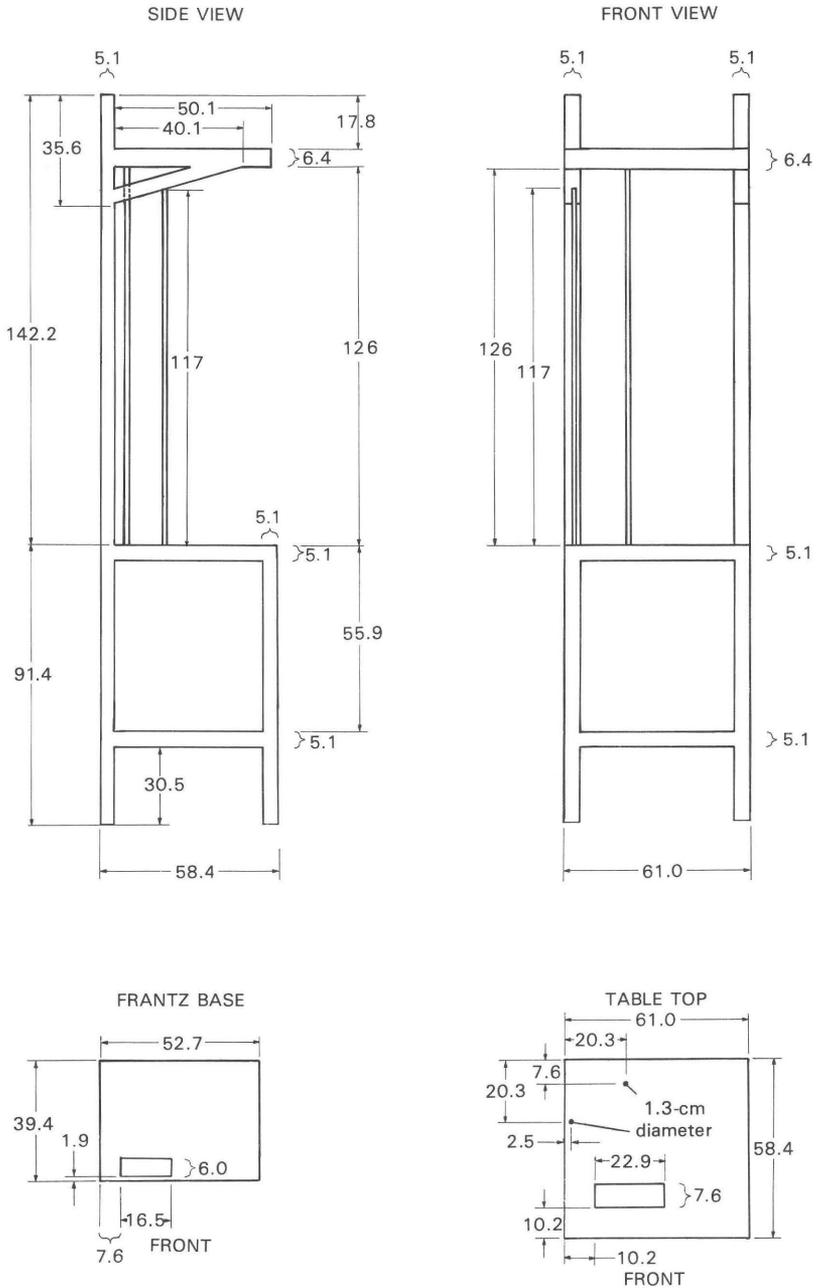
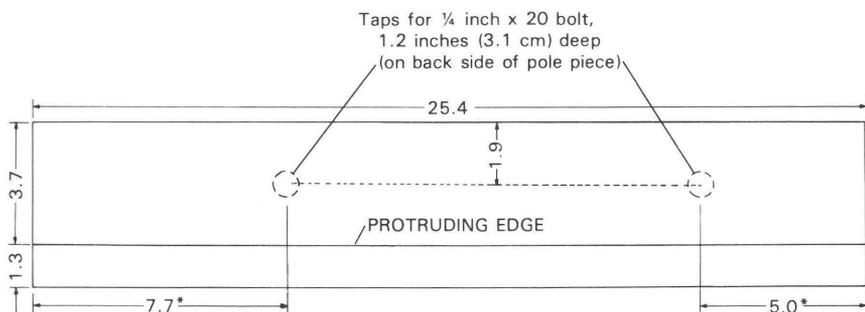
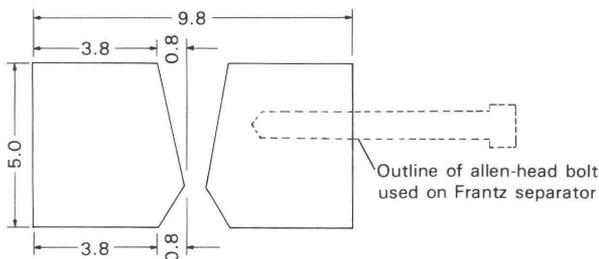


FIGURE 3.—Plans for a specialized MHS mounting table and a modified Frantz Isodynamic Separator base plate. All measurements in centimeters.



FRONT VIEW OF LEFT POLE PIECE

*Note: These measurements will be reversed on right pole piece



END VIEW

FIGURE 4.—Plans of modified pole pieces used for MHS separator. Measurements in centimeters except as noted. The new pole pieces should be machined from the mildest available steel to minimize residual magnetism.

with the horizontal. A Plexiglas separation chamber (fig. 5) is mounted within the air gap as shown in figure 6. It is important that the wedge-shaped splitter within the separation chamber be in line with or somewhat above the line formed by the narrowest portion of the air gap. Within the paramagnetic solution, light mineral grains float above the level of this line and exit the chamber through the upper tube, and the heavier grains fall below this level and are removed through the lower tube. It is also important that the separation chamber be positioned in such a manner that mineral grains entering it via the inlet tube fall vertically into progressively stronger portions of the magnetic field rather than being trapped in the back portion of the chamber behind the magnetic field.

Figure 7 is a schematic diagram of the MHS separator with the electromagnet omitted. The heavy arrows indicate that portion of the separator through which the sample flows. The various components of this portion must be connected with glass tubing and ball and socket

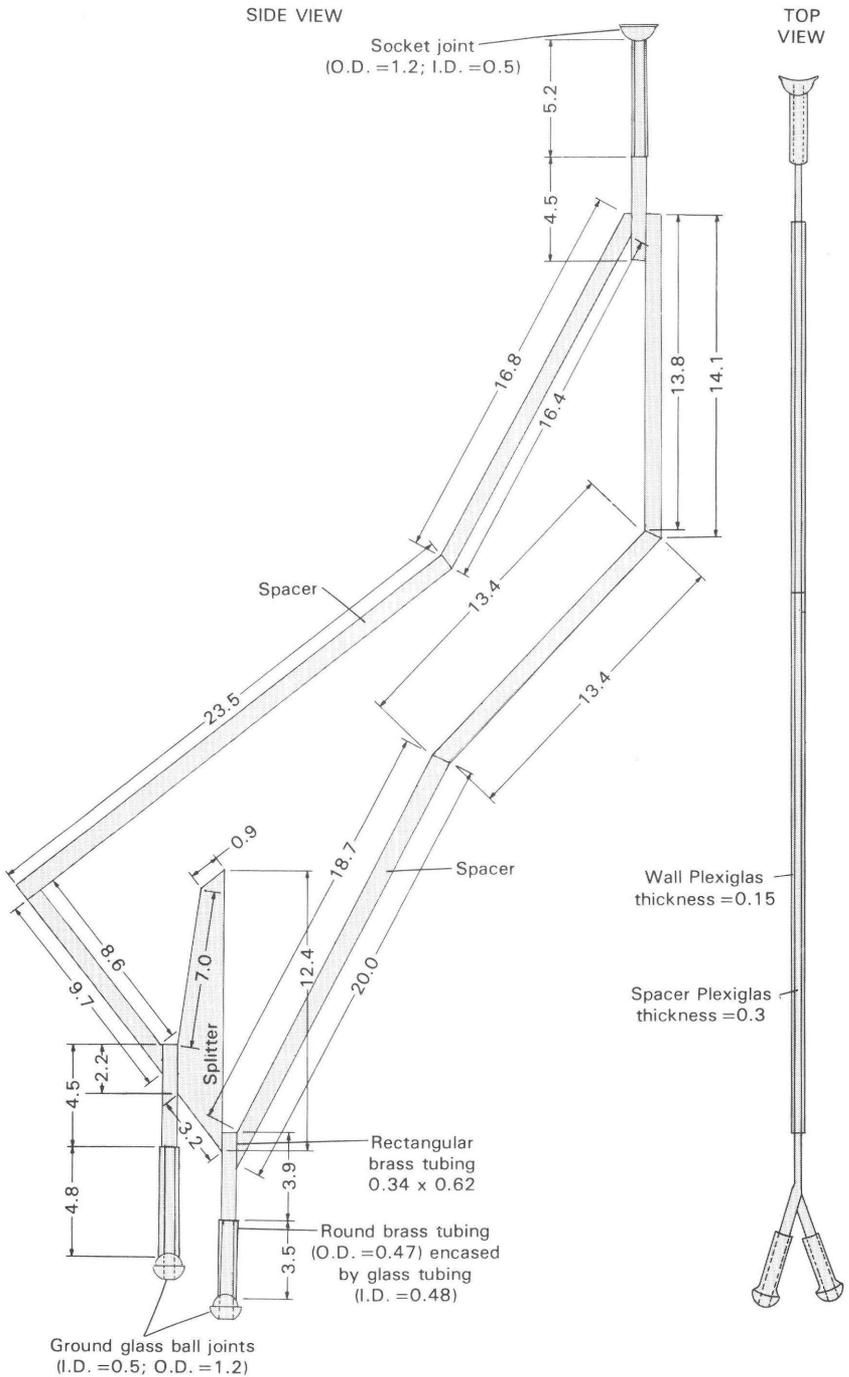


FIGURE 5.—Plans of separation chamber for the MHS separator. All measurements in centimeters.

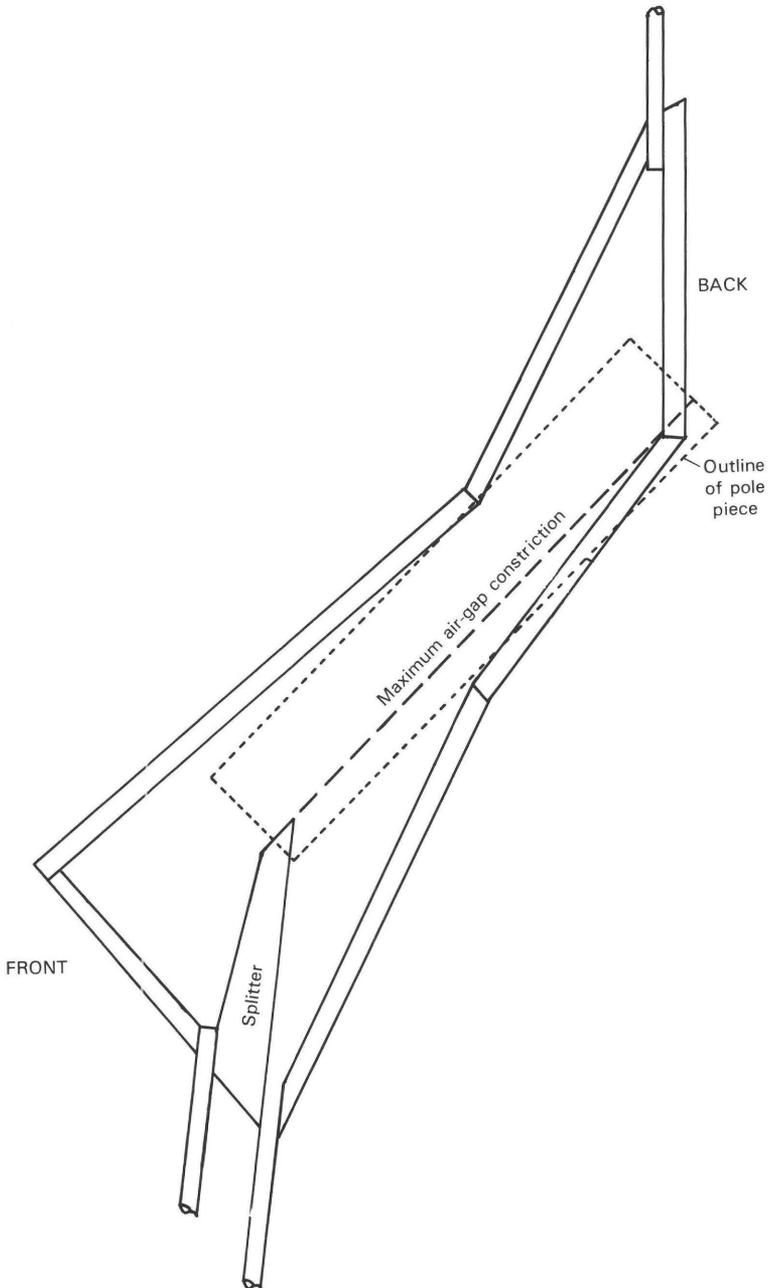


FIGURE 6.—Proper separation chamber orientation relative to the electromagnet pole pieces.

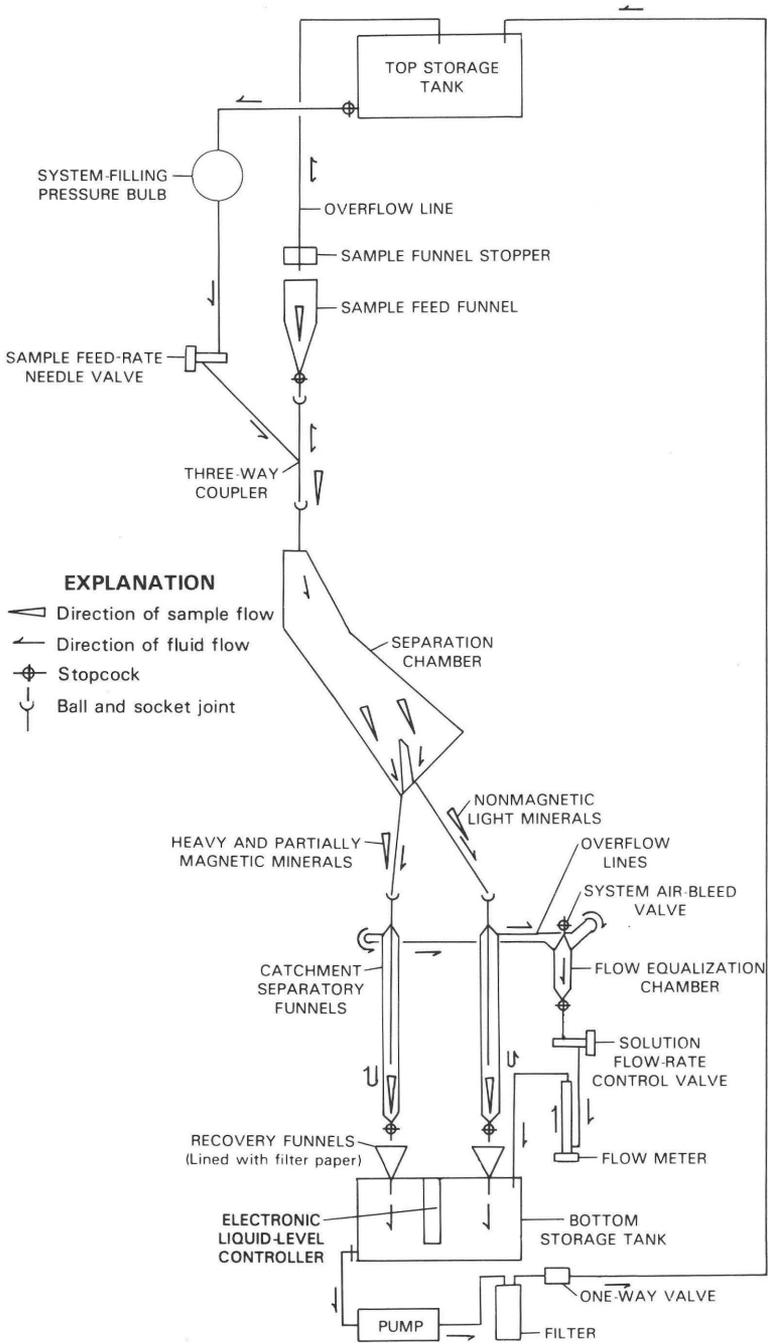


FIGURE 7.—Schematic diagram of the MHS separator.

joints to permit easy passage of particulate matter. The balls and sockets are lightly coated with silicone stopcock grease to prevent leakage. The fine arrows indicate the portion of the system through which solution flow occurs. The components within that portion of the system where only solution flow occurs can be interconnected with flexible plastic tubing.

In addition to the pole pieces and separation chamber, the sample catchment funnels, the flow equalization chamber, the three-way coupler, and the sample feed funnels were custom made, and plans are shown in figure 8. The other components are commercially available items and are listed below:

- Two (top and bottom) tanks (rectangular plastic 15-L containers)
- Two needle valves (200 mL/min range)
- One liquid-flow meter (100 mL/min range)
- Two plastic funnels
- One 250-mL gas-washing bottle used as filter
- One one-way ball valve
- One $\frac{1}{25}$ th-horsepower electric pump
- One electronic liquid-level controller

MHS SEPARATOR OPERATION

Before a sample is introduced into the separator, certain steps are advisable:

1. If a sample is rich in clays, it should be washed to remove most of them. Clays will flocculate in the solution and clog the system.
2. The sample should be sieved to ensure that the largest mineral grains are smaller than the smallest opening within the mineral-flow path.
3. Strongly magnetic minerals (such as magnetite, ilmenite, and maghemite) should be removed from the sample to prevent excessive buildup within the separation chamber.

This MHS separator can be operated with or without solution flow. The same equipment and orientation are used in both instances. Solution flow speeds up the separation process but somewhat reduces separation precision. The decrease in precision is the result of the complexity of motion occurring within the separation chamber; that is, the movement of the grain relative to the fluid and of the fluid relative to the chamber walls. As flow rate is increased, grain configuration and grain size become important factors in determining whether the grain goes into the light or heavy fraction. Turbulent flow occurs within the separation chamber as a result of high flow rates and tends

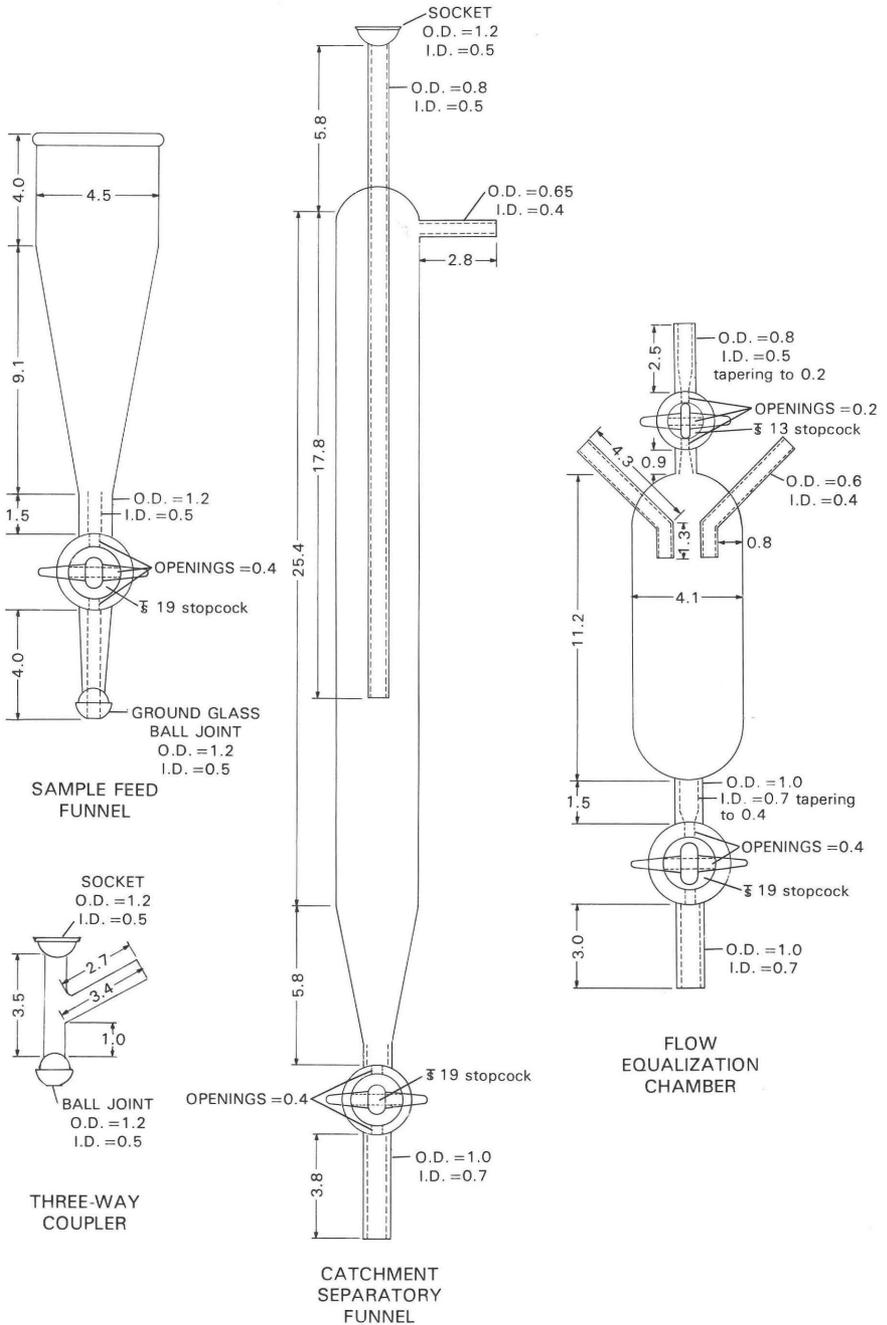


FIGURE 8.—Plans of custom-made components for the MHS separator. All measurements in centimeters.

to force light minerals into areas of higher solution specific gravity. Figure 9 shows the behavior of the light fraction under various rates of solution flow.

The graphs shown in the "Results" section were established using a system flowing at the rate of 30 mL/min. In this mode, there is continuous solution flow through the system while the separator is in operation. Starting at the top storage tank (fig. 7), the solution flows through the sample feed-rate needle valve, the three-way coupler, the separation chamber, the two catchment separatory funnel overflow lines, the flow equalization chamber, solution flow-rate control valve, flow meter, and into the bottom storage tank. Here the solution accumulates until it reaches a preset level, at which point the electronic liquid level controller activates a pump to force the solution through a filter (adapted gas-washing bottle) and a one-way valve back into the top storage tank. The desired solution flow rate is established by opening the top tank stopcock and the sample feed-rate needle valve and then adjusting the solution flow-rate valve to the proper setting. The desired magnetic field strength is established by adjusting the variable rheostat controlling the electromagnet current (read in amperes).

The sample is introduced into the partly filled sample feed funnel and is thoroughly wetted with solution using a wash bottle. The funnel is capped with a soft rubber stopper equipped with an overflow line leading into the top storage tank. Sample flow is established by opening the stopcock at the bottom of the sample feed funnel and simultaneously adjusting the sample feed-rate needle valve until the desired rate of sample flow is established. The back pressure of the solution flowing up into the sample feed funnel permits one to establish and maintain a uniform sample flow rate over a wide range. Upon leaving the sample feed funnel (fig. 7), the sample material drops vertically through the three-way coupler into the vertical portion of the separation chamber. Here, the sample material, somewhat spread out by the solution flow, sinks till the various mineral components reach the level at which the solution has an equivalent apparent specific gravity. The nonmagnetic light-mineral fraction (fig. 10) slides along in a series of closely spaced stratified layers above and parallel to the line of the maximum air-gap constriction, passes above the splitter, and exits through the upper line into a catchment separatory funnel. The partially magnetic and nonmagnetic (at this amperage) heavy-mineral fraction drops to the bottom of the separation chamber and is saltated via the lower exhaust tube into a catchment separatory funnel. The grains of the magnetic fraction become attached to the chamber walls along the maximum air-gap constriction and are retained within the chamber until the electromagnet is turned off.

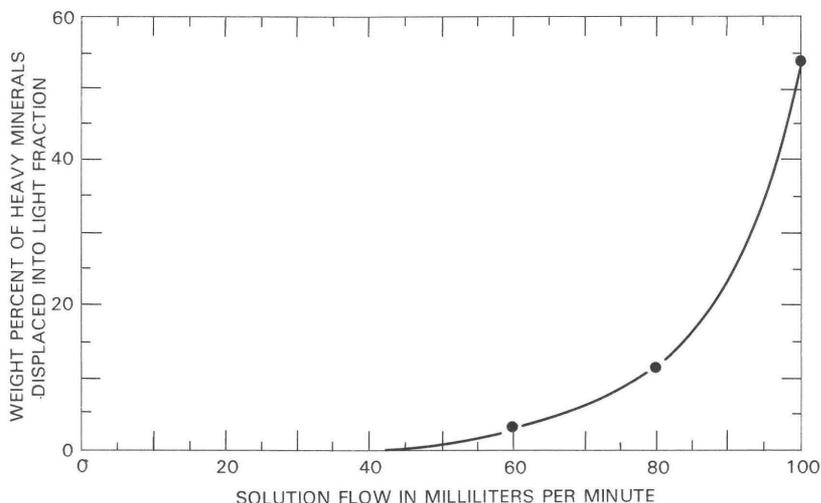


FIGURE 9.—Solution flow rate versus precision of separation in the MHS separator.

The light- and heavy-mineral fractions can now be drained into the filter paper-lined funnels, and then the magnetic fraction can be recovered by turning off the electromagnet and catching the material in the heavy-fraction catchment separatory funnel. The sample material in the filter funnels can be washed with water and dried on a hotplate. The separator can be cleaned between samples by opening the fluid flow control needle valve wide open for some time and removing any mineral grains that might get flushed down into the catchment separatory funnels. A more vigorous flushing can be obtained by opening both catchment separatory funnel stopcocks. Cleanliness can be completely ensured by draining and refilling that portion of the system between the sample feed funnel and the tops of the catchment separatory funnels.

If the separator is operated without solution flow, the sample is introduced into the open sample funnel via a vibrator-mounted hopper attached to the rod above the funnel. The sample feed rate is governed by a variable rheostat controlling the vibrator. The sample flow pathway and sample recovery are the same as described for the solution flow mode.

RESULTS OBTAINED WITH MHS SEPARATOR

The graphs shown in this section were established using the following sample preparation and separator parameters:

1. The mineral samples were crushed and sieved to >107 and <503 μm (165 to 38 mesh).

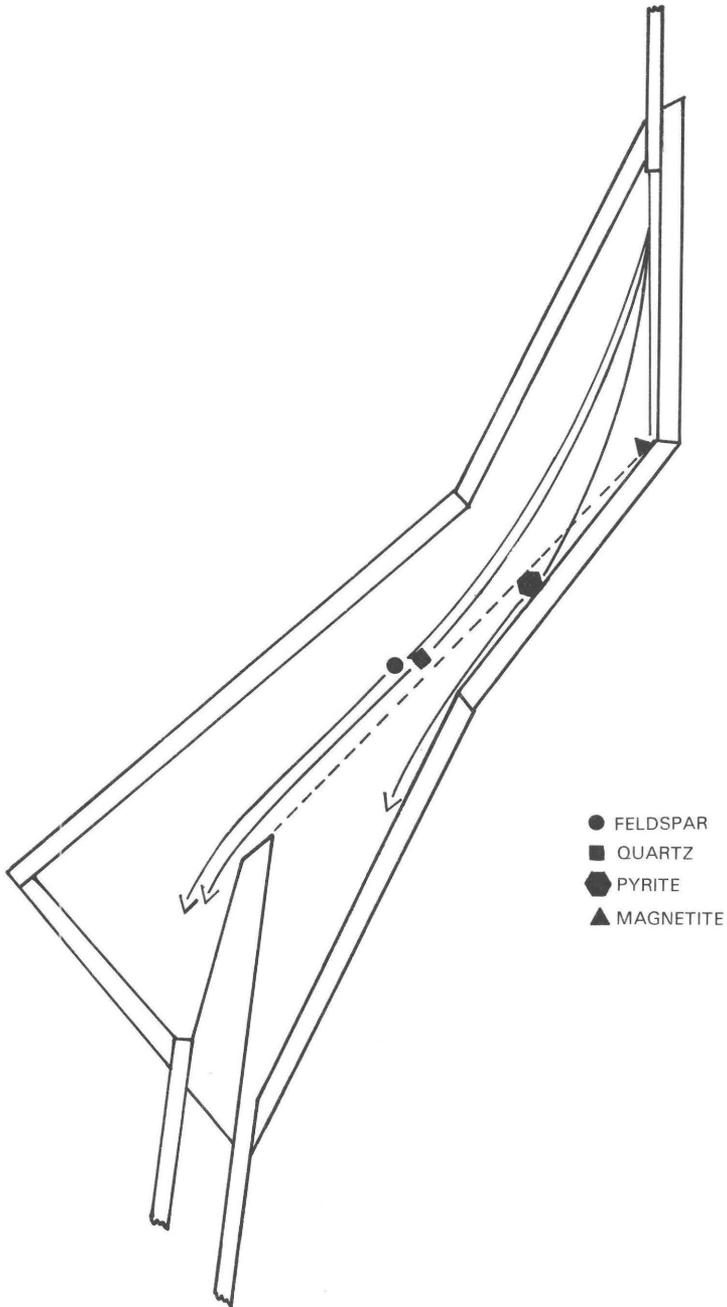


FIGURE 10.—Behavior of mineral grains of varying specific gravity and magnetic susceptibility within the separation chamber while separator is in operation.

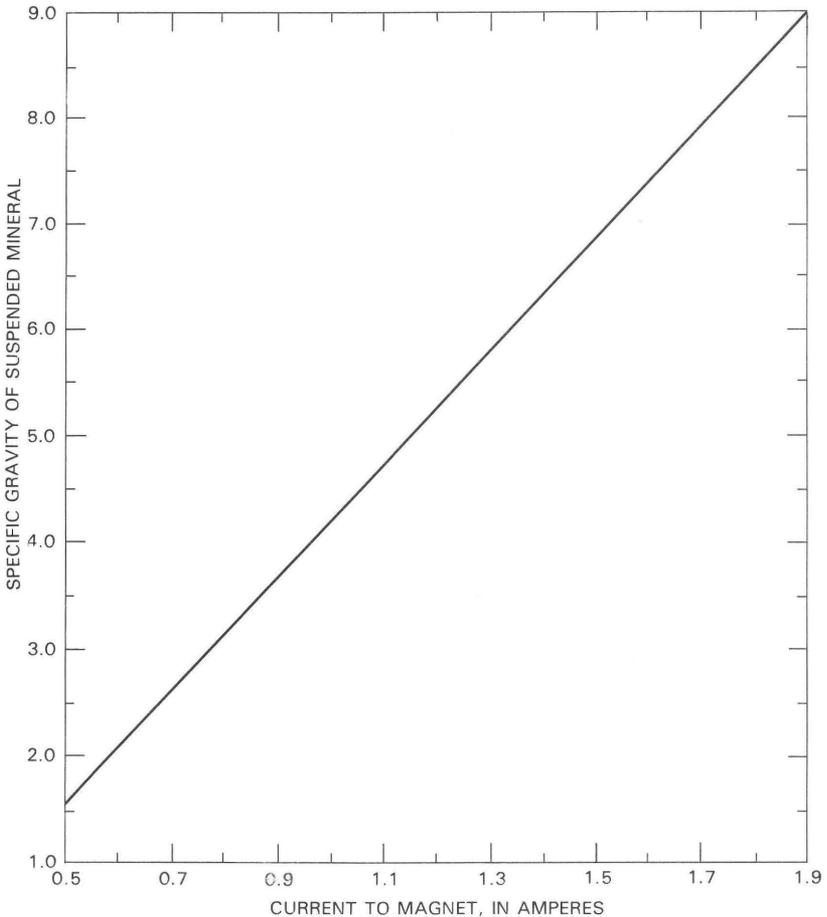


FIGURE 11.—Amperage settings on the USGS magneto-hydrostatic separator versus specific gravities of nonmagnetic minerals suspended in the MnCl_2 solution. Caution: identical amperage settings on other MHS separators will probably produce different specific gravities. Each device should be calibrated separately.

2. The sieved sample material was washed with water to eliminate the dust coating that collected on the grains during the crushing.
3. A 5-gram sample was used to establish each point on the graphs.
4. The separator was operated in flowing solution mode with a flow of 30 mL/min.
5. The solution concentration used was 150 g $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ /100 mL H_2O , which produced a specific gravity of 1.42 at 24°C.

The graphs are plotted to show weight percent of mineral suspended at a given amperage. In using this information, it is important to

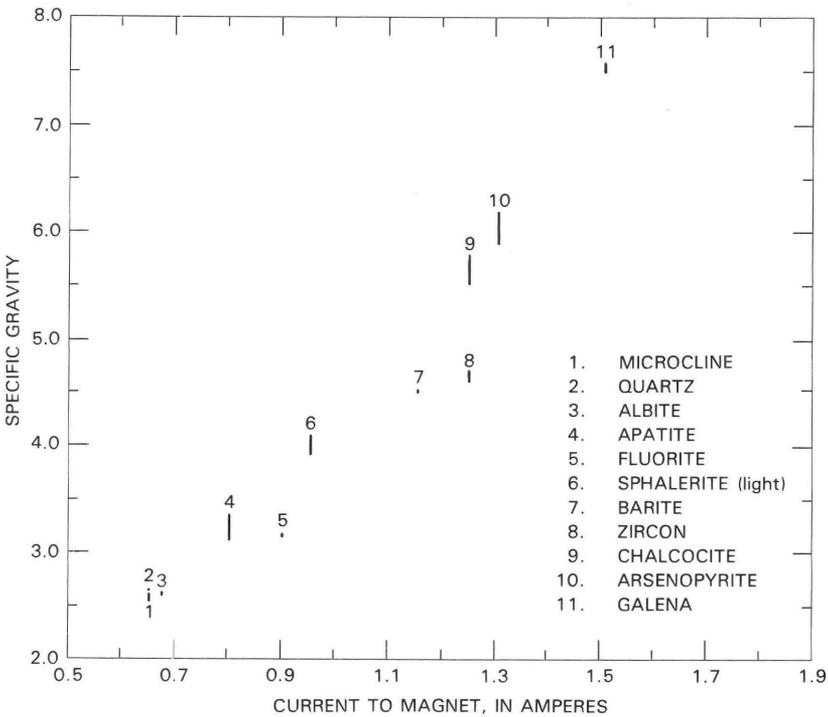


FIGURE 12.—Specific gravity ranges of 11 nonmagnetic minerals versus amperage values required for 100 percent suspension.

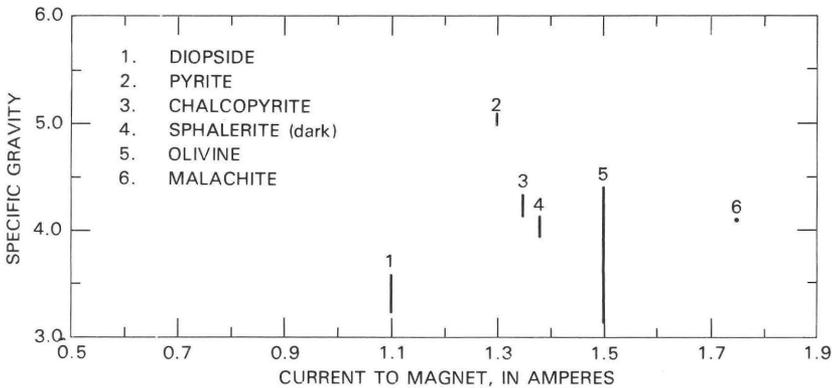
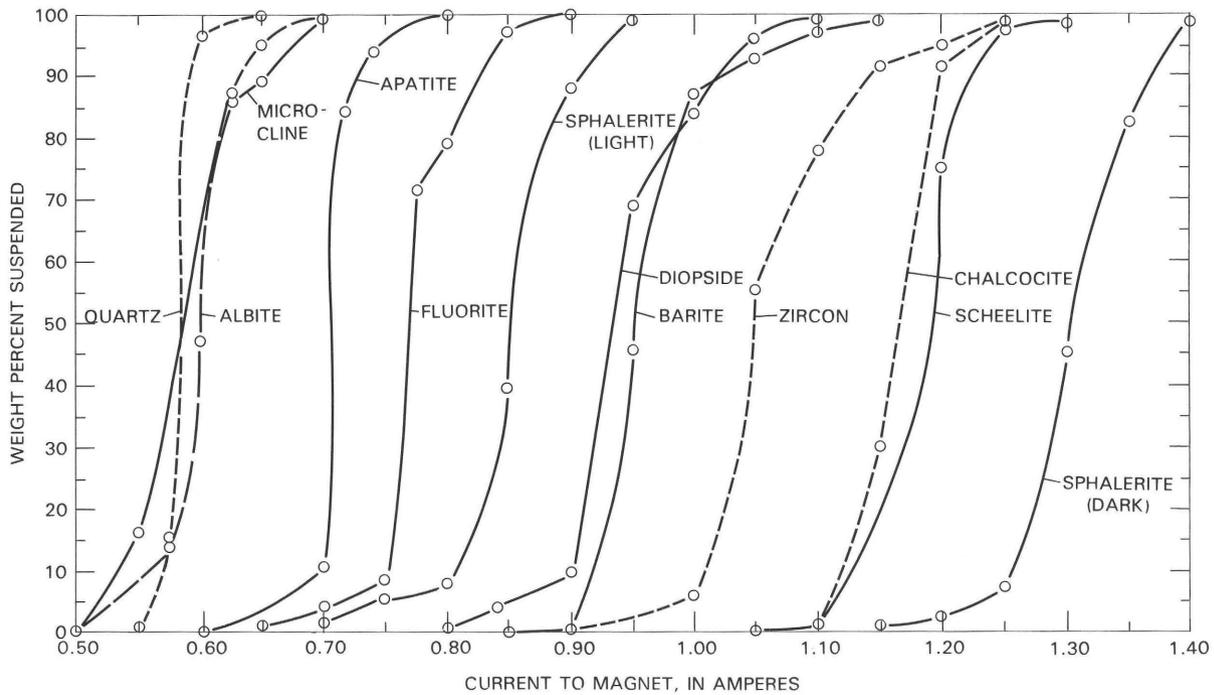


FIGURE 13.—Specific gravity ranges of six partially magnetic minerals versus amperage values required for 100 percent suspension.

keep in mind that the actual magnetic field strength produced by any two Frantz electromagnets, at a given amperage reading, will differ somewhat. This variance may be brought about by a number of factors, such as ammeter error, slight differences in coil winding, or



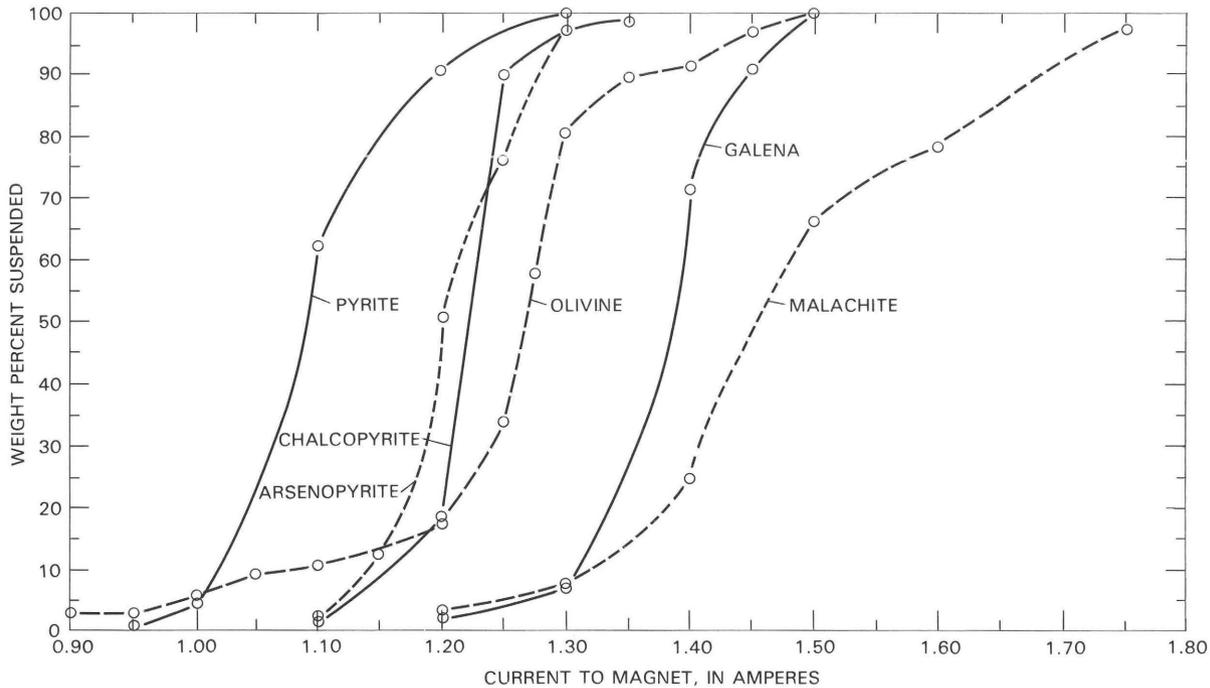


FIGURE 14.—Suspension curves for 18 selected minerals, showing percentage of each mineral suspended in the $MnCl_2$ solution versus amperage flowing to the electromagnet on the MHS separator.

slight differences in the air-gap dimension or pole-piece construction. As a result, the actual field strength produced at various amperage readings should be checked for each instrument used.

The field strength of the electromagnet used to establish these graphs was checked at 10 places along the long axis of the pole pieces and has a range of 10,460–10,600 gauss and an average of 10,564 gauss at 1.0 ampere.

The configurations of the low- and high-amperage ends of the individual mineral curves (fig. 14) to a degree reflect the impossibility of obtaining pure mineral samples. Some of the curvature also results from intramineral fractionation brought about by variation in specific gravity due to metamictization, hydration, crystal imperfections, substitutions in the crystal lattice, and inclusions of other minerals or by the variation in magnetic susceptibility due to staining, substitution in the crystal lattice, and inclusion of other mineral species.

Figure 11 is a plot of specific gravity against amperage. The line gives empirically determined amperages at which a nonmagnetic mineral of a given specific gravity can be suspended. Figure 12 shows the specific gravity ranges and amperages required for 100 percent suspension for 11 nonmagnetic minerals. Figure 13 shows the same for six weakly magnetic minerals. Figure 14 shows individual mineral suspension curves for 18 selected minerals.

For geochemically oriented routine application, this separator will process approximately 1 g/min of pan concentrate at a bromoform-equivalent setting and a solution flow rate of 30 mL/min. At this processing rate, approximately 1 percent of the heavy-mineral fraction will consist of light minerals.

SUMMARY

For most purposes an MHS separator can be used as an alternative to the traditional heavy-liquid techniques to separate minerals on the basis of specific gravity. Of equal or greater interest is the potential of this instrument in solving specialized mineralogic problems requiring high-specific-gravity separation, fine specific gravity differentiation in the range of 1.4 through >9 , or single-pass separation capability based on specific gravity and magnetic susceptibility simultaneously. Listed below are some of the advantages offered by this method of separation:

1. The device uses an essentially nonvolatile, nontoxic, and totally nonflammable solution (Friberg and others, 1979).
2. No special installations, such as hoods, are required.
3. Subsequent to installation, operating costs are extremely low.

4. The method makes available the equivalent of an instantaneously variable heavy liquid that has a specific gravity range of 1.4 through 10 for all nonmagnetic minerals and a more restricted range for weakly magnetic minerals.
5. It has a single-pass separation capability, based on specific gravity and magnetic susceptibility simultaneously.

Some of the disadvantages inherent in the system are as follows:

1. Initial setup is relatively expensive.
2. The sample handling capability of the device is limited by the strength of the available electromagnet.
3. The device is unable to separate the more magnetic minerals on the basis of specific gravity.
4. The paramagnetic solution has greater corrosiveness than the most common heavy liquids.
5. The operator training period is longer than that required for standard heavy-liquid techniques.

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