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A Solids Concentration Pilot-Plant Process Using Ferromagnetic Fluid as the Variable Density Medium

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Abstract

Ferromagnetic fluid, FMF, is a stable colloidal suspension of 0.01 μm diameter magnetite particles in a carrier fluid and has the unusual property of exhibiting an infinitely variable apparent density in the presence of appropriate magnetic field gradients. Recent cost reductions for the fluid make its use in sink/float-type concentrations evident. In practice, only a partial beneficiation is obtained in a single pass, therefore the process is repeated as often as necessary; such a repetition is called cascading. In practice, a batch technique has been used to simulate the operation of a continuous cascade system. The data obtained from this technique have been used in turn to model a continuous cascade whose viability has been checked in the laboratory with positive results. Several cascade systems have been proposed: the best practical design depends on the economics of the system which are envisioned to be favorable.

INTRODUCTION

There are various physical methods of solids concentration. For example, methods based on size/shape difference such as screening or sievings; optical methods based on reflectivity, color, or fluorescence differences; and also methods based on density differences between various liberated fractions in a given solid feed material.

The solids concentration method based on this last criteria, the density difference among the various fractions of the solids, is quite well established in the industry. Mineral beneficiation claims fame to the largest single tonnage operations utilizing such equipment as jigs, shaking tables, spirals,

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and flotation cells (*1*). A variety of secondary metals is reclaimed from automotive scrap yards by the utilization of dynamically stabilized suspension of galena or ferrosilicon as the dense media (*2*). These methods have several things in common; all operate with a media having a specific density, are difficult to maintain, and their separating efficiencies are somewhat lower than desired.

In contrast to the two separating media mentioned above (that is, the true liquids having a specific density: water, carbon tetrachloride, ethylene dibromide, tetraiodomethane, Clerici solutions) and dynamically stabilized suspensions such as ferrosilicon or galena, there exists a third type of fluid, namely, ferromagnetic fluid, which could also be described as a combination of the first two types of fluid. In fact, ferromagnetic fluid is a stabilized colloidal suspension of magnetite in a carrier liquid. The average magnetite particle size is about 0.01 μm. Because each particle is individually solvated by surfactant and its size is below the intrinsic magnetic domain size (soft magnet), their tendency to agglomerate in a gravitational or even magnetic field is thus fully inhibited. Such ferromagnetic fluids synergistically combine the unique magnetic properties of fine ferromagnetic particles with the hydrodynamic properties of the base or carrier fluid. To a good approximation, the fluids act as a magnetically responsive homogeneous liquid continuum in the presence of the applied magnetic fields. Their unusual ability to directly convert magnetic force fields into fluid pressure and fluid potential energy gives rise to a variety of unique and useful responses. In turn, such properties have led to technical applications in a wide variety of different technologies.

In particular, when such ferromagnetic fluids are placed in a variable magnetic field, they act as a "fluid" transducer of that field by exhibiting the associated magnetic force fields as fluid potential energy or apparent density. Hence, when a mixture of different density particles are placed in the ferromagnetic fluid (FMF) within the field, the particles with higher densities than the apparent density of the FMF medium will sink and those with lower densities will float on top of the FMF. Thus a separation by the sink-float method has been effected. In practice, such separations are less than perfect, and thus beneficiation or concentration is a more proper description of the process.

The intended feedstocks could be ores, nonmagnetic residues from municipal refuse, manufacturing or machine shop by-products, and a host of other aggregates where the products occur as a physical mixture (all liberated).

Because, to a great extent, the separability of the feedstock depends on the density difference only of the components, a wide variety of difficult to sort materials can be separated by the use of this process.

There are two basic processes for the manufacture of FMF. One is long-term (~1000 h) comminution of slimy magnetite particles in the presence of surfactants and the carrier base. Obviously, such a process is performed in small batches, is costly, and is only applicable where the amount of fluid used is small or no other method will do.

The other basic process is a precipitation of magnetite from solution in the presence of surfactants and the carrier base followed by peptization to stabilize the product. The process is adaptable to the manufacture of large volumes of FMF and is considerably less expensive than the comminution process. It is this precipitation and peptization process that will be used for any future development (*3*).

The nature of the carrier fluid is important from both the economic and functional viewpoints. For the feedstock separation of large volume materials such as from mining or recycling, a water-base FMF (WB-FMF) is most desirable. The simplicity of handling the WB-FMF as opposed to kerosene-base FMF (KB-FMF) is obvious.

However, besides kerosene and water, there are other fluids that can be used as carrier bases. FMF has been made in various hydrocarbons, fluorocarbons, silicones, diesters, aqueous systems, and liquid metals (gallium, mercury, and their low melting alloys) (*4*). These fluids have various applications such as heat transfer, inductive couplings, nonevaporative liquid "O" rings, shaft seals, and low temperature nonviscous lubricants.

The rest of this paper will concern with KB-FMF and WB-FMF as applied to separations or concentrations.

PROCESS DESCRIPTION

The process for concentration of liberated solids in a mixed feed stream is shown schematically in Fig. 1. It is based on the phenomena described earlier in that the FMF is able to acquire or exhibit an infinitely variable apparent density in the presence of appropriate magnetic fields. The desired density could then be tuned to an intermediary between two fractions in the feed stream. Separation or, in practice, a concentration of both fractions takes place when such a feed stream is fed to a separator which contains the FMF with the desired apparent density.

The process operates as follows: Incoming feed material is comminuted (if need be) to an equivalent particle size such that the various fractions are mostly liberated. This is in contrast to flotation which requires a specific particle size for optimum operation; FMF sink/float separations require only liberated particles, the size and shape effects are minimal for a given size, and density effects are maximal. Thereafter, the wet ground feed material is

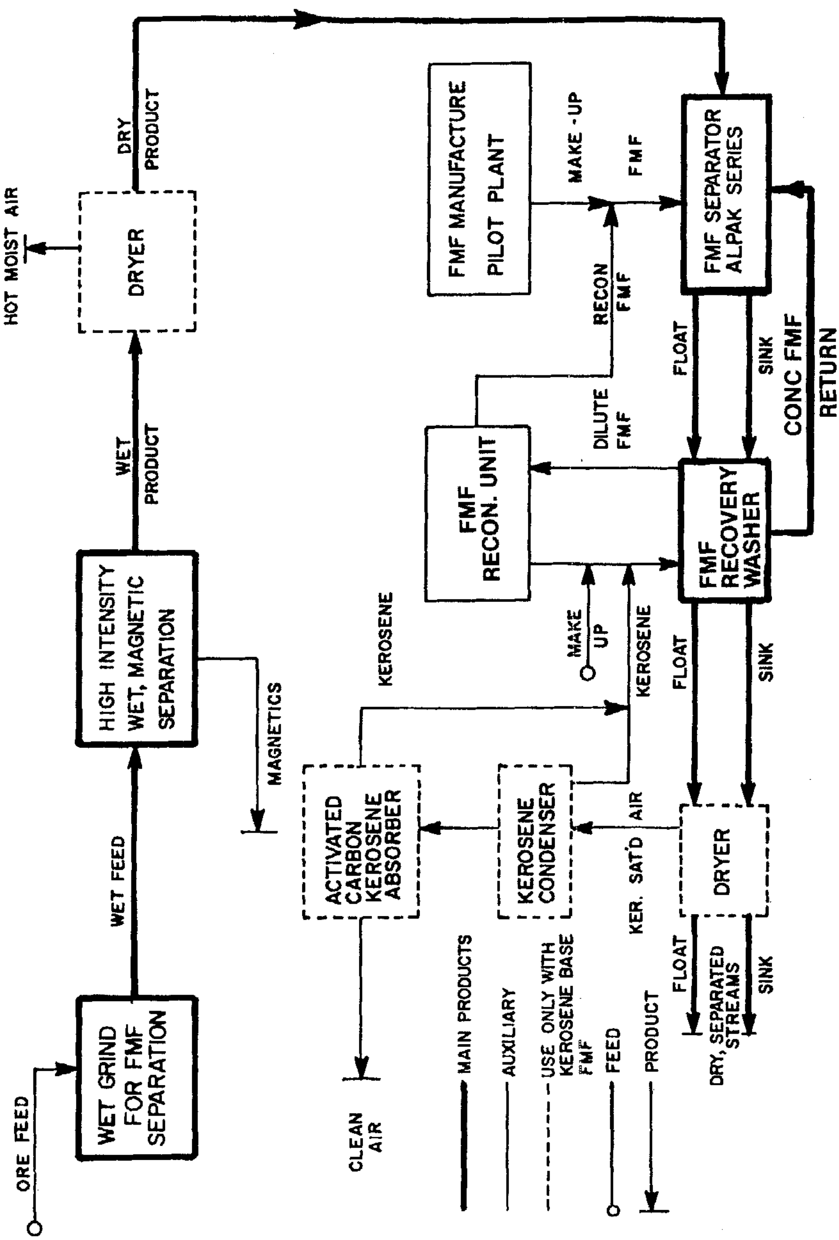

FIG. 1. General process diagram for solids concentration pilot plant using ferromagnetic fluid as the variable density medium.

"demagnetized"; that is, all ferromagnetic materials are removed with conventional technology. A nonmagnetic wet product is dried (if need be) with conventional technology. The dry product is prewetted with FMF to enhance the solids dispersion in the FMF separator. Note that the dashed unit operations in Fig. 1 are necessary only if KB-FMF is used in the separator. If WB-FMF is used, those unit operations are not needed, and the process is somewhat simpler.

The solids, now ready to be concentrated, are fed to the FMF separator where the various feed fractions are split into a float and sink fraction. The nature and type of the FMF separator is the concern of the rest of this paper. They will be described in detail shortly.

The float and sink fractions carry a certain amount of FMF with them to the FMF recovery unit which is a type of washer. Part of the drag-out is returned to the separator whereas the other part is recovered as a dilute FMF. The dilute FMF is reconcentrated in another unit operation. The FMF recovery and reconcentration unit operations are the subject of another article (*5*), whereas FMF manufacturing has been described previously (*3*). The now-solvent-wet float and sink streams are dried (if need be) with conventional technology. If KB-FMF is used, the kerosene or for that matter similar carriers, are recovered with the dashed unit operations shown. In the case of a mineral beneficiation, in which case WB-FMF has been the separating medium, a water-wet concentrate stream may be perfectly acceptable for a subsequent leaching process.

Thus, in essence, this is the description of a pilot-plant process for concentration of liberated fractions. The process is nonpolluting; only air and water are discharged. Utilities used consist of electricity, compressed air, and steam, depending on economics.

SINGLE-STAGE FMF SEPARATORS OR CONCENTRATORS

Because physical separation processes operate with less than 100% efficiency, the products may be recycled (in which case they are called middlings) to obtain the desired purity. However, for a fundamental understanding of the process, a single-stage device serves as an adequate model.

Electromagnetically Driven Single-Gap Separators

Such separators consist of a "C"-shaped electromagnet whose gap is filled with FMF in a suitable container. The magnetic field is a function of the

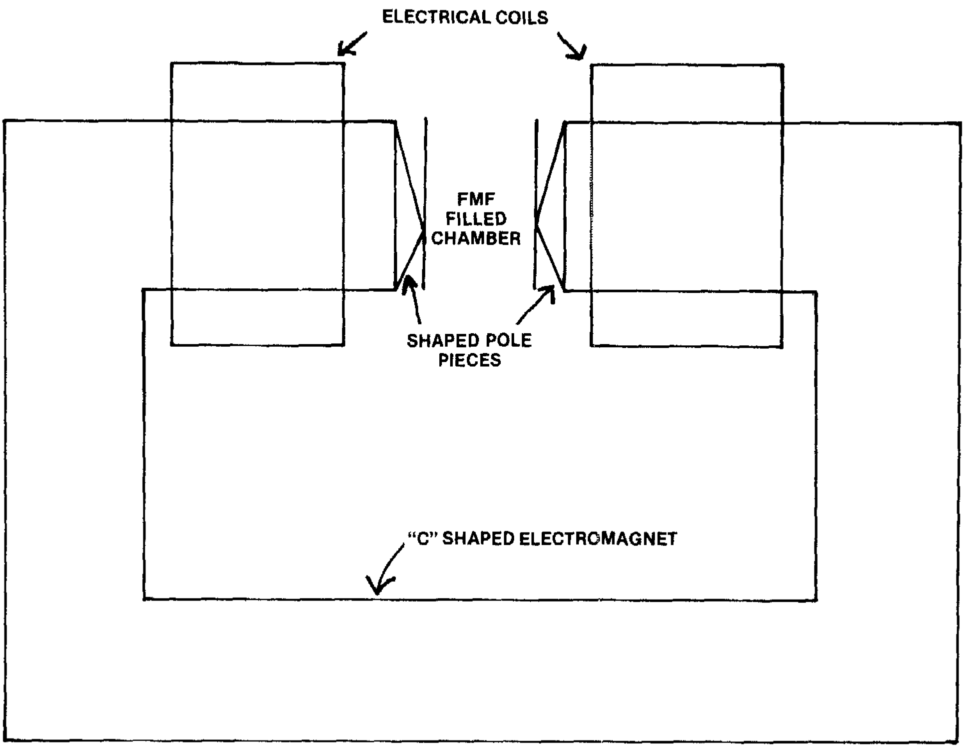

FIG. 2. Illustration of the magnetic circuit required for obtaining a tunable density FMF.

current through the coils on the magnet. The FMF in the gap completes the magnetic circuit while simultaneously transforming the gradient of the magnetic field into fluid pressure or apparent density. The principle is illustrated in Fig. 2 whereas a practical single gap separator is shown in Fig. 3 and a picture of it in Fig. 4. The principle or process of separation by using a tunable density fluid has been patented (*6*). Extensive operating experience with such single gap separations is given in Refs. *7* and *8*. Various feed materials were mentioned in these previous works.

The nonmagnetic inorganic fractions of municipal refuse and automobile shredding operations, as well as several industrial refuses such as Ti machining chips and Ta capacitors, have been tested for their separability by single gap FMF separators. The USBM has also successfully beneficiated diamonds (*8*). It must be realized that the apparent density of FMF decreases dramatically as the gap between the magnetic poles increases. The

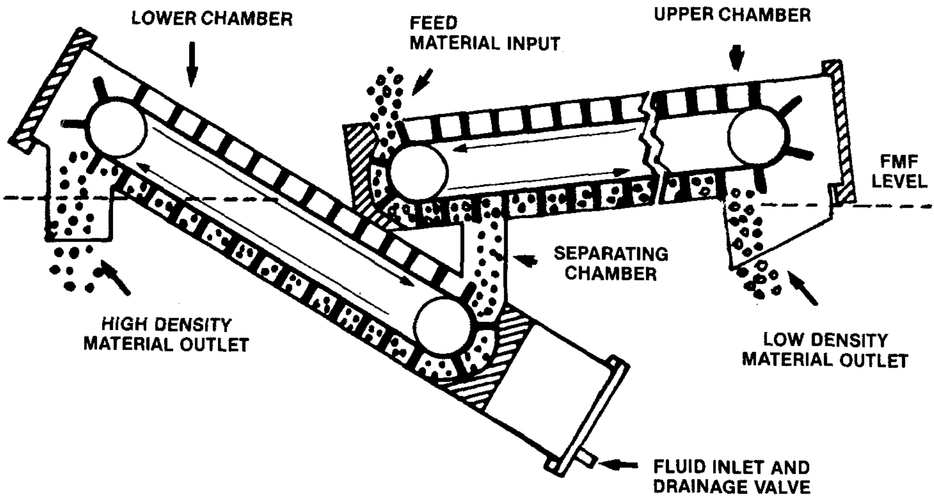

FIG. 3. The single-gap separator and how it works. A decision by part of the feed material to sink or float is made near the top of the separating chamber. High density material sinks to the bottom conveyor belt by which it is picked up and discharged through the left. Low density material floats on the surface of the FMF near the level and is discharged by the top belt through the right outlet. As shown, the separating chamber is perpendicularly (from both sides) surrounded by an electrically driven "C"-shaped magnet. The FMF completes the magnetic circuit while simultaneously transforming the magnetic field gradient into fluid pressure or apparent density.

magnetic field strength and its gradient are inversely proportional to a higher than unity power of the gap width. Therefore, as the gap widens, the uniformity or homogeneity of the apparent density FMF decreases to the point where the separating efficiency diminishes to lower than practically acceptable. Therefore, there is an upper particle size limit which is somewhere around 150–200 mm as estimated by various workers in this field (*7, 8*).

If the applicability of such a concentration process is to be considered for mineral beneficiation, then there are large tonnages of several comodities. In contrast to the large liberated particle size of the secondary feed materials (municipal refuse, car shreddings), the ores to be beneficiated are liberated at well below 1000 μm size, mostly in the 200–20 μm size. In this particle size range the interaction of the particles with any fluid (be it FMF or any other) is rather complicated and mostly of a transitory nature. Several interacting phenomena exhibit themselves in the range in question: the particle surface-to-volume ratio increases dramatically with the particle diameter decrease

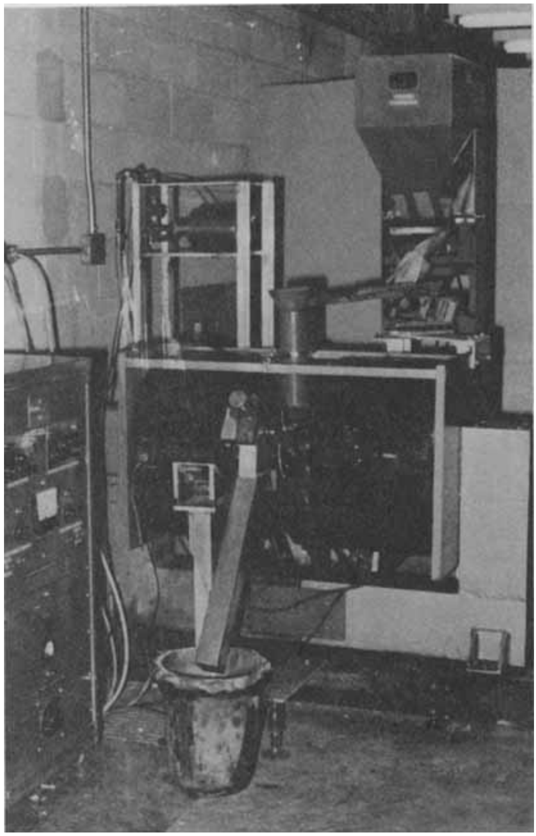

FIG. 4. Picture of single-gap separator showing electromagnet and various conveying systems.

and the gravitational settling of the particles is hindered due to tremendous drag forces. As the particle becomes smaller and smaller, it acts more and more like a fluid whose behavior makes the entire FMF-particle cluster exhibit paste-like characteristics. These phenomena and the great potential for the appliction to mineral beneficiation of the FMF sink/float process prompted investigation into circumventing the above fluid–particle problems. The solution is explained in the next section.

Permanent Magnet Driven Multigap Filters—MGF's

Union Carbide Corp., at its Corporate Research Labs in Tarrytown and Sterling Forest, New York, has used single gap separators for studying their behavior with various feed materials. When particles smaller than about

3000 μm were fed to the single-gap separators, the above-mentioned problems arose. Circumventing these problems posed a challenge to the research people. The problem was solved by radically new and ingenious patented (*9*) equipment. The invention consisted in realizing that it is not necessary for the FMF to be contained within a magnetic gap but rather, the reverse could also be a viable solution; that is, a single or a multitude of magnetic gaps could be contained within a container filled with FMF. Such an arrangement immediately suggested the idea that an equivalent separating surface could be obtained by several narrower gaps which in turn could be driven by permanent rather than electromagnets. These ideas were reduced to practice by constructing an array of shaped steel bars with alternating magnetic poles at the end. The whole array was then immersed in a pool of FMF. The array could be tilted at various angles. The feed stream was fed at the upper end whereas the separated streams consisted of a sink stream which went through the array or magnetic grid filter and a float stream which slid down the slope. This process is illustrated in Fig. 5 and is described in detail by the inventors in Ref. *10*.

It was immediately evident that in this new "packaging" of the magnetic gaps, the MGF has several advantages over single gap separators. Some of these advantages are:

1. It is easily scaled-up since it requires expansion only in two dimensions therefore it is capable of high throughputs.
2. Because the magnetic gaps can be smaller, a more dilute FMF can be used to achieve the same apparent density, thus saving on FMF drag-out losses.
3. Can be easily designed for specific applications.
4. Uses permanent magnets whose investment costs are relatively lower than the operational costs of electromagnets (some may need to be force-cooled).
5. Foremost of all, it can be used for beneficiation of minerals.

This capability is not immediately evident, however, as the design in Fig. 6 shows. Once the particle has passed the critical density region, it gets a magnetically enhanced push or enhanced settling. Thus, in effect, the particle behaves as if it were of larger diameter. These favorable combinations of the various phenomena then allow the MGF to be utilized for mineral size particle beneficiation. In fact, such behavior was observed in the Union Carbide Labs (*11*).

The practical application of such a device needed several accessories, mostly material conveyance and fluid recovery systems. The reduction to practice of such a possibility is shown in Fig. 7 and an actual picture of the

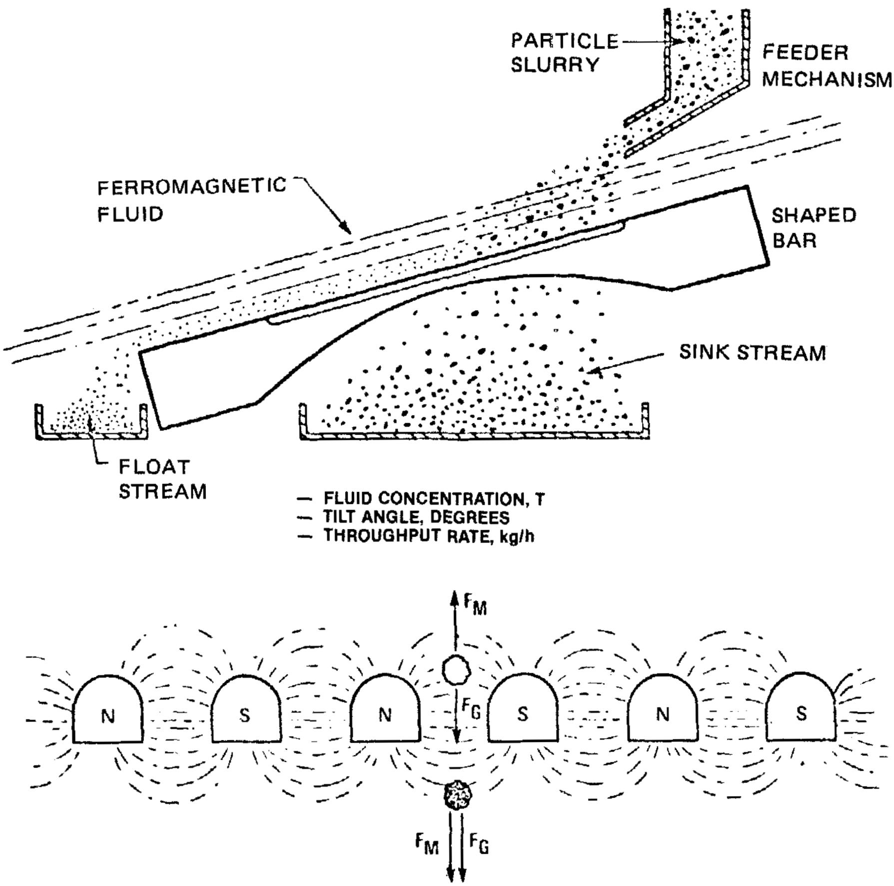

FIG. 5. Critical parameters in density separation.

pilot plant unit in Fig. 8. The functioning of such a unit can be best described by reference to Fig. 7. Feed material is conveyed with the feeder table from the hopper onto an inclined plane. This plane is wetted by a laminar flow of FMF. The particles flow on the laminar film and then another laminar film of FMF covers the flowing mass (not pictured). This arrangement ensures very quick and thorough wetting by FMF of the feed material. This method has been patented by Union Carbide Corp. (*12*). The FMF wet particles now fall on an MGF inclined at a desired angle. Separation takes place according to the process described earlier. The separated streams are prevented from remixing by a built-in baffle.

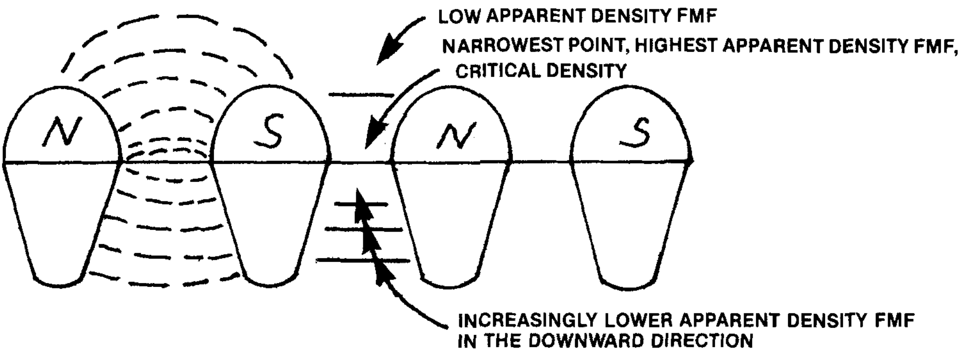

FIG. 6. Various density regions in an MGF. As the particle descends with gravity, it meets an increasingly higher apparent FMF density until the critical density region where the particle will decide to float or sink. The sunk particles now pass through an increasingly lower apparent density zone, thus in effect getting a magnetically enhanced kick, or enhanced settling.

The slurry of separated particles is removed from the separator by screw conveyors which discharge the slurry onto a moving belt filter equipped with spray washers to recover the entrained FMF. The details of FMF recovery and reconcentration are the subject of another paper (5).

Statistically designed experiments were performed with the units shown in Figs. 7 and 8. The experiments revealed that, in practice, the product obtained with a single pass of the feed material through an MGF-type separator is seldom of the desired purity or with the desired recovery. Therefore, the same solution was applied to this separation process as to any other physical separation process—namely, recycling of the product (i.e., middlings) as feed to deplete and enrich the two product streams as is done with flotation.

The successive passings of a feed stream through more than one separation stage is called cascading. Several such potential cascading systems are now described.

MULTISTAGE FMF SEPARATORS OR CONCENTRATORS

What is a Cascade System?

Chemical engineering practice makes use of several mass transfer unit operations such as filtration, distillation, crystallization, and others (*13–17*).

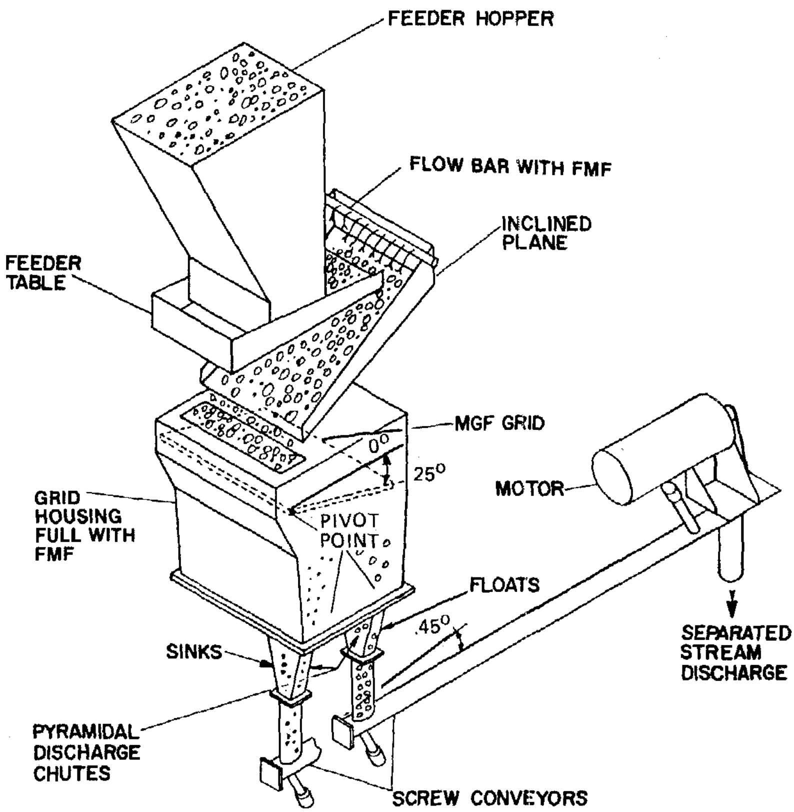

FIG. 7. Pictorial view of an MGF-type separator.

These processes are usually based on exploiting some difference in the physical properties of the mixtures. Broadly, all the processes can be called physical separation processes. The merit or applicability of these separation processes is measured by how effectively the separation is carried out. In other words, pure product streams are not obtained. Rather, an enrichment of one component in one stream and a depletion of the same component in all other streams is obtained. This then constitutes a partial separation or a concentration. To achieve the end result, the product will have to be passed several times through the process equipment. However, rather than do that, several pieces of equipment are tied together. Such a system, where the desired result is obtained by several successive passes through similar

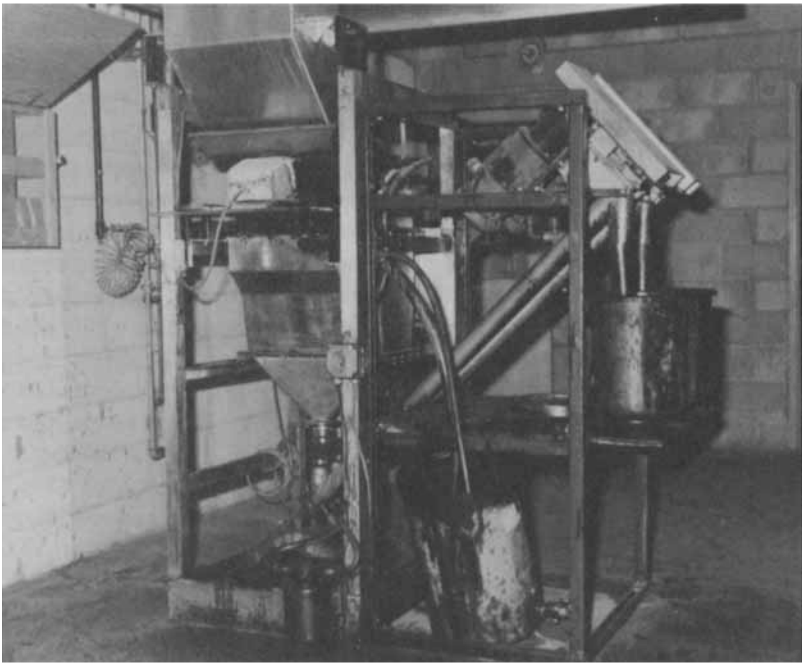

FIG. 8. Picture of the MGF-type separator.

process equipment, is called a cascade system. The processing in each piece of equipment is called a stagewise process and each piece is called a stage. There are several types of cascade systems, namely cocurrent, countercurrent, and crosswise.

History of Usage

The oldest incorporation of a cascade system into a separation process is fractional distillation. In this process the relative difference in the volatility or boiling points of the various components is used to achieve the desired separation. Other examples of cascade systems are countercurrent leaching and extraction, countercurrent decantation and repulping of solids, and many similar examples.

Purpose

This work was undertaken to identify the basic cascade system for solid concentration via the ferromagnetic fluid, FMF, sink/float method.

The Union Carbide Corp. Corporate Research Labs at Tarrytown and Tuxedo, New York, have been engaged in research on the applicability of using FMF for solids concentration. While municipal garbage seems to be a very good choice, other solid mixtures, such as liberated minerals in ore mixtures, are also good candidates. There are two basic differences between municipal garbage (the nonmagnetic inorganic residue) and the primary ore: the municipal garbage, being a secondary source, has particles which are 5.0 to 10.0 mm in size and the concentration of a desired component may be several percent. On the other hand, the ores are a primary source and the particle size of the mineral and gangue is in the 50 to 300 μm range, and the mineral concentration ranges from less than 1% to several percent. Municipal garbage and similar feed material can be fractionated with the float/sink method by utilizing equipment containing a simple electromagnet gap as described earlier. Such equipment has been designed by UCC, USBM, AVCO, and other concerns; basically, all the designs are similar. In contrast, the much smaller particle size range and lower desired mineral component concentration in the primary ores cannot be upgraded with conventional FMF equipment. UCC has invented and patented a device (U.S. Patent 4,062,765) which utilizes permanent magnets and is able to fractionate the smaller particle size range feed. Being that the mineral occurs in the ore at low concentrations, and the imperfect separation of a stage, a cascade system is needed to achieve the desired results.

Fully Countercurrent Cascade System

A fully countercurrent cascade system is illustrated in Fig. 9. It consists of a feed stage, stripping stages, and enriching stages. On the model shown in Fig. 9, feed material comes in at the feed stage and is split into a float stream moving up to the stripping stages and a sink stream moving down to the enriching stages. By definition of the separator, the float stream from the feed stage is leaner in mineral content than the feed stream, whereas the sink stream from the feed stage is richer in mineral content than the feed stream. The feed to any stage yields two product streams, each respectively richer or leaner than the feed. A successive application of this process yields terminal product streams called concentrate and tails. Recycling is necessary to maintain satisfactory recovery.

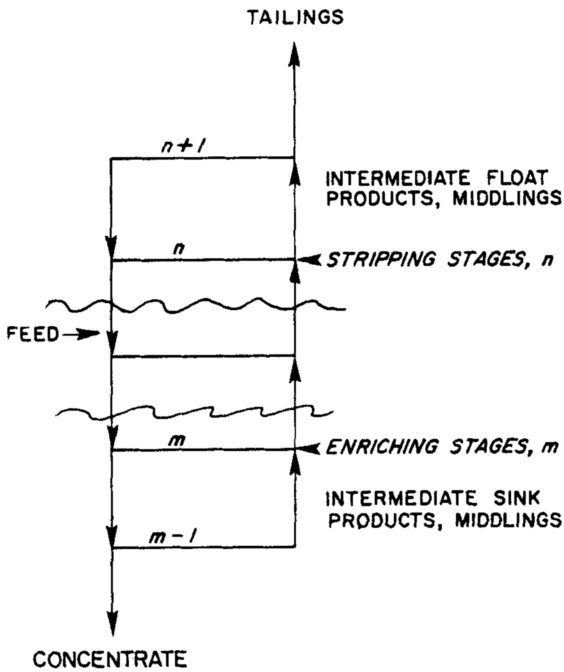

FIG. 9. Fully countercurrent cascade system.

The performance of the model can be analyzed with the use of mass balance equations.

Overall Material Balance

$$Q_F = Q_C + Q_T$$

where

Q_F = feed stream flow rate

Q_C = concentrate stream flow rate

Q_T = tailings stream flow rate

Overall Component Balance

$$Q_F Z_F = Q_C X_C + Q_T Y_T$$

where

Z_F = wt% mineral in Q_F

X_C = wt% mineral in Q_C

Y_T = wt% mineral in Q_T

The above equation could be applied to any stage in the cascade system. In this case the feed streams consist of two portions: the float stream from the stage below it and the sink stream from the stage above it. For the special case of the feed stage, the feed stream would be the third portion to the above-named feed constituents.

Simulation of a Cascade System with Alternatives

The design and building of an actual cascade system with MGF utilizing FMF is not possible now because not enough information is known about the behavior of such a system. Nevertheless, the cascade can be simulated with a batch technique described in detail in Chapter 9 of Ref. *13*. As a result, the cascade models described below can be considered.

The "Open Cascade" System

The open cascade system is shown in Fig. 10. This arrangement is the simplest and least complicated model from any viewpoint. It operates as follows: Feed material goes into Stage 1 which yields two product streams, a float and a sink. The float stream is leaner in the mineral, whereas the sink stream is richer in the mineral than the feed stream. Thus, a partial concentration has been accomplished. The float stream from Stage 1 goes as feed to Stage 2, again resulting in a float and sink stream which are respectively leaner and richer in the mineral than the feed stream to that stage. Thus, by repeating the process enough times, the desired stripping can be attained. In a similar manner, the sink stream from Stage 1 is the feed to Stage 6 where the float is leaner and sink is richer in mineral concentration

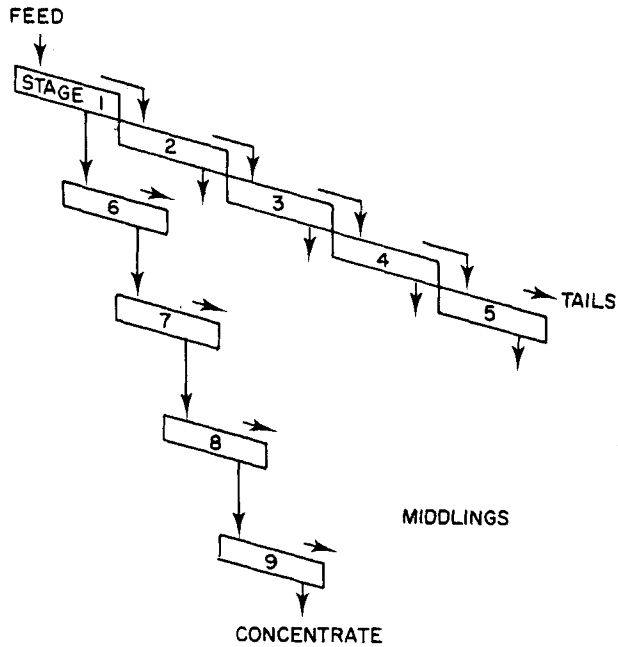

FIG. 10. Open cascade system.

than the respective feeds. By repeating this process enough times, the desired concentration is attained.

Although this simulation produces a lot of middlings, it is the preferred way to obtain distribution data of a component in the two product streams. This method has the advantage of requiring only one physical unit which can be used as Stages 1 to 9. Such simulation tests have been carried out with several ores as feed materials. Details of the testing process appear in Ref. *10*.

The "Closed Cascade" System

Although the open cascade system is quite satisfactory for obtaining distribution data, it does not simulate well at all the dynamic conditions in a cascade system.

A better practical model of a cascade system can be obtained by the use of a closed cascade system as shown in Fig. 11. Such a system simulates the behavior of a fully countercurrent cascade system better because inter-

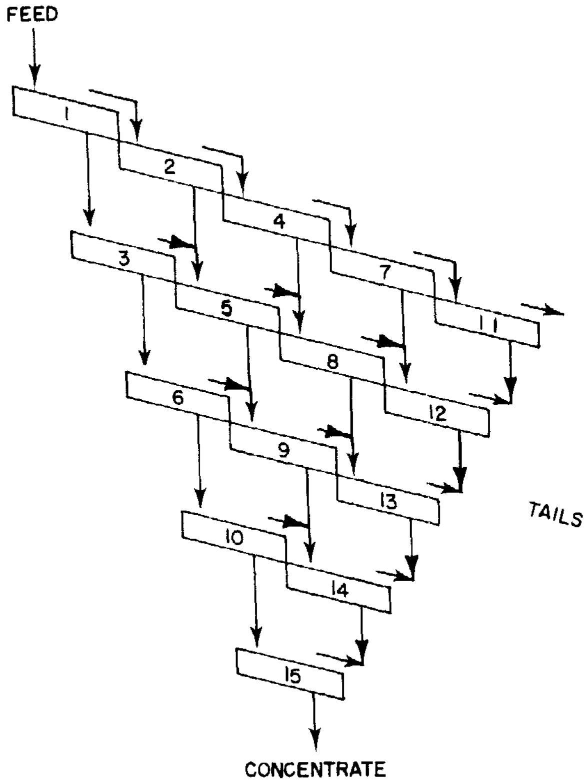

FIG. 11. The closed cascade system.

mediary sinks and floats do have an opportunity to mix and recycle. It must be run at steady state because departure from it would bias both product streams. The closed cascade operates on the same principles as the open cascade; however, more of the middlings are recycled and thus a further enrichment of the last concentrate is obtained. The tailings obtained in this process are leaner in the mineral than in the open cascade system. This process has also been tested in the lab. The results appear as previously mentioned. However, even this system produces middlings which are not lean enough to be classified as tailings and, therefore, some recycling is necessary. A possible system which might produce lean enough middlings to be discarded as tailings is an expanded version of the closed cascade system as shown in Fig. 12. In this system the various intermediary sinks and floats are recycled, though not in a countercurrent mode. However, this does not limit the performance of the system. The cascade as shown is a symmetrical

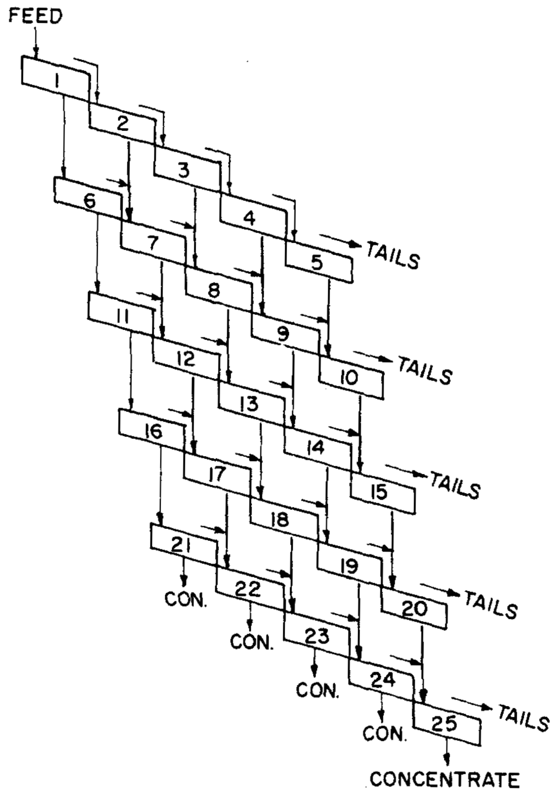

FIG. 12. Expanded closed cascade system.

design; however, it is by no means necessary to have a symmetrical unit. The object of the cascade system is to process a given feed to the required tailings and concentrates. Thus the system is very flexible and can be modified to include more float or sink stages, as desired, until the required products are obtained. The system must again be restricted to steady-state operation for meaningful results. Otherwise, the system is in a transient state and biases the products.

This variation has not been tested in the lab; it is only a proposal.

The Most Probable Cascade System

The most probable cascade system to be used for mineral beneficiation is not possible to specify because there is not enough information available.

However, the system as shown in Fig. 12 makes it a very good candidate. The "expanded closed cascade" has several advantages:

1. It is continuous, gravity driven, and not energy consuming.
2. Each stage could be tilted to a different angle, thus optimizing its performance.
3. It is most likely to produce lean enough middlings to be discarded as tailings and rich enough concentrates to be acceptable as such.
4. It can be extended at will by adding more sink and/or float stages until the desired tailings and concentrates are achieved.
5. If the above is not practical, then some middlings (which would be a small weight percent of the total feed) could be recycled on an interim basis to the feed or other stage.

Basically, the system is flexible and adaptable to the required end conditions. Thus, based on the above criteria, such a system has the potential of becoming the preferred cascade system. The "expanded closed cascade" system, therefore, has been chosen as the most likely practical candidate short of a cumbersome (in this case), completely countercurrent system.

Economics

The economic merit of such a cascade system, at present, can only be inferred from its theoretical aspects. The actual, continuous performance of a cascade has not been tested. Judging from the simplicity and gravity driven aspect of the most likely design, it can be inferred that both the investment and operational cost of the cascade system would be economically viable.

Feed rates are a direct function of the feed grid physical surface area. As in any separating system, saturation can occur. The desired separation can be obtained by tailoring the number of stages. The above two criteria play a principal role in the overall economics of the cascade system.

CONCLUSIONS

A batch process sequence has been developed (*10*) whose data can then be used to model a continuous cascade process system. This assumption has been confirmed in the laboratory.

Various practical cascade systems have been proposed; the best practical design depends on the process economics of the system. The economics are envisioned to be favorable because the system has few moving parts, uses very little energy, and it should be inexpensive to build and operate.

RECOMMENDATIONS

Based upon the conclusions given, it is recommended that:

1. Grid design be optimized as a function of feed material.
2. Further tests with various feed materials be performed to substantiate the generality of the developed cascade modeling method.
3. A flexible cascade system be built which would operate continuously. The purpose here is to obtain actual continuous operating data, thus further refining and adapting the modeling method to the FMF sink/float separation process.

Acknowledgments

This work was done at the Tuxedo, New York, facilities of Union Carbide Corp. while the author was employed by the Corporate Research Labs of Union Carbide, Tarrytown, New York.

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