Treatment of fine particles poses severe problems in both mining and mineral processing. As ore grades decline and demand for mineral products grows, increasingly large tonnages of ores must be mined and milled. During mining, large amounts of fines are often generated that cannot be easily processed. Such excessive production of fines leads to an increase in the cost of mineral products. Thus, advances in mining and transportation methodologies for reducing the generation of fines have become highly necessary, not only to reduce the cost of producing mineral products but also to retard the rate of depletion of our natural mineral wealth.

Closely linked to the problem of declining ore grades is the more serious problem of decreasing liberation size of minerals in ore. A direct consequence of this decline is an increase in the amount of fine grinding needed to process the ore. Because grinding is the most energy intensive operation in milling, any increase in grinding is economically undesirable.

More important, the technology for beneficiating finesized mineral matter is, for all practical purposes, yet to be developed. In some cases, incredible percentages of fines are discarded. In the early 1970s, for example, one-third of the phosphate mined in Florida, one-half of the tin mined in Bolivia, and one-fifth of the world’s tungsten were lost as fines. Significant amounts of fines are also lost in copper, uranium, fluor spar, bauxite, zinc, and iron production. In addition to representing a loss in values, fines often present severe environmental problems. In Florida, phosphatic waste produced at a rate of about 40 million stpy is stored in thousands of acres of ponds behind dikes. These dikes have been known to breach, hence the slime may remain as an environmental hazard for decades.

In the future, the amount of fines generated during milling is likely to increase. Unless improved technology is developed for processing fine-sized particles, we will continue to throw away increasing amounts of valuable, nonrenewable mineral resources.

Today, neither the needed technology nor sufficient basic understanding of the behavior of fines to develop such technology is available. Most conventional mineral processing techniques fail in the sub-sieve size range (Fig. 1). Gravity concentration techniques become unacceptably inefficient. Flotation, the most important mineral beneficiation operation today, usually fails when used alone in the ultrafine size range. In fact, in phosphate rock processing, flotation is not even used for the beneficiation of the minus 150-mesh fraction, which contains more than one-third of the phosphate value and a number of accessory elements such as uranium. Equally serious problems exist in the processing of cassiterite, taconite, and pentlandite ores.

Clearly, we need to understand the basic reasons for the existence of lower particle size limits for applying and operating separation and sizing devices. We need to establish whether these reasons are intrinsic to the process and are thus unavoidable.

At this point, it might also be noted that challenging problems also exist in extending some of the mineral processing techniques to coarser size ranges. Flotation of coarse-sized potash and high-gradient magnetic separation of plus 100-micron mineral particles fall into this category.

### EFFECTS OF PARTICLE SIZE

In gravity concentration, the effectiveness of equipment such as jigs, heavy-media hydrocyclones, and hindered-settling classifiers decreases rapidly for minus 100-micron material. Shaking tables, Humphrey’s spirals, pinched slucies, buddles, Burch shaken helicoids, Barltes-Mozley tables, vanners, and strakes are reported to be operative down to 10 to 20 microns, but below this size range these devices become totally inefficient. Even in the 10- to 20-micron size range, their efficiency is very low.

In some cases, the lower limit on particle size is in part determined by the limited capacity of the concentrator, which can only treat one or two layers of particles at a time. As particle size decreases, such operations will require concentrators of increasing surface area. Multi-deck concentrators partially overcome this problem. Thus, Barltes-Mozley tables with 40 fiber glass decks reportedly have been used to recover cassiterite particles down to 8 microns.

The basic reasons for the failure of gravity concentrators in the ultra-fine size range are not currently known. It has been suggested that in this size range, particles begin to lose their identity and act as fluids. Under such conditions, separation based solely on differences in specific gravity becomes almost impossible. However, since even macromolecules can be separated using ultracentrifuges, ultra-fine size cannot be considered a true limit for gravity concentration.

More important, the size limit might be determined by the interference between transport and separation functions in a separator. Design of devices that produce minimum interference may actually be the key to extending gravity concentration techniques to lower size ranges. In this regard, it is vital
to fully understand the hydrodynamics of solid-fluid suspensions, so that working models can be developed for the best transport and separation functions with minimum interference between them.

In gravity processes, separation is essentially dependent on the difference in the positions taken by various particles in the separator. It would be most worthwhile to determine what other forces, such as centrifugal forces, can produce such differences and thereby extend the operating range of these techniques. Similarly, it is also important to identify the properties of fluids that would help produce better control of fluid drag forces and thereby produce better separations.

In flotation concentration, a number of studies have been made on the effect of particle size. The first may have been by Gaudin in 1931. A recent, detailed analysis of past data by Trahar and Warren has clearly shown the nature of dependence of flotation efficiency on particle size. Generally, best recoveries were found for intermediate-sized particles in the 10- to 100-micron size range. However, in several cases, contrary to normal observations, flotation of fines has been found to increase with decrease in size. This effect is thought to result mostly from the mechanical entrainment of fines during flotation, which has an undesirable effect on the grade of the concentrate.

Studies have also been conducted on flotation rate as a function of particle size. These studies have confirmed that the flotation rate of the sub-sieve size fraction is lower than that of the coarser size. Furthermore, it has been suggested that each of the ultra-fine fractions can be considered to be composed of a fast-floating and a slow-floating fraction and that the decrease in the rate of flotation is due to a decrease in the rate of flotation of the fast-floating component. The reasons for such decrease in flotation rate with particle size are not yet known, however.

Theories developed to explain the poor flotation of fines include those based on collision by interception of particles and bubbles in streamline flow, collision by inertial impact, collision by diffusiophoretic motion, and collision by entrainment in turbulent eddies, as well as those based on attachment due to increased dynamic contact angle and due to lower momentum of fine particles (Fig. 2). However, none of these theories explains the observed dependence of flotation on particle size. Particle size can also affect such physico-chemical properties as surface energy, solubility, and rate of adsorption of flotation agents. However, such effects might be negligible in the size range of interest here.

Slime coating is yet another factor to be considered in this regard, having been shown to reduce flotation in certain systems but not in others. Slimes also have been thought to affect flotation by causing excessive reagent consumption. While this may be true for certain systems, Iwasaki et al. observed very little difference in the residual concentration of the reagent when deslimed and undeslimed ores were used.

The above discussion clearly points out the contradictions in our understanding of the particle size effect on flotation and the need for detailed, basic research. Better understand-
ging of size effects can help in extending conventional froth flotation techniques to lower size ranges.

Currently, three possibilities hold promise for extending flotation to fine size ranges:
1) Development of flotation reagents that can selectively adsorb onto minerals. For example, oximes can be used in the flotation of oxidized lead and zinc ores.
2) Use of variables such as temperature as a means of process control. For example, Cleveland-Cliffs Iron Ore Co. makes use of hot flotation to float finely ground iron ore.
3) Use of techniques that permit refluxing, such as column flotation.

In each of these three areas, there has been only limited application so far. For example, temperature has been used as a process parameter in only a few cases on a commercial scale, namely treatment of fluorite, some sulphides, and taconite ore. Also, little basic research has been conducted to elucidate the mechanisms that relate to temperature. Similarly, column flotation, which has been reported to give results that are superior to conventional flotation for underslaked uranium ore, fine graphite containing clay, and minus 100-mesh copper ore, has experienced scale-up problems. Additional work in modifying conventional flotation for use on fine material is greatly needed.

In magnetic separation, both low- and high-intensity wet magnetic separators have been used for separation in the sub-sieve size range, the former to treat minus 325-mesh magnetic taconites and the latter mainly for purification of minus 2-micron kaolin and for removal of pyrite and ash from fine coal in water slurry.

High-gradient magnetic separation is a new technology that appears to hold enormous potential for processing mineral fines. The technique reportedly has been used successfully to beneficiate semi-taconites, oxidized taconites, coal, and kaolin. However, to the author’s knowledge, commercial application has been limited to the beneficiation of kaolin. Use of extraneous agents to treat the ore to generate areas of higher magnetic susceptibility might possibly extend the application of this technique.

The use of superconducting magnets is another area for potential development. The need for washing the matrix intermittently without having to switch off the magnet creates problems, and it would be worthwhile to develop a separator that separates particles using a stream splitter instead of a matrix. Such a system is being developed by both Cohen of the Royal School of Mines in London and Boom of the University of Wisconsin. Hopstock recently pointed out the need for the development of a superconducting magnetic separator with stream splitter for treatment of sub-sieve size particles. Such a separator could be capable of high throughput without use of moving parts.

On the other hand, use of air instead of water as the fluid medium has been suggested, to minimize the problem of fluid-drag forces in the fine size range. Use of air also avoids the deleterious effects water may have on the system.

Water is also avoided in electrostatic separators, which might be applied in the fine size range with the help of pulsed corona discharge, high rotor speed, and external electric field.

FINES CONCENTRATION

The techniques for concentrating fines are charted in Fig. 3. The techniques that currently appear to be most promising are discussed here:

Flocc-floatation techniques can be used to minimize such factors as lower collision and adhesion rates of fines. On a laboratory scale, at least, such techniques reportedly have been used for the removal of colloid material from effluent waters. In mineral processing, the technique can be employed profitably if the process of aggregation can be made to take place selectively.

Selective flocculation has been used successfully on a commercial scale for the beneficiation of low-grade iron ore.
Fig. 3—Separation of mineral values

Specific aggregation of collectors

Conventional flotation (modified)

Hot flotation

Column flotation

Specific adsorption of collectors

Aggregation

Oil

Fine bubbles

Miscellaneous field forces

Chemical

Emulsion flotation

Ultra flotation

Spherical agglomeration

Pressure release flotation

Vacuum flotation

Electro flotation

Foam separation

Gravity

Magnetic

Electrostatic

Electrophoretic

Hydrometallurgy

by Cleveland-Cliffs, and the process has tremendous potential when it is accompanied by flotation, elutriation, filtration, etc. However, various problems will have to be solved both at the basis and applied levels before this potential can be fully realized. For example, the advantages and disadvantages of various combination techniques are not known.

In the case of flocc-flotation, flocculants can be expected to interact with the subsequent flotation process. For example, the flotation of sphalerite and smithsonite has been found to be enhanced by the addition of Separan and certain Aerofloc and Nalco flocculating agents up to certain concentrations and to be depressed above them, according to Usui, et al. Such interactions need to be understood fully so that they can be controlled beneficially. In this regard, development of reagents containing specific chelating ligands should also be of significant benefit to the advancement of mineral processing technology.

Ultraflotation involves flotation of ultra-fine anatase from clay using an auxiliary coarser material such as calcite. Since anatase does not float by itself, it is co-floated in the presence of the coarser calcite particles, which possibly act as a carrier for the anatase. This technique has been used on a commercial scale by Engelhard Minerals & Chemicals Corp. for more than 10 years, but it has not been applied successfully in benefiting any other ore.

Further development of ultraflotation technique is handicapped at present by a lack of understanding of the basic mechanism by which the process works. Basic research is needed on this mechanism to allow it to be used in other systems.

Spherical agglomeration is yet another technique that depends on the aggregation of particles. In this case, the fines are tumbled in an aqueous solution containing an immiscible liquid that will form capillary bridges between reagentized particles and thereby cause their aggregation. This technique has been used on a laboratory scale by the National Research Council of Canada to agglomerate graphite, chalk, zinc sulphide, coal, iron ore, and tin ore suspensions in aqueous solutions. Further development work on this process—especially with respect to affects and interactions of major process variables on grade, recovery, agglomerate strength, porosity, etc.—could prove very useful for systems in which the fuel value of the oil in the agglomerates could be extracted during subsequent stages in the processing.

Emulsion flotation and liquid-liquid extraction are other processes that use significant amounts of oil. In emulsion flotation, oil droplets are used for collection of mineral fines. In liquid-liquid extraction, the particles collected at the oil-water interface are removed mostly by phase separation. In these processes, the greater momentum of oil droplets than air bubbles during collision may be a contributing factor in increasing the flotation rate of fines. Another factor, suggested by Lapidot and Mellgren, involves the possible formation of a quasi-continuous oil film between particles during reagglomeration. Again, additional work is needed on various chemical interactions at oil-solid interfaces to develop a full understanding of the mechanisms that determine size distribution of droplets in various mineral-collector/solution-oil systems. Control of size distribution can provide the opportunity to optimize recovery and grade of the mineral values.

Fine bubble flotation can more easily collect fines than flotation by bubbles of the size generated in conventional flotation cells. Techniques that yield fine bubbles include vacuum flotation, pressure release flotation, and electrolotation. Improved selectivity can be expected in the first two processes because bubbles are likely to be generated preferentially on hydrophobic sites. Indeed, the presence of air pockets can be detrimental on particles that can act as nuclei.

Klassen and Molokourov have obtained improved selectivi-
TARGETS FOR FINE-PARTICLE RESEARCH

PROCESSES USING OIL
(Emulsion flotation, liquid-liquid extraction, spherical agglomeration)
Work is needed on the molecular ionic interactions at various oil-solid interfaces, on the effects of variables and interactions between variables, and on mechanisms involved.

FINE BUBBLE FLOTATION
(Vacuum flotation, pressure release flotation, electroflotation, foam separation techniques)
What is the potential for combining electroflotation with conventional flotation? What is the best size distribution of bubbles and the best electrode geometry? What are the side effects of mineral surface and solution species?

FINE GRINDING
What are the mechanisms of fracture in polycrystalline and polyminal specimens? How can the practical limit of grind size be reduced? What is the best size distribution of fines and what are the mechanisms involved?

FINES CHARACTERIZATION
How do size distribution, surface area, surface charge, and other physical characteristics affect process control? What can be done to characterize surface composition, heterogeneity, oxidation state, and other surface characteristics?

DEWATERING OF SLIMES AND SLUDGES
What prevents the water from separating from the slimes? What determines whether the supernatant is turbid or clear? What causes the coarse-particle effect? What causes the seepage effect? What is the potential for combining techniques?

OTHER PROBLEMS
In addition to the beneficiation of fines, other major problems related to fines processing include production and characterization of fines and dewatering of fine suspensions. Production of fines by comminution is a major consumer of energy, and to reduce energy use, every effort must be made to devise methods that produce intergranular rather than the usual indiscriminate intragranular fracture of particles. In this regard, basic studies to identify means by which applied force can be focused at the grain boundaries can be expected to yield results.

Effort must also be made to utilize the beneficial effects that grinding aids may produce in enhancing liberation processes.

An important problem in fine grinding is the existence of a practical grind limit that is often the result of a physical equilibrium created between the processes of size reduction and reagglomeration of fines. Identification of chemical or physical means for reducing agglomeration, and thereby the grind limit, should be of significant use.

Fine products also have to be properly classified and characterized. There is a need to develop new classification devices, especially for the minus 30-micron size particles, on an industrial scale. More important, inconsistencies between various measurement techniques in the fine size range have to be monitored and eliminated.

It would also be desirable to develop classification techniques based on surface area, especially for the sub-micron size range. Characterization of mineral fines in terms of shape, internal structure, mineralogical heterogeneity, and surface chemical composition are also essential to facilitating meaningful research.

Dewatering of mineral slimes and sludges is another serious problem facing the US mining industry. For example, filtration of the product of selective flocculation was the major technical problem faced during the recent commercial development of this process by the taconite industry, and, as mentioned above, the problems caused by phosphatic slime are notorious. Similar problems exist in the treatment of coal slimes, red mud, etc.

There is a definite need to determine the cause of the pertinacious behavior of slime-sized particles in suspensions and for developing economical processes for dewatering the slimes. Fundamental studies also are needed on the permeability properties of capillary systems made up of mineral fibers and fines, so that methods can be developed for controlling fluid flow in sedimentation and filtration systems. Also, the effects of chemical additives as drying agents and physical properties such as temperature on fluid flow should be understood to produce any significant development in this area.

In summary, the treatment of mineral fines has become a major problem of increasing magnitude. While several techniques can be seen on the horizon for concentrating such fines, a number of problems have to be solved before they become commercially successful. These problems have to be solved in order that minerals demand can be better met from existing reserves.

It is most important to recognize that solution of these problems is dependent to a large measure on achieving a full understanding of the fundamental behavior of fine particle systems. This can be accomplished only by research on a significantly expanded scale. The magnitude of the problems is such that it is essential to have greater cooperative efforts and exchange of information between academic, industrial, and government institutions.

REFERENCES