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DIFFERENTIAL FLOTATION

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definitions</td>
<td>5</td>
</tr>
<tr>
<td>Principles Involved</td>
<td>6</td>
</tr>
<tr>
<td>Varying or Altering Interfacial Tension System</td>
<td>9</td>
</tr>
<tr>
<td>Nature and Amount of Pre-agitation</td>
<td>20</td>
</tr>
<tr>
<td>Material and Design of Machine</td>
<td>21</td>
</tr>
<tr>
<td>Temperature</td>
<td>21</td>
</tr>
<tr>
<td>Amount of Reagent Used</td>
<td>22</td>
</tr>
<tr>
<td>Amount and Nature of Aeration</td>
<td>22</td>
</tr>
<tr>
<td>Conclusion</td>
<td>23</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>21</td>
</tr>
</tbody>
</table>
LIST OF ILLUSTRATIONS

Fig. 1—Water Spreads on Mineral ................................................. 6
Fig. 2—Oil Spreads on Mineral ...................................................... 7
Fig. 3—Air Bubbles Passing Up Through Oil-Water Emulsion .......... 8
Fig. 3-A ................................................................................. 9
Fig. 3-B ................................................................................. 9
Fig. 4—Low Oil-Solid Interfacial Tension ................................... 11
Fig. 5—High Oil-Solid Interfacial Tension .................................. 12
Fig. 6—Immiscible Liquids ......................................................... 12
Fig. 7—Water in Continuous Phase ............................................. 13
DIFFERENTIAL FLOTATION

By A. W. Fahrenwald

Definitions

The flotation of one mineral in the presence of another floatable mineral has frequently been referred to as "selective," "differential," or "preferential" flotation. The use of these terms in speaking of the same process leads to confusion and should be discouraged.

There seems to be no reason why these terms should be used so indiscriminately, and why such a process could not be properly called "differential" flotation to the exclusion of other terms. Such a discrimination, if generally accepted, would make it plain to the reader of an article that the separation of one floatable sulphide from another was the subject of the discussion, and would eliminate the annoyance of reading an entire article only to find that collective flotation of all the sulphides was meant.

A somewhat new classification or compromise in the use of these terms has been made recently. According to C. C. Freeman in Australian flotation parlance the terms "preferential," "selective," and "differential" are practically synonymous. On the other hand, Freeman, as a matter of convenience, uses "preferential" to refer to methods based on chemical alteration of the surfaces of one or more of the sulphide minerals, and "differential" to include all methods where no definite chemical alteration can be detected. C. A. Wright makes a similar compromise in the use of the terms. He stated: "Differential flotation is the flotation of one floatative mineral in the presence of another ordinarily floatative mineral; preferential flotation is a name applied to a special type of differential flotation in which a mixture of two floatative minerals is given a light roast in order that one may be oxidized while the other remains unchanged. Only the surface of one of the minerals is oxidized, but this suffices to keep it from floating."

The writer can see no basis for such discrimination in the use of the terms when speaking of two phases of one process involving identical principles and seeking similar results, for it can not

always be told whether the conditions of floating one mineral in the presence of another are due to a chemical or a physical action. While in this paper the terms will be used in this latter sense, it is hoped that some common system or classification of terms will eventually be adopted.

Principles Involved

Differential flotation is based on the differences that minerals can be made to show in the degrees to which they are wetted by water and oils, and the whole problem resolves itself into one of bringing about preferential "spreading of liquids on solids." This preferential spreading is in turn dependent upon the relations between the physical properties of the various phases composing the system, in other words, it is dependent upon the interfacial tension system made up of solid-water, solid-oil and oil-water phases. For example, if conditions in the system represented in Fig. 1 are such that algebraically

$$ T_{gw} < T_{go} + T_{wo} $$

Note: $T_{gw}$=Galena-water interfacial tension, $T_{go}$=Galena-oil interfacial tension, $T_{wo}$=Water-oil interfacial tension.

the mineral galena will be wetted by the water and not by the oil, will not be drawn into the water-oil interface, and will not float.
Again, in the system represented in Fig. 2, if conditions with respect to the floatable mineral sphalerite are such that

\[ T_{sw} \geq T_{so} + T_{ow} \]

**Note:** \( T_{sw} \) = Sphalerite-water interfacial tension.

the sphalerite will not be wetted by water but will be enveloped by a film of oil the thickness of which is probably several molecules. The oiled sphalerite particle, if placed in a bubble column, will be drawn into the oiled water-air interface and carried to the surface.

If, in the treatment of an ore containing both galena and sphalerite, we can control conditions so as to establish at the same time the relations depicted in Figs. 1 and 2, it is evident that a removal of the sphalerite can be made by flotation, and that the galena will remain non-responsive. The galena can be subsequently floated by changing the balance of interfacial tensions in its favor. Flotation conditions can theoretically be made to favor any mineral in this way.

It is interesting to consider still further the behavior of oil, air, and mineral particles in water. Suppose we take a small quantity of one of the common flotation oils, say G.N.S. No. 5 pine oil, shake it with water until the two are thoroughly mixed, and allow the mixture to stand; a plainly visible film of oil will collect on the surface. Part of this oil is dissolved and part is probably emulsified in the water. This oil, like so many others, greatly lowers the surface tension of the water (one drop, 8 milligrams, emulsified in
100 c.c. of water, lowers the surface tension of the latter from 72.8 dynes per cm. to 64.0 dynes per cm.), and therefore obeys the experimentally determined law that any substance which lowers the surface tension of water becomes concentrated or adsorbed at its surface. If bubbles are passed up through such oiled water, they give added surface on which oil at once concentrates. The rising bubbles carry this adsorbed oil to the surface, and if the surface water be removed continuously as the bubbles burst, a large part of the oil in the water can be removed.

![Diagram](Surface of Oil-Water Emulsion)

Fig. 3.—Air Bubbles Passing up Through Oil-Water Emulsion.

If an arrangement is provided to pass a given number of bubbles of a known diameter up through the oil-water mixture, and if the surface tension of the skimmings and of the main body of the mixture is measured, it is possible to calculate the surface concentration of the oil molecules. Fig. 3 shows, in an exaggerated form, the condition described.

If now we take an identical oil-water mixture or solution, and instead of passing bubbles into it, we drop a weighed quantity of galena particles of known size down through it, we can show by actual measurement that the surface tension of the oil-water is increased. This increase indicates that adsorption of oil molecules at the surface of the mineral has removed part of the oil from the water, and thereby has increased its surface tension. Fig. 3-A represents what goes on in this process.

In these cases the oil lowers the water-air and the mineral-water interfacial tensions respectively, and is concentrated at these interfaces. If we have both air and galena present, concentration of the oiled-mineral particles will take place at the water-air interface, as shown in Fig. 3-A, and flotation of the mineral will result.
If instead of galena we take quartz, any number of particles can be dropped down through the watery-oil without increasing noticeably its surface tension, indicating that oil is not adsorbed at the surface of this mineral, and is not removed from the water. On the contrary, water molecules are adsorbed at the quartz surfaces, and no doubt a decrease in surface tension is produced, though apparatus sufficiently delicate to measure it can not be had.

If air is bubbled up through oil-water in which these quartz particles are suspended, the bubbles will push the quartz out of their way and rise to the surface; the quartz is repelled from the oiled air-water interfaces of the bubbles and sinks with little interference. Fig. 3-B illustrates what happens.

As pointed out below, many substances in a state of high dispersion affect flotation by adsorption or surface concentration. There are two possible ways of varying or altering an interfacial tension system, namely:

1. Through the use of a reagent or a contaminant
2. Through the use of heat
   a) on the solid phase
   b) on the liquid phase.
By the word "contaminant," is meant any substance or reagent (solid, liquid or gas) that is capable of being adsorbed at the surfaces of the various phases, or in their interfaces. Interfacial tension is affected by adsorption and it can be increased or lowered by the use of suitable contaminants. Molecules of liquids or gases, ions, colloids, and electrical charges may be adsorbed at surfaces, and any of these may play an important role in results. Colloids are capable of adsorbing ions to the extent of assuming their properties and migrating in an electric field toward the anode or cathode according to the sign adsorbed; sulphide particles in a flotation pulp are similarly capable of adsorbing colloidal particles to an extent sufficient to cause them to behave as large particles of gangue material. Gases likewise are strongly adsorbed at the surfaces of all solids. The immense specific surface of colloids would make them readily adsorbed, and would account for the mischief they sometimes play in preventing clean concentration; the use of another contaminant more strongly adsorbed obviates their deleterious effect. To illustrate, in one case when oil alone was used, a heavy, dirty concentrate was produced; when sodium phosphate, two pounds per ton, was added to the pulp, a concentrate free from gangue came up.

Too much emphasis can not be placed on the importance of adsorption and the behavior of exceedingly small particles (colloids). They can act as contaminants and produce either deleterious or beneficial effects in flotation, depending upon their physical properties, the surface on which they are adsorbed, and the tenacity with which they are held there. It is not unreasonable to believe that in some cases colloids promote differential flotation by being more strongly adsorbed at the surface of one mineral than at the surface of another; however, the writer does not know of any differential results that are attributable to such selective adsorption of colloids.

Contaminants may be arbitrarily classified according to some such system as the following:

(1) Oils and their fractions
(2) Acids and alkalies
(3) Salts
(4) Colloids
(5) Gases.

While it is well known that oil is not essential to flotation and that it is not used at several mills, it remains the chief contaminant for flotation. The term "oil" flotation, occasionally seen in
writings, is used wrongly, "froth" or "bubble" flotation is more strictly proper.

A contaminant may be soluble or insoluble. In either condition it can be adsorbed, but decidedly more strongly so when dissolved. When a substance goes into solution, it becomes molecularly dispersed; the molecules travel rapidly, they are very susceptible to the influence of the other molecules, are drawn closer to surfaces than colloids or suspensions, and are therefore held more strongly. In one case sodium chloride acts as a flotative agent, salt cake is quite a common agent in flotation and sodium carbonate acts in a small degree as a frother and as a mineral collector.

![Diagram](image)

**Fig. 4.—Low Oil-Solid Interfacial Tension; Small Oil-Solid Contact Angle a**

Oils usually wet or adsorb on sulphides but do not have any tendency to spread on quartz—here is a definite selective wetting action. In the case of the sulphide the interfacial tension system, oil-water, oil-sulphide and water-sulphide, Fig. 4, is in an equilibrium in which

\[ T_{\text{mw}} > T_{\text{ow}} + T_{\text{mo}} \]

Note:  
- \( T_{\text{mw}} \) = Mineral-(sulphide) water interfacial tension  
- \( T_{\text{ow}} \) = Oil-water interfacial tension  
- \( T_{\text{mo}} \) = Mineral-oil interfacial tension

and the oil readily spreads on the sulphide.

In the case of quartz, Fig. 5,

\[ T_{\text{qo}} > T_{\text{qw}} + T_{\text{ow}} \]

Note:  
- \( T_{\text{qo}} \) = Quartz-oil interfacial tension  
- \( T_{\text{qw}} \) = Quartz-water interfacial tension  
- \( T_{\text{ow}} \) = Oil-water interfacial tension,
however, the latter is wetted by water and not by oil, and in a flotation cell is repelled from the bubbles.

In the case of the sulphide galena and quartz, the natural tendencies in the spreading of oil and water on sulphide and quartz respectively are as opposite as can be imagined. There is not such a wide difference displayed by different sulphides in the degrees to which they are wetted by oil. Some of them, in their normal oil-attracting tendencies, are intermediate between quartz and galena, and the oil-mineral and water-mineral contact angles are in the neighborhood of 90 degrees. In this case a sulphide generally sinks. Those minerals not under the influence of such positive selective wetting, as galena and quartz, can be caused to behave after the manner of either by the introduction of a small amount of a substance that affects the energy at the interface. Most substances do affect the energy in varying degrees.

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**Fig. 5.—High Oil-Solid Interfacial Tension; Large Oil-Solid Contact Angle.**
If we have two immiscible substances, neither of which will spread on a solid or liquid surface, they will take the positions shown in Fig. 6; the interfacial tensions are all a maximum and flotation will not result. However, if neither spreads on the solid, but the two are miscible in each other, the mixture may or may not wet the solid; and we have no way of telling which except by experiment. The mixture may show a differential tendency between two different sulphide surfaces not shown by either of its constituents. The impossibility of forecasting anything in flotation testing is quite apparent.

For the sake of speculation let us take the same two immiscible liquids and the same solid as indicated in Fig. 6. If we shake the two liquids violently together and form a permanent emulsion of either in the other, the emulsion or either phase will not spread. If the water is the continuous phase, Fig. 7, and a third substance

![Emulsion of oil in water](image)

Fig. 7.—Water in Continuous Phase.

or contaminant be added which is soluble in the water but not in the oil, the contaminated emulsion may or may not wet the solid, depending on how the water-solid and water-oil interfaces are affected by the addition. If the contaminant added is miscible in the oil and not in the water, it would probably have little effect due to its inability to diffuse through the continuous (water) phase.

This discussion serves to point out some of the phenomena fundamental to flotation and the present impossibility of predictive analysis with our meager knowledge of the physics of the subject.

As has been pointed out in the case of a mixture of quartz and galena or another sulphide, the selective spreading of oil and water is very marked and a separation of these two minerals is a very easy matter; we have a good deal of latitude within which to alter the interfacial tensions by the introduction of a contaminant into such a system without upsetting conditions to the point of producing poor results. If, however, we have two sulphides, say sphalerite and galena, we do not have such a wide range between the tensions of the two liquid-mineral interfaces; if we wish to separate these by flotation, a true differential problem, our
problem is to cause either the sphalerite or the galena to be temporarily wetted by water as quartz normally is, without destroying the natural tendency of the other to be selectively wetted by oil. Usually galena is slightly more floatative than sphalerite and a small degree of differential separation of these two can be effected in the flotation cell by careful manipulation or regulation of the quantity of oil and air. But the real problem here is to decrease the sphalerite-water and the galena-oil tensions and to increase the sphalerite-oil and the galena-water interfacial tensions respectively, in order to float the galena, or vice versa to float the sphalerite. It cannot be predicted what contaminant should be added to affect the system of interfacial tensions in the manner mentioned, and it is along this line that untiring efforts are put forth by flotation metallurgists; every conceivable kind of material, compound, etc., has been tried in the blindest and most empirical way.

In the hundreds of thousands of tests that have been made by different experimenters, a few agents or combinations of reagents have been stumbled upon that give, in some degree, differential flotation. The unfortunate thing about it, however, is that a combination of reagents giving differential flotation with one ore does not necessarily do so with another ore of apparently similar mineralogical and physical character. Every problem has been one of tedious cut and try, a fact which has effectually retarded progress in differential flotation.

As mentioned above, there are two methods available for controlling the interfacial tension system of the three phases—solid, liquid and gas; the alteration or modification of any one of these will affect the entire system of forces. In the interest of economy, it is most feasible in practice to modify the liquid phase by the use of suitable agents. The solid phase is altered by roasting at carefully regulated temperatures; by this means the surfaces of one mineral can be altered chemically and physically while another remains, under the conditions of roasting unaltered. The Horwood process for galena-sphalerite ores involves roasting at a low temperature (about 400 degrees Centigrade); at this temperature the galena is superficially oxidized; while the zinc sulphide is quite stable and remains unaltered. The unaltered sphalerite is floated away from the roasted galena which is selectively wetted by water after the manner of quartz. This process has not gained much headway for the reasons that it requires great care in the manipulation of the roast, and is usually an expensive process of preliminary treatment.
Other chemical processes are and have been used to alter the surface of one mineral in the presence of another. For example, carbonate ores, which normally show little flotative tendency, are made to float by giving them a preliminary treatment with hydrogen sulphide (H₂S) gas or some soluble sulphide; sodium sulphide (Na₂S) is among the commonest and best. Of course, the use of a chemical for altering the surface of a solid inevitably alters the surface tension of the liquid phase also. Other oxidizing and reducing processes are treatment with ferric chloride or hot acid solutions, and the Bradford acid-salt method; the latter attacks and alters the surfaces of the galena, and some of the lead passes into solution as the chloride.

The surfaces of solids are sometimes altered by the adsorption of colloids, in many cases to the extent of doing actual mischief. This is rightly classified among those processes in which the liquid phase is the one modified, for these colloids could not be adsorbed if they were not first suspended in the solution. The action of water glass (Na₂SiO₃), which in some cases has given good differential flotation of galena from lead-zinc ores, cannot be definitely ascribed to an alteration of either the liquid or the solid phase. It is not known whether the selective action is due to contamination of the liquid, to chemical action on the sulphides, to selective adsorption at the surfaces of one sulphide in preference to the other, or to a combination of all these actions. It is possible that a deposition of silica on one or the other of the metallic mineral faces prevents the adsorption of oil. The fact remains, however, that it does assist in promoting in the pulp conditions favorable to differential flotation.

Other substances which enhance lead flotation and suppress zinc and iron are soda ash (Na₂CO₃), sodium hydroxide (NaOH), sodium phosphate (NaHPO₄), potassium permanganate (KMnO₄), salt, lime, potassium bichromate (K₂Cr₂O₇), coal tar, cresote, alcohol and gasoline. The effectiveness of these may be modified by the gangue constituents of the ore and the nature of the water used in milling.

The Bradford SO₂ process, in which SO₂ is introduced or generated in the flotation pulp under proper control of quantity and temperature of the gas, pulp dilution, etc., seems to neutralize the natural tendency for the ZnS to float without affecting the flotative properties of the galena. The action is only temporary and the natural flotative property of the zinc is restored by heating the pulp or by adding acid, aerating and adding such salts as Na₂SO₄,
CuSO₄, etc. This process happily differs from other chemical contamination processes in that it is applicable to a high percentage of all lead-zinc-iron ores. The action of SO₂ gas is not definitely known, though the fact that it gives differential results so consistently leads the writer to believe that it must be a definite chemical alteration of the zinc sulphide surfaces. The small quantity of gas used would make the depth of this action very slight.

Reginald S. Dean⁴ advances the theory that the action of the SO₂ in deadening the zinc is due to the sphalerite dissolving in acid and producing H₂S which is readily adsorbed by sphalerite. If this is true, then, as Dean points out, we have sphalerite with a gas envelope of H₂S and the galena enveloped in air. The H₂S is then removed by reaction with SO₂, and the sphalerite rendered unresponsive to flotation. This is an interesting theory of the action, and an altogether likely one.

Experience has shown that it is usually essential to have salts or acids present in solution to obtain best results with the Bradford process. Acid is used in all Broken Hill plants. The writer has used with decided advantage a little sugar or glycerine in the pulp before adding the SO₂. Their presence increases the solubility of SO₂ in the water and gives a more rapid action on the sphalerite. He has also found that acid (H₂SO₄) is usually necessary, the lead apparently being floated away from the zinc and gangue more cleanly than in a neutral or alkaline solution; also that in the same ore, if made alkaline with NaOH or Na₂S the zinc floats in preference to lead; in addition, that the amounts of SO₂ and acid or the temperature are not as important as has frequently been stated. On an ore which had been ground in water containing a good deal of organic colloids, all methods other than the addition of permanganate (KMnO₄) as a contaminant and the Bradford process failed. The time of treatment of the pulp with the gas and the amount of acid (H₂SO₄) before actual flotation were found to be important factors.

A new method, recently patented by T. H. Palmer, H. V. Seale and R. D. Nevett, and mentioned by C. C. Freeman,⁵ it is claimed, gives results similar to those yielded by the Bradford SO₂ process. The patentees claim to make a solution of sulphur by boiling tar or other oils in a weak solution of H₂SO₄ in the presence of excess of sulphur. Just why and how such a mixture promotes flotation of galena and suppresses sphalerite is difficult to explain. Whatever the action may be, this process it is said has fulfilled all

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claims of the patentees at the Junction North mine, and has displaced the Bradford SO₂ process. In view of the fact that subsequent blende flotation can be obtained by heating the pulp only to about 120 degrees Fahrenheit, the process, where applicable, appears to be less costly than the treatment with SO₂. To get best results when using the oil-sulphur mixture, it is claimed that soluble salts in the mill circuit water are necessary.

As already pointed out, a great variety of reagents and their combinations have been tested to determine their selective action in flotation. The use of all the common and many of the less common reagents has been patented. The following reagent mixtures that have given differential results on various ores are interesting:

F. J. Lyster⁴ effects a separation of lead and zinc in an ore by agitating and aerating the pulp with a solution of Na₂CO₃ or NaHCO₃ containing eucalyptus oil or frothing agent, with or without neutral salts.

U. S. Patent 1,203,374 specifies the use of NaCl in solution with Ca(OH)₂ and a frothing agent, and U. S. Patent 1,203,375 specifies the use of CaSO₄ instead of NaCl. Although eucalyptus oil is specified above (and it is among the best for the purpose) coal tar creosote No. 21, Flotation Oil & Chemical Co., gives a good selection of the lead. Pine oil and hardwood creosotes, No. 17 G.N.S. and No. 1 Cleveland Cliffs, serve well.

Lyster⁴ effects a separation of lead and zinc by agitating and aerating the ore pulp with eucalyptus oil and a slightly alkaline solution containing such metal salts as sulphates and chlorides of Ca, Mg, and Mn.

Luther L. Kirtley⁵ obtained a close separation in a lead-zinc ore by floating the galena with 2 pounds per ton of hardwood creosote, known as Cleveland Cliffs No. 2, with the addition of Na₂CO₃ to suppress zinc, subsequently raising the sphalerite with a fuel oil, Texana No. 7 or No. 8. Georgia pine turpentine No. 205 and Pensacola crude pine oil No. 350 worked well as frothers. The use of 0.25 pound of CuSO₄ per ton increased the recovery in the lead cells, while 0.50 pound CuSO₄ per ton increased the recovery in the zinc cells.

J. M. Callow⁶ was able to raise zinc in preference to pyrite by using fuel oil 34 degrees Baume in combination with No. 17 G.N.S. hardwood creosote oil and 0.1 lb. CuSO₄ per ton treated.

At the Utah Apex plant each ton of ore, consisting of zinc

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blende associated with pyrite, is treated with 2 pounds of an oil mixture of 33 per cent No. B-14 wood tar (U. S. Naval Stores Co.) and 67 per cent No. 150 pine oil (Pensacola T. & T. Co.), 1 pound HSO₃ and 100 pounds salt cake (NaHSO₃) per ton are added to the pulp flowing into the Callow cells.

In the zinc section of the Magma Mill in Arizona, a mixture of fuel oil 34 degrees Baume² with G.N.S. oil No. 17 floats zinc away from pyrite.³ The writer has found that this mixture gives good differential results on many zinc-iron ores particularly after one or two pounds of CuSO₄ have been added.

The Terry differential flotation process⁴ is based on the discovery that NH₄ in solution promotes oxidation of metallic sulphides by air introduced into the pulp. As the oxides of Zn, Cu and Pb are soluble in NH₄OH and most ammonium salts, their sulphides are cleaned and their floatability unimpaired.

C. Paul and H. Lavers⁵ float Zn and Pb differentially by aeration in the presence of metallic Hg and a small amount of cresol; in this case the sphalerite floats and the galena remains in the tails. An alkaline dichromate and sodium silicate also give selective results.

E. Edser and S. Tucker⁶ use a small amount of Na₂SiO₃ and a soluble soap in the flotation pulp; upon agitation and aeration these reagents form a froth floating certain minerals.

From what has been stated it is evident that such mixtures are purely empirical and a mixture that is effective on one ore may be absolutely worthless on another and apparently similar one. Generally speaking, certain classes of oils in combination with acids, salts, etc., are more effective than others; more specific than this we cannot be. Sodium carbonate seems to suppress sphalerite and to increase in some degree the ease with which galena is floated. It serves also as a frothing agent, but usually requires the use of an additional soluble frothing agent in very small quantities. Coal tars with Na₂CO₃ are also very effective on some ores. Hardwood cresotes are among the best flotation oils.

After the removal of the lead, the zinc is rendered floative by the use of acid, CuSO₄, or Na₂SO₃ and suitable oils. CuSO₄ is very effective in intensifying the floatativesness of zinc. Where clear water is used sodium bi-phosphate (Na₂HPO₄) is an agent that gives a most striking differential separation of lead and zinc on some ores. It is cheap, 3 to 4 cents a pound, and the amount required is usually from 2 to 4 pounds per ton.

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¹ Mineral Ind. 1916, p. 609.
³ U. S. Patent 1,059,894, Mar. 5, 1918.
⁴ Canadian Patent 184,278, Nov. 30, 1919.
Differential Flotation

The following two tests, one using phosphate and one not, other conditions remaining the same, prove in an interesting manner that this agent as a contaminant has a decidedly sharp and positive action.

**WITH SODIUM PHOSPHATE (Na_3PO_4)**

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The use of KMnO₄ was patented early by Mr. Tom M. Owen but as far as the writer is aware it has never been used outside the laboratory. The reason can perhaps be attributed to its present cost, which is 75 cents per pound in car lots. In order to warrant its use at this high cost the amount required to produce good results would have to be small.

The writer, assisted by Mr. R. B. Elder, during the past summer has gotten some very good differential flotation results in the mills of the Coeur d'Alene district, using as little as ½ pound of KMnO₄ per ton of ore in a pulp dilution of 4 to 1. It seems to be particularly effective on pulp in which organic colloids give trouble. This is, no doubt, due to its powerful oxidizing action on such material. The following two tests illustrate its action in producing differential flotation of lead and zinc.

**WITH POTASSIUM PERMANGANATE (KMnO₄)**

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Reagents: KMnO₄, ½ lb.; No. 1 Cleveland Cliffs, 0.2 lb.

**WITHOUT POTASSIUM PERMANGANATE (KMnO₄)**

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1 Ass't. Manager Federal Mining & Smelting Co., Wallace, Idaho.
In testing any ore for differential or collective flotation, particularly differential, the utmost care should be taken to vary but one factor at a time in some systematic and logical order. For example, the amount of dry solids and of solution should be as nearly constant as possible. In making tests in a mill on the actual flotation feed, this will be a little difficult to do; with care, however, the pulp ratio and amount of pulp tested in the machine can be kept fairly constant over a series of tests. The practice in testing mill flotation feed is sometimes to thicken it to 80 per cent solids, agitate it with the oils and agents at this consistency, and then bring the pulp level up to the proper height in the testing machine. This is a mistake and may lead to erroneous results that cannot be duplicated in the mill; the mere addition of clean or dirty tap water has given conditions different from those of milling practice.

In a series of tests to determine the value of a given chemical as a contaminant, one, and only one, oil should be used, and the amount should be kept constant. The time of pre-agitation of the oil with the pulp, the length of the frothing period, temperature, amount of air, speed of machine, etc., are also factors that should be constant in such a series. The time of pre-treatment of the pulp with the contaminant should be kept constant while the amount is made the variable factor, and the amount should be constant while the time of pre-treatment is made the variable factor. A watch should be in plain sight of the operator.

When the quantity of contaminating agent and the time required for its action have been established, a series of tests to determine the most suitable oil should be carried out. With a given ore there are usually several oils that will give equally good recovery and grade of product, the choice then depends upon the character of froth formed and the cost of the oil. In such systematic conducting of tests lies the secret of successful testing—successful in that the results of the laboratory can be duplicated in the mill.

Other factors that have an important bearing on the success of differential flotation are discussed below:

(1) Nature and Amount of Pre-agitation

The importance of thorough pre-agitation of the pulp with the reagents in order to secure a homogeneous mixture of ore, water and reagent is well recognized by flotation engineers. Each particle of the ore must have the greatest possible chance to adsorb to its surface the contaminant used and to be wetted by either
water or oil, as the case may be. It is a relatively simple matter to meet these requirements in the case of readily soluble reagents such as some oils, the acids, and the salts generally used. If the action of the reagents is purely physical, the time of pre-treatment with the contaminant and of pre-agitation with the oil need only be long enough to distribute them homogeneously through the pulp. Soluble contaminants may be added to the pre-mixer in the solid form, as they will dissolve rapidly in the large volume of pulp.

The amount of pre-agitation of the pulp with a contaminant to effect differential flotation is of great importance. Agitation which introduces numerous air bubbles into the pulp is usually most efficient and, by greatly increasing the total air-water interface, assists in the thorough dissemination of insoluble liquids, as some oils, that readily spread on the surface of the water.

In most cases the ball mills can not be used as pre-agitators for the chemicals and oils as the pulp is greatly diluted in the subsequent milling circuit, and is thickened by a Dorr thickener or Callow cone previous to flotation. The clear water overflow of the thickeners would represent a loss of reagent in case the ball mills were used as pre-agitators.

(2) Material and Design of Machine

The material out of which the testing machine is constructed is important. Cases of inability to duplicate laboratory tests on a mill scale have been found, due to the difference in the materials of which the laboratory and commercial machines were made. For example, a certain patented process specifies pre-treatment in a wood machine, followed by differential froth concentration in a copper machine, the differential contaminant being produced by chemical action between the ore pulp and the copper. In all flotation testing work the machine should be constructed of material that is chemically and physically inert toward the ore pulp and the contaminants used. Aluminum or lead is good, sheet iron is moderately satisfactory; for commercial work wood is satisfactory. The machine should be easy of manipulation and flexible in adjustments controlling the mechanical factors of flotation. Several suitable machines are available.

(3) Temperature.

The effect on interfacial tensions of a change in temperature may be both direct and indirect; direct in that the tension at the interface of two given substances may increase or decrease with
rise of temperature, and indirect in that one or both of the given substances may be altered by chemical action promoted by rise of temperature. The interfacial tension between water and air, for example, decreases with rise in temperature.

(4) **Amount of Reagent Used**

It is true that a certain amount of oil or other flotative agent is necessary to bring about the best flotation results. By carefully regulating the amount of oil a fair differential separation of two minerals can be made. For instance, chalcopyrite can be floated away from pyrrhotite by limiting the amount of oil to that which will wet the chalcopyrite particles and not the pyrrhotite; the separation is most easily brought about by the use of cedar leaf oil. In this case the interfacial tension system oil-water-pyrrhotite is such that oil has less tendency to spread on pyrrhotite than on chalcopyrite, consequently the latter is selectively wetted by the limited amount of oil. If, however, more oil than sufficient to wet the chalcopyrite particles is added, some pyrrhotite will at once make its appearance in the froth. In general, a given contaminant will be adsorbed in turn by each of a series of substances in the order of decreasing adsorptive power. An excessive amount of oil is harmful, inasmuch as all the sulphide minerals, whether of economic value or not, are floated together with considerable gangue. In addition, difficulty is experienced in thoroughly disseminating a large amount of oil through the pulp and most of it is frothed off in the first two cells of the flotation machine.

The selection of the proper addition agents to give differential flotation of minerals is not quite parallel to the selection of an oil; two important factors in their use must be given careful examination, namely, amount of reagent used and time of pre-treatment of the pulp. Two series of tests varying each of these two factors, while all other factors are kept constant, should be made with each reagent before conclusions as to its value as a differential flotation agent are drawn. Failure on the part of the flotation metallurgist to do this is the direct cause of the often seen statement that a certain chemical failed to give good results or that the results of small tests could not be duplicated in practice. The only reason they can not be duplicated is that the true conditions which brought success in the small scale test are not known.

(5) **Amount and Nature of Aeration**

Differential flotation may also be assisted by a careful regula-

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1. The use of a large quantity of any contaminant that lowers the water-air or the sulphide-water interfacial tension will be detrimental in flotation.
tion of the amount of air introduced into the aqueous-ore-pulp. A very finely divided mineral may be floated wholly by surface concentration at the surfaces of the bubbles, provided the interfacial tensions are such that it is adsorbed. As already mentioned air in the pulp at the time of agitation assists in oil-mineral adsorption.

Conclusion

The secret of success in differential flotation lies in the scientific adjustment of the controlling factors above mentioned. The ideal condition for differential flotation is one in which the surfaces of one mineral are temporarily but positively altered, causing it to be inert toward flotation, as is quartz, while a second mineral remains unaltered and can be floated. Positive control of this ideal condition is the goal of the present flotation research.

ACKNOWLEDGEMENTS

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For further information as to the author's views on this subject readers are referred to "SURFACE REACTIONS IN FLOTATION" Serial No. 1283-W, obtainable from the Secretary, American Institute of Mining and Metallurgical Engineers, 29 W. 39th St., New York, N. Y.