TESTING

FOR THE

FLOTATION PROCESS

BY

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To His Wife
LOLA ELLSWORTH FAHRENWALD
THIS BOOK IS DEDICATED BY
The Author

PREFACE

This work was undertaken with the object in view of furnishing, as far as possible, the required information, to give students and any one else testing for the flotation process, a sufficient insight to conduct experiments in an intelligent manner.

The theory of flotation has been taken up in a general way, no effort being made to advance any special theory. Those which have been most strongly emphasized have been discussed quite fully and the reader is left to decide for himself whether flotation can be satisfactorily explained by any one of them.

The knowlege of the effect of oil, acid, and other reagents is absolutely essential to the experimenter, and these have been taken up with the object in view of throwing light on the reason for their use.

To those who have contributed to the usefulness of this book, I express my extreme indebtedness. The work of O. C. Ralston and Glen L. Allen has been frequently referred to and the material of Chapter VI is largely taken from their invaluable article, " Testing Ores for the Flotation Process."

I am especially indebted to my wife who has made this compilation possible by her aid in preparing the manuscript.

If this book aids those testing for the flotation process its purpose will have been accomplished.

A. W. FAHRENWALD.

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TESTING FOR THE FLOTATION PROCESS

CHAPTER I

CONCENTRATION BY FLOTATION

Due to the lack of a definite and formulated state of the art of flotation a great deal of testing is necessary before an ore can be treated on a large-scale practice.

The process of reducing the bulk of an ore by decreasing the percentage of gangue in it, and thus increasing the percentage of mineral content, or what is usually known as the concentration of the ore, is both an important and interesting part of metallurgy. Increasing the percentage of valuable substances in the ore is brought about by separating the mineral from the gangue. Such a separation was effected, until about the end of the nineteenth century, by mechanical devices, such as jigs, tables, and vanners, where the separation takes place in virtue of the weight of the sulphide as compared with that of the gangue. There are also other methods of separation, the processes depending upon one or more of the different physical properties of the valuable and waste material. The difference in the specific gravity of a mineral and a rock, or of minerals, affords a very safe and sure way of separating them from each other, the separating depending entirely on the difference in the settling powers of the different kinds of particles in air, water, or any other medium. Other properties of minerals are also taken advantage of, as electro-conductivity, magnetic susceptibility, etc.

At the present, however, another method of concentration, called "Flotation" (a definition for which is, apparently, hard to supply), has attracted the attention of the Mining World. "Flotation, in its latest phase, is a process of concentrating ores by frothing. When crushed ore, previously mixed with water and a relatively minute addition of oil, is agitated violently in the presence of air, a froth is formed. This froth, rising to the surface of the liquid mixture, is laden with sulphides or other metallic particles, while the earthy material, or gangue, subsides to the bottom. The froth is thick, coherent, and persistent."[1]

"The flotation process for the concentration of ores is a method by means of which one or more of the minerals in the ore (usually the valuable ones) are picked up by means of a liquid film and floated at the surface of a mass of fluid pulp. Here they are separated from the other minerals which remain immersed in the body of the pulp. In general the minerals which are floated are sulphides of metallic luster, but

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[1] Description given by the Minerals Separation Metallurgists; it is a description denied by others, more particularly those using the Callow machine.

some other minerals of metallic luster, such as graphite, and some sulphides with adamantine luster, such as sphalerite and cinnabar, are amenable to treat by this process."[1]

Some of the points to explain in the flotation process are:

1. The flotation of solid particles in a liquid the specific gravity of which is less than that of the solid.

2. The preferential flotation of the sulphide portion of the mass.

3. The functions of the reagents used.

$CaO + H_2O =$ Ca [illegible]

$CaO + H^{+}OH^{-}$

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[1] "An Explanation of the Flotation Process," by Arthur F. Taggart and Frederick E. Beach, *Bull. A.I.M.E.*, August, 1916.

CHAPTER II

CLASSIFICATION OF THE FLOTATION PROCESSES

The apparatus used in flotation have been classified a great many times,[1] so it has not been deemed necessary to describe the various apparatus used in the flotation process but only a brief classification of the process will be given.

They are conveniently divided into three main classes as follows:[2]

1. Film-suspension, as in the Wood and Macquisten methods.
2. Oil flotation, as in the Robson and Elmore bulk-oil methods.
3. Bubble-leviation, as in the Elmore Vacuum, Delprat, Fromont, and Sullivan-Picard methods.

The third class can be further subdivided according as carbon dioxide or air is the principal gas utilized for making bubbles.

Finally, the air-bubble methods can be classified according to the way in which the air is introduced:

(*a*) From the bottom of the vessel, as in the Callow and Owen cells.

(*b*) By being entrained or dragged into the

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[1] "The Flotation Process," by T. A. Rickard, Hoover, Stander, and Megraw.

[2] "The Flotation Process," by T. A. Rickard, p. 9.

pulp by the beating of paddles or some other form of impeller, as in the Gabbett and Hoover mixer.

(*c*) By escape from solution in water, as in the Elmore vacuum machine and the Norris.

Another classification of the flotation processes is that given by H. J. Stander:[1]

1. The process in which mechanical agitation and oil are used to form a froth.
2. The purely surface tension process.
3. The process known as bulk-oil flotation.
4. Acid used to generate gas from the ore which helps in the formation of the froth.
5. A process in which the dissolved air in the water, with or without the help of oil, is used to form a froth.
6. Pneumatic flotation, a process in which air is forced into the mixture of ore, water, and oil.

Another classification is that given by A. F. Taggart and F. E. Beach, and is as follows:[2]

1. Film flotation, exemplified by the Wood and Macquisten processes. When finely-ground ore containing sulphides mixed with a siliceous or earthy gangue is brought gently onto the surface of a body of water in a direction forming an acute angle with the surface of the water, a considerable portion of the sulphide constituent of the ore floats on the surface of the liquid while the gangue sinks.

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[1] "The Flotation Process," by H. J. Stander.

[2] "An Explanation of the Flotation Process," by Arthur F. Taggart and Frederick E. Beach, *Bull. A.I.M.E.*, August, 1916.

2. Froth flotation, exemplified by the Minerals Separation apparatus and the Callow pneumatic machine. When gas bubbles are introduced into a fluid pulp composed of finely-ground ore and water, to which has been added (1) a small amount of certain oils, or (2) a small amount of certain acids or acid salts, or (3) a small amount of certain alkalis or alkaline salts, or (4) a small amount of a mixture of oil with acid or alkalis or alkaline salts, the sulphide particles in the ore are brought to the surface on the gas bubbles. These collect in a froth heavily laden with sulphide particles. The gangue particles are not brought up by the bubbles but remain in the mass of the pulp.

This classification, it will be seen, is very similar to the first, leaving out "bulk-oil" flotation, which, of course, is only of historical interest.

CHAPTER III

THE THEORY OF FLOTATION

The great unsolved problem in flotation is the identity of the forces that do the floating. Some say that it is surface tension, some electricity, and some molecular attraction between the air bubbles and the metallic particles; and there is always the mystery as to exactly the part played by oil. In fact, there has been little agreement among writers as to "why is flotation."

It has been found that in order to grasp the ideas connected with the flotation process, and to be able to conduct experiments on any given ore with any degree of intelligence, some knowledge of colloidal chemistry, physical chemistry, and electrical principles is absolutely essential. Those who have been dealing with the laws of gravity in connection with concentration will find it to their advantage to review the theory of colloids, and their general physico-chemical properties, and the principles of elementary physics.

In the many articles which have come out in the *Technical Press* within the last two years, the following terms have been used frequently by the different writers:

(*a*) Colloids, (*b*) Surface Tension, (*c*) Contact Angle, (*d*) Capillary Attraction, (*e*) Osmosis, (*f*) Viscosity, (*g*) Adsorption, (*h*) Emulsification, (*i*) Electrical Phenomena, and (*j*) Preferential Flotation.

Colloids

Since the size of many of the particles of minerals treated by flotation is of the same magnitude as that of many colloids we cannot escape from calling ore-slime " coarse suspension colloid " and must apply all the laws of colloid chemistry to our problem. Physical chemistry has been a recognized tool of metallurgists for some time, although little used by most of them, and now a particular branch of physical chemistry — colloid chemistry — is beckoning to us alluringly. All questions in the treatment of ore-slime should be studied in this new light.[1]

Colloid Terminology.[2] — Colloid chemistry has developed a system of terminology of its own, and while it is not at all necessary to use this terminology in discussing the subject matter of the science, many of the terms are convenient and are now thoroughly engrafted into the literature. Most useful is the concept that regards the size of particle as due to the " degree of dispersion " of the particulate substance. A decreased size of particle is spoken of as a greater " dispersion " or the substance as more highly " dispersed." By extension all suspen-

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[1] "Why Do Minerals Float?" by Oliver C. Ralston, *Min. & Sci. Pr.*, October 23, 1916.

[2] "Colloid and Colloidal Slimes," by Edward E. Free, *Eng. & Min. Jr.*, February 5, 1916.

sions and colloids are "disperse" (or "dispersed") systems of "dispersoids;" the particles compose the "disperse" phase and the medium is the "dispersion medium." A true solution possesses a molecular or ionic degree of dispersion and is a "mol-" or "ion-dispersoid." These terms include all colloidal systems, regardless of the solid, liquid, or gaseous state of particle or medium. Colloidal solutions with a liquid medium are frequently referred to as "sols" (the oppositive term of "gel" will be discussed in a moment). If the medium is water, the colloid is a "hydrosol;" if alcohol, an "alcoholsol" or "alcosol," etc. By analogy with the systems of coarser particles the solid-particle sols are frequently called "suspensoids;" those of liquid particles, "emulsoids." The terms "sol," "suspensoid," and "emulsoid," with their compounds, are properly applied only to systems within the assigned colloidal range of particle size. The adjectives "hydrophile" and "hydrophobe" are remnants of a terminology that is disappearing. They were supposed to refer to the affinity or lack of affinity of the substance for water. Roughly, they are equivalent to "emulsoid" and "suspensoid" respectively.

Much confusion has arisen from a loose use of the terms "sol" and "gel" in metallurgical literature. As noted, a sol is a colloidal solution having a liquid medium and possessing the essential properties of liquids. It happens that some emulsoid colloids, of which gelatine is a good type, have the property of setting under certain conditions to form a more or less stiff jelly-like table gelatine. These jellies are known as "gels." They have much importance in biology and some, perhaps, in the study of ore genesis, but it does not appear that they are important in metallurgy. They are produced only by the special colloids of the type mentioned, and gelatinization is not a general property of the colloidal state. The resemblance between a jelly-like thickened slime and a real gel is superficial only, and any consideration of this resemblance in metallurgical investigations is productive merely of confusion. A similar confusion has arisen through the use in the connection of the concepts of amorphous and crystalline and from the definition of colloidal substances as those which are not crystalline. It is open to question whether real amorphity exists except in fluids, but this discussion would lead us too far into the minutiæ of modern theories of matter. For present purposes it is enough to recall that the particulate theory of colloids, as we have developed it, includes no assumption as to the amorphous or crystalline nature of the particles, and it may safely be asserted that none is necessary. "Gel" and "sol" and "amorphous" in these senses could be well spared from metallurgical terminology.

The Concept of Colloid Chemistry.[1] — Colloid chemistry is not the study of colloid materials

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[1] "Handbook of Colloid Chemistry," by Ostwald Fischer.

but that of the colloid state of materials. " Colloid " is not a chemical entity like salt, acid, or base, oxidizing like mechanical heterogeneity. The concept " colloid " does not even correspond to that of " precipitate " since only special forms of precipitates may be termed " colloid." Nor may " colloid " substances be discussed as we discuss " radio-active " substances, for radioactive properties are more closely associated with certain chemical compounds showing definite properties (high atomic weight, etc.) than are the colloid. Like considerations hold when we try to parallel the colloid condition with the " liquid crystalline," though as our knowledge has increased we have found the latter state less and less directly connected with definite chemical compounds. In the same sense "colloid phenomena " are not to be regarded as due to the properties of colloid materials but rather as characteristic of any material observed in the colloid state. The difference between these two definitions will perhaps be clearer if we compare colloid chemistry with thermo-chemistry. Just as the latter is not a study of " warm " and " cold " materials, but a study of the thermal condition of the material and its changes, so colloid chemistry is not a description of individual colloid materials but treats of the properties of which colloid systems are but examples. Colloid chemistry deals with the relations of the surface energies to other kinds of energy as shown in an especially characteristic way in dispersed heterogeneous systems.

Thus viewed, colloid chemistry appears as a branch of physical chemistry coördinated with electro-, thermo-, photo-, radio-chemistry, etc., in other words, with sciences which also treat of the relations of one kind of energy to others.

Classification of Colloids[1]

Solid Medium	*Liquid Medium*	*Gaseous Medium*
Many cryptocrystalline ores, especially those containing finely-divided metals. Most solidified slags. Glazes, glasses, etc.	Ordinary suspensions and colloidal solutions of solid particles. Slimes, thickened or not. Wet plastic clays, etc. Turbidity in water. Deflocculated graphite, etc.	Fume and smoke. Flue dust. Dust of mines, flour mills, factories, etc. Systems involved in processes of air separation, etc.
Liquid inclusions in crystals. Much occluded water and water of crystallization. Some filter cakes, etc., while wet.	Emulsions. Oil in condenser water and water in fusel oil. Oil-flotation systems. The glue-like organic colloids.	Fog, cloud, and wet steam. Acid fume. Collection of acid from smelters, fertilizer works, etc. Oil sprays, oil burners, etc.
Dry filter cakes. Silica brick and many other refractories. Mineral wool and metal sponge. Gas inclusions in crystals, etc.	Foams and froths. Wet steam (phenomena of foaming in boilers). Systems used in gas and foam processes of ore separation.	No tangible examples.

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[1] "Colloid and Colloidal Slimes," by Edward E. Free, *Eng. & Min. Jr.*, Feb. 5, 1916.

Properties of Colloids. — How do we know when we are dealing with a colloid? This question can best be answered by presenting the elementary properties and the experimentally observed behavior of colloid substances.

1. Colloid properties are in no way connected with substances of definite chemical composition, in other words, " the colloid state is independent of the chemical composition " and we can speak of colloids only as we speak of crystal, amorphous substances, soluble and insoluble substances, or better still of gaseous, liquid, and solid substances.

2. All substances can appear as colloids under appropriate conditions.[1]

3. Only one law has thus far been deduced governing the relation between chemical constituents and colloid state: the more complex chemically the compound, the greater the probability that it is in a colloid state.

4. Typical " mechanical suspensions " of substances but slightly soluble in liquids, as suspension of quartz, kaolin, or oil in water, are turbid in transmitted light, and their individual particles can be recognized under the microscope.[2]

If no microscope is available, filtration is the next simplest method by which a suspension can be recognized. Ordinary filter paper holds

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[1] Depending upon experimental conditions one and the same chemical compound can appear either as a colloid or a non-colloid.

[2] Though sometimes only with high magnifications and special optical means.

back particles having a diameter greater than about 5 μ; a hardened filter (Schleicher and Schull, No. 602, e.h.) those about 2 μ in diameter.

TABLE I. SIZE OF PORES AND FILTERS

(*According to H. Bechhold.*)

Filter.	Average size of pores (permeability to water).	Size of largest pores (permeability to air).
Ordinary thick filter paper...	3.3 μ	....
Filter paper No. 556 (Schleicher and Schull).............	1.7 μ	....
Filter paper No. 602 (extra hard, Schleicher and Schull)	0.89–1.3 μ	1–1.5 μ
Chamberland filter...........	....	0.23–0.41 μ
Reichel filter................	....	0.16–0.175 μ

Clay cylinders or so-called Pukall filters which are frequently employed bacteriologically will even hold back particles 0.4 to 0.2 μ in diameter.[1] When applied to emulsions, that is, suspensions of droplets in a liquid, filtration is successful only when the suspended droplets are not molecularly deformed during filtration.

5. True solutions may be distinguished from colloid solutions by their optical differences. A liquid which is not chemically homogeneous and which is not in coarse suspension is seen to be turbid; we may suspect that it is a colloid solution. The existence of a slight turbidity may be recognized on inspection of a rather thick

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[1] For details regarding permeability and size of pores in various filters, see H. Bechhold, *Zeitschr. f. physik. Chem.*, **64**, 328 (198).

layer of the liquid in a thin-walled glass vessel against an opaquely black background.

A far more delicate method of demonstrating the presence of a very fine turbidity lies in the use of the so-called Tyndall phenomena.[1] Extraordinarily fine turbidities can be rendered visible by such means; in fact this holds true to such an extent that special measures become necessary if we would obtain, for example, an absolutely "optically empty" distilled water; ordinary distilled water regularly shows individual dust particles.

Liquids which show no definite Tyndall light-cone or show it only in high concentrations are "molecular disperse" (true solution) solutions. Practically all colloid solutions give a positive Tyndall effect.

6. Substances in the colloid state practically do not diffuse at all; at the best they diffuse with extreme slowness when compared with the behavior of substances in molecular solution.

7. Dialysis, a process closely related to diffusion, depends upon the fact that animal, plant, and artificial membranes hold back substances in colloid solution while they allow substances in molecular solution to pass through whenever such a membrane separates the liquid under examination from the pure dispersion means. The dialyzer distinguishes colloid from

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[1] It is well known that when, for example, the air of a room is intensely illuminated, say by sunlight, from one side only, dust particles are rendered visible which cannot be seen when illumination is equal on all sides.

true solutions in that it does not allow the former to pass through the membrane into the outer liquid.

Suspensoids and Emulsoids. — These two classes of colloid solution, namely, " suspension colloids " (suspensoid) and the " emulsion colloids " (emulsoids) have interesting peculiarities. Some of importance are:

1. The viscosity of a suspension colloid, particularly in low concentration, is imperceptibly greater than that of the pure dispersion means. In contradistinction, the viscosity of an emulsion colloid even in low concentration is much greater than that of its dispersion means.

2. The viscosity of an emulsion colloid generally increased rapidly with decrease in temperature which is not the case with the suspension colloid.

3. It is characteristic of colloid solutions that the substance in colloid solution may be easily precipitated or " coagulated " through various agencies. Electrolytes, such as neutral salts, are particularly effective. The suspension colloids are easily coagulated when minute quantities of salts, especially those having polyvalent ions, are added to them, while the emulsion colloids are precipitated only after the addition of much larger quantities of salt. This is particularly true of hydrosols (that is, of colloids having water as the dispersion means). If, for example, aluminum sulphate is selected as the coagulant, it is found that almost all suspension colloids are precipitated by this as

soon as it is present in a 1 per cent concentration.

4. Colloid solutions have a characteristic electric behavior which explains many of their peculiar properties. Most substances in colloid solution assume an electric charge toward their dispersion means, though the magnitude of this charge varies greatly. Colloids can be separated from their dispersion means by capillary analysis. If the lower end of a strip of filter paper is immersed in colloid solution one of two things may happen, depending upon the character of the electric charge of the colloid; if the colloid carries a negative charge it wanders up the strip of paper along with its dispersion means. If the colloid carries a positive charge the dispersion means continues to rise to the normal height, but the " colloid phase does not." Oppositely charged colloids precipitate each other.[1]

The character of the charge of the colloid phase may be determined by noting the direction in which it moves when subjected to the action of an electric current.[2] To do this the colloid is poured into a U-tube closed with corks and provided with platinum electrodes which dip into the solution; a few storage cells may suffice. If the colloid wanders toward the anode it is

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[1] If two typical test solutions are kept in stock, for example, a positive colloid such as ferric hydroxide and a negative colloid such as sulphur or arsenious sulphide, the charge of an unknown colloid may frequently be determined by ascertaining with which of the two solutions it yields a precipitate.

[2] Migration in an electric field.

negatively charged; if it wanders toward the cathode it is positively charged.[1]

Control of Colloid Condition.[2] — Colloidality will be increased by:

1. The presence of small amounts of free alkali (except lime).
2. Prolonged grinding or long exposure to water or the atmosphere.
3. Grinding or storage at high temperatures.
4. The presence of organic material such as would be supplied by decaying animal or vegetable matter.

Colloidality will be decreased by the avoidance of the four conditions just cited and also by:

1. The presence in solution of acids or of neutral salts or of certain alkalis in certain concentrations.
2. Rapid grinding and handling.

The relative quantitative importance of the various factors mentioned and the decision as to which should be selected as a means of practical improvement will depend upon local conditions different in each case. In general the presence of organic matter has the most effect, but is rarely encountered. Next in quantitative importance is the presence of dissolved acids, salts or alkalis. Of much less effect is the time of grinding or storage, unless it runs into years and of still less effect are changes of temperature between usual limits.

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[1] Above remarks largely taken from "Handbook of Colloid Chemistry," by Ostwald Fischer.

[2] "Properties of Slime Cakes, II," by Edward E. Free, *Eng. & Min. Jr.*, June 24, 1916.

Surface Tension

Definition. — Every liquid surface in contact with a gas or its vapor behaves as if it were under tension. The value of this contractile force per unit width can be measured.

The basic factor in the making of bubbles is surface tension. This is the force that causes the surface to resist rupture. The particles at the surface have a greater coherence than the similar particles within the body of the liquid, or the tendency of a liquid to reduce its exposed surface to a minimum, that is, the tendency of any liquid surface to act like a stretched membrane is called "surface tension."[1]

Effects of Added Substances. — Surface tension has been thrashed out pretty thoroughly by articles appearing in the Journals of the American Chemical Society beginning in 1908.

Jour. Am.	*Chem. Soc.*,	Vol.	XXX,	No.	3, Mar., 1908.
"	"	"	XXX,	"	7, July, 1908.
"	"	"	XXXIII,	"	3, Mar., 1911.
"	"	"	XXXIII,	"	5, May, 1911.
"	"	"	XXXIII,	"	7, July, 1911.
"	"	"	XXXV,	"	10, Oct., 1913.
"	"	"	XXXV,	"	11, Nov., 1913.
"	"	"	XXXV,	"	12, Dec., 1913.

Some of their conclusions are that:

(*a*) The drop-weight of any liquid is proportional to the diameter of the dropping-tube. These tubes are uniform in diameter, thus differing from the ordinary burettes.

(*b*) The weight of a drop, other things being

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[1] "First Course in Physics," by Millikan and Gale, p. 107.

the same, is proportional to the surface tension of the liquid.

(*c*) It is possible to calculate the temperature at which the drop-weight would become zero, namely, the critical temperature of the liquid, for at that point the drop would disappear, there being no distinction between the gas and the liquid.

In the course of these experiments the surface tension of a number of organic liquids in aqueous solution was determined by drop-weight and found to range from 21 up to that of water. The tabulated results cover several pages in the Journal:

AQUEOUS SOLUTIONS AT 30° C.

Ethyl alcohol.		Methyl alcohol.		Amyl alcohol.		Acetic acid.		Formic acid.	
Per cent.	Sur. ten.	Per cent.	Sur. ten.	Per cent.	Sur. ten.	Per cent.	Sur. ten.	Per cent.	Sur. ten.
0.000	71.030	0.000	71.030	0.000	71.030	0.000	71.030	0.000	71.030
0.979	65.600	1.011	68.120	0.250	53.712	1.000	67.756	1.000	69.816
2.143	60.847	2.500	64.845	0.500	46.157	2.475	63.995	2.500	68.024
4.994	53.137	4.097	60.294	0.750	41.247	5.001	59.435	5.000	65.706
10.385	44.668	9.994	53.661	1.000	37.631	10.010	53.500	10.000	62.061
17.979	37.311	10.000	48.817	1.500	32.504	14.980	49.451	15.000	59.197
25.000	32.941	25.000	41.809	2.000	28.667	20.090	46.455	25.000	55.190
50.000	26.521	50.000	31.843	2.498	25.726	49.960	37.109	50.000	48.112
75.000	23.850	75.000	26.173	.....	....	79.880	31.026	75.000	41.990
100.000	20.756	100.000	21.073	100.000	22.296	100.000	25.725	100.000	35.281

It is to be noted that in all cases the very first addition causes a very considerable lowering of surface tension. The decrease in the surface tension of water caused by the addition of a small amount of amyl alcohol is especially striking. Thus the presence in solution of even so small an amount as 0.25 per cent changes the surface tension of water from 71.030 to 53.7, or nearly 25 per cent at 30° C.

Morgan and Schramm studied many concentrations of a few salts. They selected the molten hydrated salts for this purpose, those salts which melt below 50 degrees in their own water of crystallization being especially satisfactory for this purpose, for the reason that concentration in some of these cases could have been carried to supersaturation.

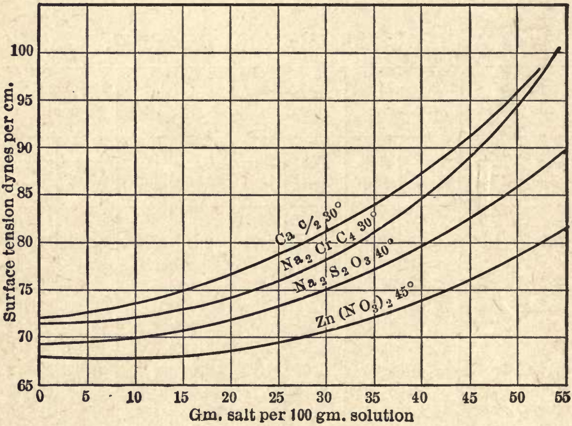

FIG. 1.

In the case of salts which they studied it is plain that surface tension is increased by the salts introduced. Where calcium chloride was used, the surface tension was increased from

71.03 to 102.57, approximately 50 per cent. Taking a few specific cases it is noted that to increase the surface tension 10 per cent it would take 20 per cent $CaCl_2$ at 30 degrees; 43 per cent $Zn (NO_3)$ at 45 degrees; 29 per cent Na_2CrO_4 at 30 degrees; 34 per cent $Na_2S_2O_3$ at 40 degrees.

The fact is that some salts elevate while others depress surface tension, but the former predominate. In addition to the salts just mentioned the tartrates, carbonates, oxalates, citrates, lactates, and a part of the acetates raise surface tension; while all the salicylates, the butyrates, part of the acetates, and all the acids lower surface tension.

Surface Tension Phenomena. — Many manifestations of surface tension on water can be cited. Fill a tumbler a little more than full and the water will have a convex surface, indicating that there is some force at work to prevent the water from spilling. Note the cohesion between two plates that have been wetted. Dip a camel's-hair brush into water and the hairs cling together; immerse the wet brush in the water and the hairs separate. Watch the formation of a drop of water and note that it behaves as if enveloped by a stretched membrane. Water-spiders can be seen running over the surface of a pond in summer; the spider makes a visible dimple without wetting his feet. The surface is not ruptured. Clean a piece of iron wire and place it gently on the surface of distilled water; it floats. The apparent attractions and repulsions exhibited by small floating bodies on the surface of a liquid are due to surface tension.[1] Thus two small pieces of wood floating on the surface of water rush together if they come within about a centimeter of one another. This is due to the fact that the angle of contact between water and wood is less than 90 degrees, so the water is slightly raised up between the floating bodies as in a wide capillary tube (Fig. 2). The pressure in the liquid between is less than in the surrounding mass and the bodies come together. In the case where the angle of contact is greater than 90 degrees, as, for instance, with needles floating on mercury (Fig. 2), the liquid between the bodies is depressed, and the hydrostatic pressure on the outside forces the bodies together.

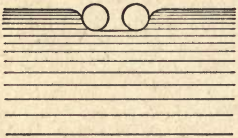

FIG. 2.

FIG. 2*a*.

The Force of Surface Tension. — The force of surface tension has been measured by ascertaining the weight that can be suspended from a film of water in air.[2] It has been stated

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[1] "A Textbook of Physics," by Watson, p. 185.

[2] "A Textbook of Principles of Physics," by Alfred Daniel, 1911.

as 3¼ gr. per inch,[1] or 81 dynes per centimeter.[2] A later determination is given by Theodore W. Richards and Leslie B. Combs[3] as 72.62 dynes per centimeter at 20° C. Many interfering factors enter into the determination of this force.

Surface tension varies as between various liquids and fluids in contact, an example being that of the tension separating mercury from water amounting to 418 dynes per centimeter, while that separating olive oil from air is only 36.9 dynes. The surface tension of an oil-water surface is only 14 as compared with the 73 of an air-water surface at a temperature of 18° C.[4] While the film of oil on water may be only one molecule thick, or one twenty-five millionth of an inch, it will suffice to reduce the effective pull of the water from 73 to 43; this latter figure repesents the effective surface tension of water modified by oil as used in flotation.

If surface energy is freed in any way it is changed into other forms of energy, especially heat, the surface of the system decreasing at the same time. Conversely, if heat is introduced into a system capable of developing free surface energy the surface tension is decreased. Roughly, the decrease in surface tension is proportional to the increase in temperature. Place powdered sulphur

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[1] "Soap Bubbles," by C. V. Boys.

[2] Clerk Maxwell in Encyclopedia Britannica, under Capillarity.

[3] "The Surface Tension of Water, Alcohols, etc.," *Jr. of Am. Chem. Soc.*, July, 1915.

[4] "A Textbook of Physics," by J. H. Poynting and J. J. Thomson, 1913.

on the surface of the water on a horizontal plate of clean metal; apply heat locally; the sulphur is pulled away by the cold liquid as against the feebler tension of the warmer liquid. If an electric surface is produced, in that two phases having different electric charges which are not permitted to neutralize each other are brought in contact with each other, the surface tension of the phase decreases.[1] Further, the value of a surface tension varies with the chemical character of the phases which are in contact with each other.

The elastic force at the surface of a liquid tends to draw it into the most compact form. That is why drops assume the form of a sphere. Let alcohol be added to water until a solution is obtained in which a drop of common lubricating oil will float at any depth. Then with a pipette insert a large globule of oil beneath the surface. The oil will be seen to float as a perfect sphere within the body of the liquid[2] (Fig. 3).

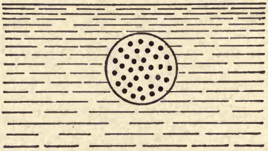

FIG. 3.

The reason that liquids are not more commonly observed to take the spherical form is that ordinarily the force of gravity is so great

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[1] "Handbook of Colloid Chemistry," by Ostwald Fischer.

[2] "A First Course in Physics," by Millikan and Gale.

as to be more influential in determining their shape than are the cohesive forces.

Water has the highest surface tension of any common liquid except mercury, so that the addition of another liquid usually lowers its surface tension. When the water is modified by oil, the contractile force of surface tension is diminished, the bubbles are less fragile, and they survive long enough to perform their metallurgical duty of buoying the metal particles to the surface of the liquid pulp.[1] In practice the modification of water is effected by minute subdivisions of an insoluble oil, or it may be done by means of a soluble oil or derivative, such as creosol and amyl acetate. The surface tension of a colloid solution at its free surface may be more, or less, or equal to that of the pure dispersion medium. The surface tension of water, while generally decreased by a contaminant, is increased by gum arabic, starch, and plum gum. Both the increase and decrease in surface tension follows the concentration of the colloid. Traces of fatty acids, soaps, resins, tannic acid, etc., suffice to greatly lower the surface tension of water.[2]

The surface tension of colloid solutions, as of liquids in general, decrease as the temperature rises, but is more marked than in the case of the pure dispersion medium alone. Coarse suspensions and suspensoids hardly alter the sur-

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[1] "The Flotation Process," by T. A. Rickard.

[2] "Handbook of Colloid Chemistry," by Ostwald Fischer.

face tension of the dispersion medium.[1] L. Zlobicki found coarse aqueous suspensions of emery, mastic, and gamboge and colloid suspensions of silver and platinum to have the same surface tension as the pure dispersion medium. The temperature coefficient of the surface tension of these systems was also the same as that of the pure dispersion means. These results seem to show that only emulsoids (colloids in the phase liquid–liquid) decrease the surface tension of their dispersion media.

Sodium hydroxide affects greatly the surface tension of soap solution.

Oil serves as a contaminant that lowers the surface tension of water, also it augments the viscosity of the liquid. These two effects unite in facilitating the formation of strong and persistent froth.

The Contact Angle

Definition. — It can easily be shown, as we know from flotation practice, that films of various kinds on particles either produce or prevent flotation. A clean copper wire floats, if the surface is oxidized it sinks promptly, while if the oxide film is changed to one of sulphide, the wire again floats.

The reason for the different behavior of these three wires is that the different films result in different "contact angles." The contact angle

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[1] "Handbook of Colloid Chemistry," by Ostwald Fischer.

is the measure of " wetness " or " non-wetness " and is shown in Fig. 4.

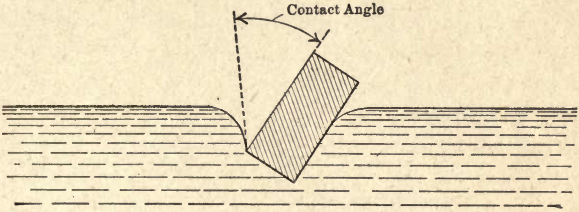

FIG. 4.

Contact Angle in Flotation. — Valentine has proved theoretically and by practical tests that one of the flotation factors is the contact angle, which must be of a certain degree to make flotation possible, and we can, therefore, say that surface films either produce or prevent flotation, according to the contact angle.

We have been talking of coatings that are solid films, but we can show that a film may be either a solid, a liquid, a gas, or an electric charge. The use of oil in practice illustrates a liquid film, and just as with the solid film (oxide, sulphide, metal) these liquid films will either produce or prevent flotation according to the resulting contact angle. Malachite particles having a film of sulphide produced by the action of H_2S floats very well; they do so by the contact angle caused by the strongly adhering film of gas.

The following quoted from Taggart and Beach is very interesting.[1]

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[1] "An Explanation of the Flotation Process," *Bull. A.I.M.E.*, August, 1916.

When, as is the common case in the flotation process, there are three substances in contact, a system of forces, as shown in Fig. 5, is brought into play. If *O* does not move indefinitely to the right or to the left, equilibrium will be attained when

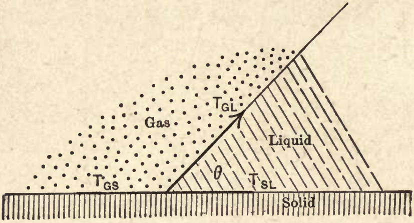

FIG. 5.

$$T_{SL} = T_{GS} + T_{GL} \cos \theta,$$

or

$$\cos \theta = \frac{T_{SL} - T_{GS}}{T_{GL}},$$

where T_{GS}, T_{GL}, and T_{SL} are the interfacial tensions or pressure at the gas-solid, gas-liquid, and solid-liquid contact respectively. From this equation is deduced the important conclusion that as T_{SL} increases with respect to T_{GS}, the angle of contact θ becomes smaller (the gas and liquid being the same), or, in other words, the angle of contact is a measure of the tendency of one fluid to replace another on the surface of a colloid. We have examined the angles of contact of the water-air, oil-air, and oil-water surfaces against a number of the common minerals. We have found, in general, that the air-water contact angle is less for gangue minerals than for sulphide minerals, that the air-oil contact angle is less for sulphides than for gangues and less for any given sulphides than the air-water contact angle, and that the water-oil contact with solids takes the form shown in Fig. 6.

We found further that the invariable effect of oiling a solid surface is to reduce the air-water contact angles. This latter phenomenon is undoubtedly aided by the reduction of the surface tension of the water due to contamination by the oil. The conclusions forced by observation of the above phenomena are:

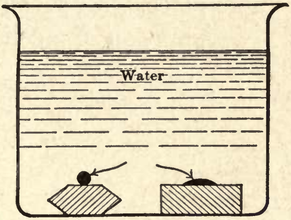

FIG. 6.

1. That water has a smaller tendency to displace air on the surface of sulphide minerals than on the surface of gangue minerals.
2. That the tendency of oil to displace air is greater on the surface of sulphide minerals than at the surface of gangue minerals.
3. That oil tends to displace water on the surface of sulphides and that water tends to displace oil at the surface of gangue minerals.
4. That water displaces air more readily on an oil-solid surface than on a clean surface of the same solid.
5. That these tendencies toward displacement are due to the interfacial tensions or pressures existing between the various substances, and that the resulting action of these interfacial forces is a manifestation of the tendency toward reduction of the total potential energy of the system. Wherever an increase in the solid-fluid interface will decrease the potential energy, such a change will occur.

It can also be shown experimentally that an electric charge will so modify the contact angle on a particle as to permit flotation that would otherwise not take place. A change of potential at the surface of separation of a solid and liquid will produce a change of surface tension and contact angle, and conversely a change in surface tension by any other means will produce a difference of potential.[1]

A particle heavier than water may be made to float provided it is small enough, of proper shape with respect to size and weight, and provided it has a surface film the resultant of which is a contact angle that permits flotation. Such films may be either solid, liquid, gaseous, or electric or a combination of any of these.

This statement is very near that for the conditions required to produce a colloid solution or suspension and it is, therefore, reasonable to look to the subject of colloids and of electrostatics, with which this is closely connected, to furnish the real reason for flotation.

An absolutely clean particle free from films of any kind (which is practically impossible) will not float; therefore, we can have no flotation without a surface film. While it is a fact that certain films produce flotation by reason of their contact angle, *how* do we account for the fact that these films produce the contact angle they do? If some mineral particles whose contact with water renders them non-wet are put

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[1] "How Flotation Works," by G. D. Van Arsdale, *Eng. & Min. Jr.*, May 13, 1916.

into the bottom of a vessel containing pure water and a bubble of air is brought into contact with this particle, they will become attached and the particle will be carried up to the surface with the bubble. This goes to show that it is not necessary to form the bubble in solution nor is it necessary to have nascent bubbles.[1] The mere attachment of the mineral to the bubble, or the simple contact of gas and liquid surface, is all that is necessary. In explaining why the bubbles attach themselves to the mineral and not to the gangue, the accompanying sketch represents a large magnified diagram of a bubble of air or gas in contact with the two particles, one of the particles having assumed a contact angle that would enable it to float on a watery surface, the other particle having a contact angle that would produce immediate sinking on a water surface (Fig. 7). Considering this diagram, it will be seen that the bubble is really only the surface of water in contact with air or gas, and that the particles float on the surface for exactly the same reason as they do in the Macquisten tube.

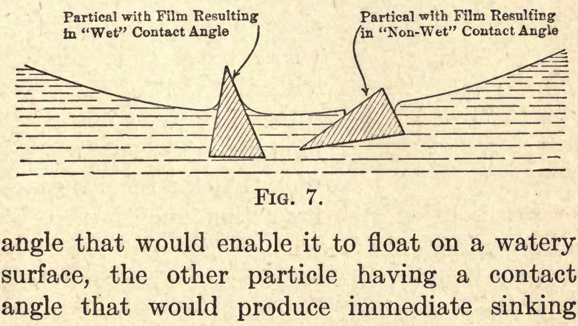

FIG. 7.

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[1] "Why is Flotation?" by Chas. T. Durell, *Min. & Sci. Press*, September 18, 1915.

Capillary Attraction

Capillary Phenomena. — A study of capillarity is of great aid in gaining a conception of the conduct of the molecular forces of cohesion and adhesion that cause some substances to float on the surface of a liquid while others sink.[1] We must keep in mind two familiar facts: First that the surface of a body of water at rest, for example a pond, is at right angles to the resultant force, that is, gravity, which acts upon it; second, that the force of gravity, acting upon a minute amount of liquid, is negligible in comparison with its own cohesive force. Consider, then, a very small body of liquid close to the point *O*, Fig. 8, where water is in contact with the wall of the glass tube. Let the quantity of liquid considered be so minute that the force of gravity acting upon it may be disregarded. The force of cohesion of the wall will pull the liquid particles at *O* in the direction of *OE*. The force of cohesion of the liquid will pull this same particle in the direction *OF*. The resultant of these two pulls on the liquid at *O* will then be represented by *OR*, Fig. 8. If, then, the adhesive force *OE* exceeds the cohesive force *OF*, the direction of *OR* of the resultant force will lie to the left of the vertical *OM*, Fig. 9, in which

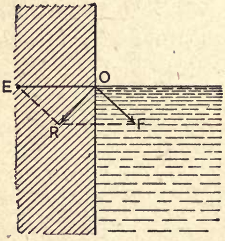

FIG. 8

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[1] "Molecular Forces and Flotation," by Will H. Coghill, *Min. & Sci. Press*, September 2, 1916.

case, since the surface of the liquid always assumes a position at right angles to the resultant force, it must rise up against the wall as water does against glass. If the cohesive force *OF* (Fig. 10) is strong in comparison with the adhesive force *OE* the resultant *OR* will fall to the right of the vertical, in which case the liquid must be depressed about *O*. Whether, then, a liquid will rise against a solid wall or be depressed by it will depend only on the relative strength of the adhesion of the wall for the liquid, and the cohesion of the liquid for itself. Since mercury does not wet glass[1] we know that cohesion is here relatively strong, and we should expect, therefore, that mercury would be depressed, as indeed we find it to be. The fact that water will wet glass indicates that in this case adhesion is relatively strong, and hence we should expect water to rise against the wall of the containing vessel, as in fact it does. As soon as the

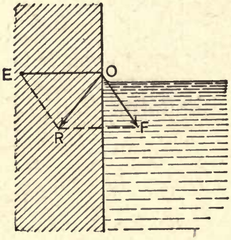

FIG. 9.

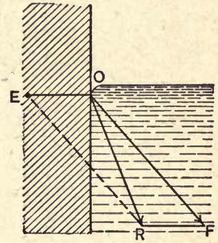

FIG. 10.

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[1] It is a well-known fact that there is a slight force between mercury and glass and that mercury exerts an attractive force upon air, but the quotation suffices for the present.

curvatures just mentioned are produced, the concave surface *aob* (Fig. 11) tends, by virtue of surface tension, to strengthen out into a flat surface ao^1b, but it no sooner begins to straighten than adhesion again elevates it at the edges. It will be seen, therefore, that the liquid must continue to rise in the tube until the weight of the volume lifted balances the tendency of the surface to flatten out. Similarly a convex surface *aob* (Fig. 12) falls until the upward pressure at *O* (which is small) balances the tendency of the surface *aob* to flatten out. If, in the case of water against glass, the water is pulled upward and in the case of mercury against glass the mercury is pulled downward, the converse must also be true, namely, that in the former the glass is pulled down and in the latter the glass is pulled up.

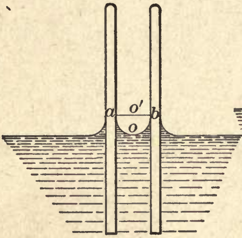

FIG. 11.

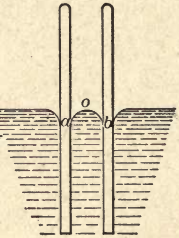

FIG. 12.

Result of the Capillary Attraction. — Now assume that you had two minerals so that they are partly submerged by a liquid and that with one adhesion is very great (relatively) and that with the other adhesion is very slight. It is obvious that the surface of the liquid will turn up at the contact with the former and down and around the other, and that if these particles are so small that the force of gravity is negligible it is impossible for the former to float and just as impossible for the latter to sink. One of them cannot ride on the surface and is actually drawn down into the liquid like gold into mercury, while the other cannot by any means enter the liquid unless its mass is sufficient to overcome the contractile force in the surface of the depressed liquid.[1]

Osmosis

Definition. — When two liquids are separated by a porous membrane, each may pass through the membrane into the other with more or less freedom; this process is called "osmose."[2]

Osmotic phenomena connected with osmosis is closely connected with the process of diffusion and dialysis. In fact, during dialysis the increase in volume in the dialyzing liquid in the interior of the cell is a phenomenon of osmosis.

Osmotic phenomena takes place whenever a dispersoid is brought in contact with the less concentrated one or its pure dispersion means, under conditions which do not allow of free diffusion. This may be accomplished by placing between them a so-called semipermeable or, better expressed, a selectively permeable membrane, in other words, a device which gives pas-

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[1] "Molecular Forces and Flotation," by Will. H. Coghill, *Min. & Sci. Press*, September 2, 1916.

[2] "Essentials of Physics," by Hoadley, p. 127.

sage to the dispersion means, but not the dispersed phase. These devices are nothing more than such as are used in the dialysis of colloid systems. In fact, osmotic phenomena may always be expected to appear during dialysis (substances which do not dialyze, or pass through parchment paper, Graham called colloids; those which do, molecular dispersoids). Osmosis, like free diffusion, tends toward the establishment of a uniform spatial distribution of dispersed phase and dispersion means.

The intensity of the tendency to bring about a uniform distribution of dispersed phase and dispersion means may be measured by opposing this osmotic leveling process by the hydrostatic pressure of a water column. The pressure thus made evident is called the "osmotic pressure" of the dispersoid.

Colloids and Osmosis. — Colloids tend to concentrate electrolytes upon themselves and thereby to increase the possibility of developing and exhibiting a greater osmotic pressure than is really due to colloids themselves.[1] This increased osmotic pressure would tend to drive the air from the metallic particles leaving them in the same condition as those of the gangue. A proper strength will sometimes "kill" the float, probably due to the above reason. However, colloidal impurities, like tannin, saponin, etc., or volatile oils and the like, destroy

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[1] The difficulty of "washing out" the last traces of electrolytes from precipitates is one fact leading to this conclusion.

bubbles by reducing the surface tension, so that the gas pressure bursts them. This weakening of the surface tension by a colloid is thus seen to be entirely different from the strengthening of osmotic pressure by a crystalloid (molecular dispersoid) although the result is practically the same — no froth.

The osmotic pressure of molecular dispersoids is governed by the important law of Pfeffer and van't Hoff: the "osmotic pressure is directly proportional to the concentration." The relations in colloid systems are not so simple. Examples are known where the law holds approximately but there are also those in which the "osmotic pressure increases faster than the concentration; or more slowly than this."

The Influence of Added Substances upon Osmotic Pressure. — The influence of added substances upon the osmotic pressure of a given system, that is, molecularly dispersed solution, is purely additive.[1] In other words, the pressure exerted by added substances is added to that of the original system. The effect of added substances on the osmotic pressure of colloid systems is more complicated. Concentration and temperature functions are encountered.

Acids or alkalis may either increase or decrease the osmotic pressure of different colloids.

Viscosity

A marked increase in the viscosity of interfacial films is produced by the presence of finely-

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[1] There are exceptions to this rule.

divided solid matter. This increase can be shown experimentally [2] by pouring any clear oil, kerosene, liquid vaseline, etc., on to water and then bubbling gas through the water (Fig. 13). The interface has all the appearance of an electric film. Bubbles rising through the water and striking the underside of the interface stretch the film *H* (Fig. 13) and rising further drag away a mass of water surrounded by this viscous layer. The system now appears as shown at *M* and rises to the oil-air surface on account of its lower specific gravity. Here the film, together with the excess of water carried up as shown at *C*, breaks away and falls back through the oil, not in spherical form, as would be the case were the water drop not surrounded by a viscous film, but in hemispherical form (see *P*, Fig. 13) often trailing behind it a film with ragged edges as it broke from the bubble. The tadpole-shaped water drops *H* (Fig. 13)

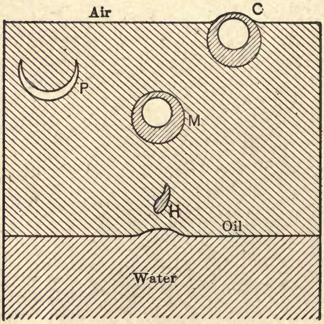

FIG. 13.

are further evidence of the high viscosity of the oil-water interfacial film.

Also if finely-powdered sulphide is thrown into the oil and allowed to settle to the interface, it will become entangled in the film; this increased viscosity is apparent. If now gas bubbles are introduced, as before, the return water drops, coated with a film containing the solid particle, are much more irregular in shape than previously, and their coalescence after reaching the interface requires days or weeks.[1] An even more convincing proof of the increase in viscosity of an interfacial film is given by the following experiment. If a needle is floated at the center of a surface of pure water in a beaker 4 inches in diameter and a chip of wood is floated near the wall of the beaker, the needle may be caused to revolve by means of a magnet without disturbing the chip. If the surface of the water is dusted over with fine ore, the whole surface together with the chip moves as though it were a rigid solid.[2]

When gas bubbles are introduced into a liquid pulp where oil is present there is formed about each bubble a liquid film whose surface tension is less and whose viscosity is greater than that of the bulk of the liquid. Some of the solid particles of the pulp move into the film and are raised to the surface with the bubble. Since

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[1] "An Explanation of the Flotation Process," by Taggart and Beach, *Bull. A.I.M.E.*, August, 1916.

[2] "An Explanation of the Flotation Process," by Taggart and Beach, *Bull. A.I.M.E.*, August, 1916.

there is a concentration of oil in the film, and since the diminution in potential energy at an oil-sulphide contact is greater than at a water-sulphide contact, the contaminated layer replaces the water on the sulphide and the sulphide moves into the bubble film, while the gangue, on which water displaces oil, remains in greater measure in the body of the pulp. The bubbles, therefore, as they arrive at the surface, carry an excess of the sulphide minerals. Upon their arrival at the surface, the bubbles of the contaminated liquid persist, owing: (1) to their low surface tension; (2) to their ability to adjust this tension to a state of stable equilibrium; and (3) to their greater viscosity which is markedly increased by the presence of the solid particles.

The following are some of the characteristics of molecular dispersoids:

1. When a solid goes into solution the viscosity of the dispersing medium is usually increased; dilute solutions of some salts, such as lithium, chloride, and potassium chloride, form exceptions to this rule.

2. In normal cases the viscosity increases progressively with concentration.

3. When gases are dissolved in a solvent they do not seem to change its viscosity.

Manifold and complicated conditions arise when two liquids are molecularly dissolved in each other. Thus, the mixture of alcohol with water shows a characteristic behavior in that the maximum of viscosity is obtained in medium concentrations of the one in the other, the value of which is considerably greater than that of pure compounds.

It may be regarded as typical of suspensoids that their viscosity is but slightly greater than that of their pure dispersing mediums.[1] Temperature affects the viscosity of the suspensoids in the same way as it does that of normal liquids: the viscosity decreases with increasing temperature. Also according to H. W. Waustra the condition of electrolytes influences the viscosity of a suspensoid silver hydrosol (and probably that of all others) in a very characteristic manner. The addition of an electrolyte decreases the viscosity; this decrease takes time, occurring in some instances only after days, and it is associated with a change in the state of a colloid, namely, with its coagulation.

The electric charge on suspended particles allow another possible explanation of flotation phenomena. Quartz particles when suspended in water are negatively charged; pyrite particles positively charged; oil drops are negatively charged, and air bubbles negatively charged. The charges are somewhat small compared with the weight of the particles, so they are hardly strong enough to cause negatively-charged quartz to stick to positively-charged pyrite, as they can have only a few points of contact, and currents in water could easily pull them apart. However, the negatively-charged droplet of oil,

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[1] It must be remembered, however, that this is true only when such systems are dilute.

which is repelled from a negatively-charged particle of quartz, can wrap itself around the positively-charged pyrite particle so that they will stick together, and the same applies to air bubbles. The other sulphides known to be flotative have positive charges when suspended in water or can be made to assume positive charges by use of the proper amount of proper electrolyte. The large effect of a small amount of sulphuric acid on the condition of flotation does not seem at all strange in this light.

The above is O. C. Ralston's theory, the logic of which is supported by Mr. Callow.

Adsorption

Explanation of the Term. — The surface layer between two physical phases is the seat of conditions of density and viscosity, also of apparent forces and energy manifestations, which are notably different from those in the bulk of either phase. On philosophical grounds it is impossible to consider that a real physical discontinuity occurs at the boundary between two media. In other words, there must be a very thin layer of transition in which there is a rapid but continuous change in the concentration of the components. This change in the concentration of a component at the interface is called adsorption, and may occur even between two phases which are ordinarily regarded as immiscible.[1]

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[1] "An Explanation of the Flotation Process," by Taggart and Beach, *Bull. A.I.M.E.*, August, 1916.

The terms adsorption and absorption have been used interchangeably in some writings, thus contributing to the already existing confusion of ideas.

Adsorption in Flotation. — The question of adsorption undoubtedly plays an important part in flotation, since it is so requisite to the production of a variable surface tension. There can be, of course, no surface tension without adsorption, which produces, in the case of positive adsorption, an increased surface concentration resulting from a lowering of the surface tension by contaminating and dissolved substances, whatever they may be. The equation of Gibbs $u = -\frac{c}{Rt} \cdot \frac{do}{dc}$ gives the relationship between surface tension and the distribution of the solute between the bulk of the liquid interface. Here the notation is

u = excess of substance in the surface layer,
c = concentration in the main body of the liquid,
R = the gas constant,
t = absolute temperature,
o = surface tension.

This shows that when the surface tension is reduced by the addition of a contaminant the quantity $\frac{do}{dc}$ is negative and "$\frac{c}{Rt}$" is positive (from algebraic considerations). The surface film, then, contains more of the contaminant than the main body of the solution. If the surface film contains less of the contaminant than the main body of the solutions it is a case of "negative adsorption."

Adsorption at a gas-liquid interface may be demonstrated as follows: If a solid, which has been heated in a vacuum, is introduced into a measured volume of a gas over mercury in a calibrated tube, an amount of the gas will be absorbed, as is shown by the change in pressure and volume compared to the space originally occupied. The following additional facts are stated by Taggart and Beach:[1]

(*a*) The amount of gas adsorbed at constant temperature increases with the pressure.

(*b*) It is different for different gases.

(*c*) It is different for different solids.

(*d*) It increases as the temperature decreases.

(*e*) There is an energy transformation which is indicated by the heat development through adsorption.

(*f*) Chemical reactions are assisted by the adsorbed layer.

It follows that the gas layers must vary in density, falling off rapidly with increasing distance from the solid. Quincke assumes that the density of the gas next to the solid is equal to that of the solid and concludes that the amount adsorbed will increase with the density of the solid. From these facts are concluded:

1. That gases and solids exhibit selective adhesion and that, therefore, gas bubbles will attach themselves more persistently to some substances than to others.

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[1] "An Explanation of the Flotation Process," *Bull. A.I.M.E.*, August, 1916.

2. That the selective adhesion is a manifestation of a definite amount of energy possessed by each unit area of a gas-solid contact, and that this potential energy is capable of variation.

3. That chemical reactions which diminish this potential energy are aided by adsorption.

Adsorption of the gas at a gas-liquid surface is indicated:

1. By the effect on the surface tension. The surface of a freshly-formed mercury surface does not change in a vacuum, but falls off in the presence of different gases for about an hour. Certainly the density of a liquid cannot be constant at the boundary but must go over continuously into that of the gas.

2. By the increase in the solvent power of the surface.

3. In the case of contaminated liquids by the concentration of one or more of the components of the liquid at the gas-liquid surface. Every unit area of such a boundary possesses a definite potential energy which always tends to a minimum. If, therefore, the surface tension of a solution depends upon the presence of any component, such a change of concentration of that component will occur as will reduce the potential energy, *i.e.*, interfacial tension. In other words, any component which reduces surface tension will be found in excess at the surface of a solution.

Emulsification

Effect upon Flotation. — By some writers the combination of pulp, oil, water, acid, or whatever other chemical substance is added, is often referred to as an emulsion. Going back to the definition of an emulsion, we find that it is a colloid suspension of one liquid in another. It is true, that oil may be so finely divided that it simulates a true emulsion. If, as has been said, the colloid condition is antagonistic to flotation success, then the pulp-oil combination is not a true emulsion since we clearly do get flotation results from it. The latter statement is true; it is not an emulsion.[1]

In this connection G. D. Van Arsdale states:[2]

From experiment I think it is safe to say that if a particle meets emulsified oil, there will be no attachment of oil to mineral unless some factor is introduced that will break up or destroy the emulsified condition, and that consequently emulsification of an oil should be avoided in flotation practice. If this is true, we would expect that substances capable of producing an emulsified condition of oils would be harmful in practice, and conversely that substances capable of preventing or breaking up emulsification would be beneficial. I believe that this is the explanation for the puzzling deleterious action of some organic substances, such as glue, tannin, and saponin, since these all belong to the class of compounds that are efficient and emulsifying oils. Furthermore, it is easy to show

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[1] "The Flotation Process," by Megraw, p. 30.

[2] "How Flotation Works," by G. D. Van Arsdale, *Eng. & Min. Jr.*, May 13, 1916.

experimentally that sulphuric acid prevents or breaks up emulsion of oils, and it seems reasonable to suppose, therefore, that this is one of the reasons, although it may not be the only one, for the use of acid. The fact that acid is not generally used at present is probably due to the fact that the oils and mixtures now in use in many places are not such as to emulsify readily.

There are a number of other substances besides sulphuric acid having the property of preventing or destroying emulsions. Table II shows the relative efficiency of some of these that have been tested.

TABLE II. EMULSION MODIFYING AGENTS.

Sulphuric acid	0.244	per cent entirely prevents emulsification.
Cresylic acid	0.006	per cent entirely prevents emulsification.
Acetic acid	0.014	per cent entirely prevents emulsification.
Citric acid	0.06	per cent entirely prevents emulsification.
Aluminium sulphate	0.06	per cent prevented emulsification.
Copper sulphate	0.30	per cent prevented emulsification.
Ferrous sulphate	....	no action.
Caustic soda	0.30	per cent no action.
Sodium chloride	....	stabilizes and increases emulsification.

In a case where sulphuric acid is used for preventing emulsification of oil, we would, therefore, expect that the substances enumerated could be substituted with equal effect in the relative amounts indicated by the figures.

Wilder D. Bancroft has written a series of articles on "The Theory of Emulsification" in the *Journal of Physical Chemistry*, out of which very useful data with regard to the characteristics of an emulsifying agent can be obtained. His article in the April number of 1915 is of special interest as quite a number of very useful experiments are cited. He says:[1]

> For a substance to be an emulsifying agent, it must tend to pass into the surface separating the two liquids and form a coherent film there. If the emulsifying agent does not form a coherent film the emulsion will crack.

When two liquids, which are partially immiscible, come together, we have a surface that separates these two liquid phases, and this surface is called a dineric[2] interface. In order to fully understand the water-air interface, it may be of value to study a case where we have a dineric interface.

The following extract from Wilson's[3] account of an experiment which he carried out as early as 1848 will serve the purpose as well as any.

> When chloroform is placed in a test-tube, or other vessel of glass, standing on a horizontal surface, it exhibits, like other substances which wet that solid, a curved surface with the concavity upwards. If water, or an aqueous solution of nitric, sulphuric, or muriatic acid, be poured upon the stratum of chloroform, the surface of the latter immediately changes the

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[1] Bancroft, *Jour. Phys. Chem.*, **19**, 275 (1915).

[2] Bell, *Jour. Phys. Chem.*, **9**, 531 (1905).

[3] *Jour. Chem. Soc.*, **1**, 174 (1848).

direction of its curve, and becomes convex upwards, the convexity induced being much greater, however, than the previous concavity. If, on the other hand, an aqueous solution of potash, soda, or ammonia be placed above the chloroform, the latter ceases at its upper limit to present a sensible curvature upwards or downwards, and shows a surface which, to an unassisted eye, appears to be flat. It is to the property of an acid to round, and of an alkali to flatten, the surface of various liquids, of which chloroform is one, that I seek specially to direct attention.

The phenomena referred to cannot seem remarkable when merely described but they have appeared strikingly, and, I may say, startling to most of those that have witnessed them. They are best observed by dropping into a perfectly clear, flat-bottomed glass vessel containing pure water, a quantity of chloroform too small in amount to touch the walls of the vessel on every side. The heavier liquid then shows itself as a brilliant, highly mobile globule. If alkali be now added the chloroform in a moment collapses, sinks as if exposed to a crushing force, and flattens out on the bottom of the glass. On slightly supersaturating the alkali with acid, the flattened chloroform starts into its previous globular shape with a momentum and rapidity such as might be exhibited by a highly elastic substance, like a ball of caoutchouc suddenly relieved from enormous pressure. When the acid in its turn is supersaturated with alkali, and the flattening again occurs, by alternating the addition of these reagents, the same globule may be successively flattened and rounded for any number of times.

Change in configuration, however, is not the only alteration which the globule of chloroform undergoes. Some of the other physical properties are markedly altered by its contact with acids and alkalis. These changes are best seen when a deep, white saucer, or flat-bottomed porcelain basin, is made use of as the containing vessel. When acidulated water is placed in this and chloroform let fall into it, the denser fluid is scarcely wetted, and, although nearly half as heavy again as pure water, sinks reluctantly. If the drops indeed be small, they never reach the bottom, but on floating on the surface, evaporate away. Those which descend form globules very mobile and readily obeying the solicitation of gravity. When separate globules melt, they rapidly flow together, and scarcely one is seen without a bubble of air attached to its upper surface adhering tenaciously. When the water, on the other hand, is an alkali, the chloroform is quickly wetted and sinks swiftly. The drops, if small, become circular discs with rounded edges; if large they are oval, or spread out into elongated, irregularly ovoidal, or flattened cylindrical forms. Their shape, however, is changed by the slightest impulse, or inclination of the containing vessel in a way which, perhaps, might best be illustrated by comparing it to the ever-varying elongation, contractions, and irregular swellings, which alter the configuration of an active living leech in a glass of water. The flattened globule, moreover, is much less mobile than the rounded one in acid. The former moves sluggishly, even down an inclination, clings to the vessel, and when compelled to move rapidly leaves a tail behind it, like foul mercury. No air-bells attach themselves to it and its brilliancy is sensibly diminished, as if its refractive index had altered.

From this experiment we can very clearly see how the dineric interface changes in shape when an acid or alkali is added to the system.

The interfacial tension is markedly altered in both cases. In the flotation process the emulsifying agent alters, in the same way, the interfacial tension existing between the surface of the water and the air bubble. The result is that the metallic sulphide particles find it more difficult to pierce the water-air interface than when there is no emulsifying agent to make a more coherent film. Thus the oil will make it possible for a larger number of sulphides to adhere to this usually spherical film.[1]

Electrical Phenomena in Flotation

Such an authority as Thomas M. Baines, Jr., states:[2]

> If one turns to "Elementary Lessons in Electricity and Magnetism," by Silvanus Thompson, and studies the fundamental principles of frictional electricity, as given in Chapter I, a clearer idea of the causes of "flotation" may be obtained. The electrical theory was taught last year as possibly explaining flotation phenomena to the class in ore-dressing, at the Case School of Applied Science.

In his article Mr. Baines gives the following summary of requirements for "flotation" from the electrical standpoint:

1. Ores containing valuable minerals or metals that are good conductors are the only ones suitable for flotation.
2. To buoy these conductors, it is necessary

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[1] "The Flotation Process," by Stander.

[2] "The Electrical Theory of Flotation," by Thomas M. Baines, Jr., *Min. & Sci. Press*, November 27, 1915.

to supply electrified bubbles from below to float particles of the conductors that are attached; hence the smaller the bubble, the better the result, the gas being the same.

3. Some dielectric fluid is necessary to cover the conductor of the bubbles to prevent the dissipation of the electric charge. The thinner the film of dielectric and the greater its dielectric strength, the greater the effective attractive force and the more permanent will be the froth.

4. Some material must be added to the water to increase its conductivity to obtain a clean concentrate; acids in small quantities are now used.

The following experiments were conducted to illustrate electrical phenomena:

If powdered galena ore with a limestone gangue be dropped into pure water, most of the powder will immediately sink to the bottom. As the air enclosed by the particles is expelled gradually, one sees the formation of "armored" bubbles, some of which may last for days. Here is flotation without oil or acid. If nitric acid is added, the gas bubbles, formed by the action of the acid on the gangue, will carry up particles of galena, some reaching the surface and bursting, while others too heavily loaded with galena particles will hover just below the surface. These will form clusters, resembling bunches of grapes, and when enough gas bubbles join the clusters, they start upwards toward the surface, but generally before reaching there they are overloaded by particles falling from the bubbles that are bursting at the surface. The bubbles with their loads often resemble balloons, with the galena hanging onto the bottoms, as do the baskets of actual balloons. Some of the bubbles will be completely "armored" while others will be nearly free from galena. Another experiment that may be successfully used in the laboratory for flotation for different sulphides, such as old rusty pyrite concentrate, like sweeping from floors of old mills, is as follows: Mix the ore with bleaching powder, some carbonate (say, sodium carbonate), and water. Put the mixture into a glass beaker and add concentrated nitric acid until red nitrous fumes are given off. Chlorine also will be evolved. The bubbles of gas are so highly charged electrically that pyrite from the Mother Lode between 10- and 20-mesh size was floated, making a complete separation from the quartz gangue. In this experiment nitrous oxide was the active agent, for if the same experiment is conducted with sulphuric acid, no such separation takes place.

Mr. Baines accounts for the electrification of bubbles as follows:

(*a*) Two different substances, whether gaseous, liquid, or solid, when brought intimately into contact and moved one over the other, always produce electrification.

(*b*) Difference of temperature of two similar substances in frictional contact will cause electrification, the warmer usually being negatively charged.

(*c*) Something certainly happens when the surface of two different substances are brought into intimate contact, for the result is that when they are drawn apart, they are oppositely charged. The nature of the charge depends on the substance. Fur rubbed on glass electrifies the glass negatively; while if glass is rubbed with celluloid it will become positively charged.

(*d*) A blow struck by one substance on another produces opposite electrical states on the two surfaces.

(*e*) The evaporation of liquids is accompanied by electrification, liquid and vapor assuming opposite charges, though this is only apparent when the surface is in agitation. A few drops of copper sulphate thrown on a hot platinum plate produces violent electrification, as the copper sulphide evaporates.

(*f*) Electrical charges are set up by various other means, such as vibration disruption of material, crystallization, combustion, pressure, and chemical reactions.

He concludes:

> It would seem easier, therefore, to electrify a bubble than to keep it from being electrified. I assume that the bubbles are electrified, whether by means of air being forced through canvas, by beating air into water with paddles, or by other means. So air bubbles that are electrified will attract conductors near them that are free to move. Air, being a poor conductor of electricity, the bubbles as a whole do not discharge immediately upon contact with a conductor. The only part of the surface discharged is that in immediate contact with the conductor, and this discharged film of air acts as a dielectric and non-conductor to the rest of the bubble, which remains charged.

The above theory has been tolerated by O. C. Ralston[1] and supported by J. M. Callow.[2]

Ralston states as follows:

> The electric charges on suspended particles allow another possible explanation of flotation phenomena. We find in some of the colloid chemical literature that quartz particles when suspended in water are negatively charged, pyrite particles positively charged, oil droplets negatively charged, and air bubbles negatively charged. The charges are somewhat small compared with the weight of the particles, so that they are hardly strong enough to cause negatively-charged quartz to stick to positively-charged pyrite, as they can have only a few points of contact, and currents in water could easily tear them apart. However, the negatively-charged droplet of oil, which is repelled from a negatively-charged particle of quartz, can wrap itself around the positively-charged pyrite particles so that they will stick together and the same applies to air bubbles. The other sulphides known to be flotative have positive charges when suspended in water or can be made to assume positive charges by the use of the proper amount of the proper electrolyte. So it can be seen that the application of these principles gives no difficulty in explaining flotation from an entirely new standpoint.

Callow's theory is stated briefly as follows:

That oil flotation is an electrostatic process. It is a scientific fact that when a solid particle is suspended in water the water will form around

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[1] "Why Do Minerals Float?" by O. C. Ralston, *Min. & Sci. Press*, October 23, 1915.

[2] "Notes on Flotation," by J. M. Callow, *Min. & Sci. Press*, December 4, 1915.

the particle a contact-film that generally possesses an electric charge, the amount and polarity of which will depend upon the nature of the surface of the particle and the electrolyte in which it is suspended. The presence of these charges can be demonstrated by the fact that particles possessing them will migrate when placed in an electric field. It has been demonstrated that floatable particles have charges of one polarity (positive), and that non-floatable particles have charges of opposite polarity (negative), and that this froth is charged negatively and so attracts the positively-charged or floatable minerals, and repels the negatively-charged or non-floatable ones. It is this, it is believed, that causes the floatable minerals, such as galena or sphalerite, to adhere to the froth and rise, while the gangue minerals, such as silica and limestone, remain in the liquid where they can be discharged as tailings.

C. T. Durell in his osmotic hypothesis states:[1]

Electricity may manifest itself in various ways, but flotation cannot take place without nascent or occluded gas and that, all theories of flotation, be they electrical or otherwise, must come to osmosis for their solution.

F. A. Fahrenwald conducted a series of experiments to investigate the phase of the process that caused the bond between the flotative mineral and the bubble carrier.

Before proceeding to the discussion of the electrical theory, he very wisely stated eight of

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[1] "Flotation Principles," by C. T. Durell, *Min. & Sci. Press*, February 19, 1916.

the most important fundamental facts of electrostatics. They are:[1]

A. The production of electricity by friction is a common phenomenon; almost any two bodies become electrified if they are rubbed together. In the case of several instances, considerable force is then necessary in order to separate them. Attraction or repulsion also occurs when an electrified body is brought near bodies that have been subjected to friction, and if these are light enough (as bits of pitch, feathers, wood, paper, etc.) they may be lifted. Bodies may also become electrified by coming in contact with other bodies that already carry a charge. In this case the first body receives electricity of the same sign from the charged body and is then repelled.

B. Bodies that when electrified at one point are immediately electrified all over are called good conductors; those over which the charge diffuses slowly are poor conductors. All metals, many metallic ores, graphite, ordinary distilled water, and aqueous solutions of salts are good conductors.

C. If a piece of metal, or other conducting material held in the hand is rubbed against a non-conductor — say, a piece of dry flannel — only the non-conductor appears afterward to be electrified. The reason is that the electrification produced on the metal spreads over the hand, arm, and body of the experimenter to the floor and walls of the room. If, however, the conductor is insulated, the degree of its electrification cannot be increased or decreased.

D. By whatever process a body is electrified there is always an equal amount of electricity of the opposite sign, which may reside upon the

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[1] "The Electrostatics of Flotation," by F. A. Fahrenwald, *Min. & Sci. Press*, March 11, 1916.

walls of the enclosing room or upon some other surface insulated from the conductor. Bodies carrying opposite charges, when brought in contact or connected by a conductor, become discharged. If the charges are equal they are neutralized, but if one carries more than the other the system takes on the sign of the excess charge.

E. If these bodies are strongly electrified, discharge can take place through an appreciable thickness of non-conducting material, such as air, oil, or glass. This discharge is facilitated by the presence of sharp projections upon either body.

F. (*a*) The space between two charged bodies is filled with lines of force that tend to move a contained body in the direction of the local lines of force leading to the surface carrying the opposite sign.

(*b*) These lines of force do not penetrate the surface of the conductors forming its boundaries and a hollow conductor is electrified on its outside or inside surface only, depending upon whether the opposite charge resides upon one contained without the sphere or upon one contained within and insulated from the shell. In the latter case the entire field is contained within the inner surface of the sphere, and in the former case there is no charge within the hollow conductor.

G. The force exerted between two small charged bodies as given in the equation,

$$F = \frac{qq'}{d^2},$$

in which q and q' are the charges in electrostatic units carried by each of the two bodies and d is the distance between their centers of charge.[1] If the bodies are separated by a medium other than air a factor K, known as its dielectric coefficient, must be used and the equation becomes

$$F = \frac{1}{k} \cdot \frac{qq'}{d^2}.$$

H. Matter itself is not acted upon by an electric force, which acts only between different quantities of electricity. When a conductor is introduced into an electric field it represents a gap or an interruption of the lines of force, resulting in an electrification of its surfaces only, that part becoming positive which is presented toward the negative boundary of the field and the reverse. In other words, the original field is divided into two. This same effect is produced in the case of a poor conductor but to an exceedingly small degree. This explains the attraction of small bodies by another that has been electrified by friction, in which case electrification by influence precedes attraction, and what is really observed is attraction between opposite electric charges.

The following experiments were conducted by Fahrenwald (see Fig. 14) which should serve to check the various points, as outlined by Mr. Baines, as requirements for the electrical theory.

1. Galena ore was ground in an agate mortar and poured from an agate spoon (to prevent discharge of positive electricity, if present, from ore) between two plates of an electrostatic machine. The material was deflected as shown. Plates were electrified almost to discharge point. This shows that galena ground under

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[1] The force by a charged sphere acts as if originated at the center.

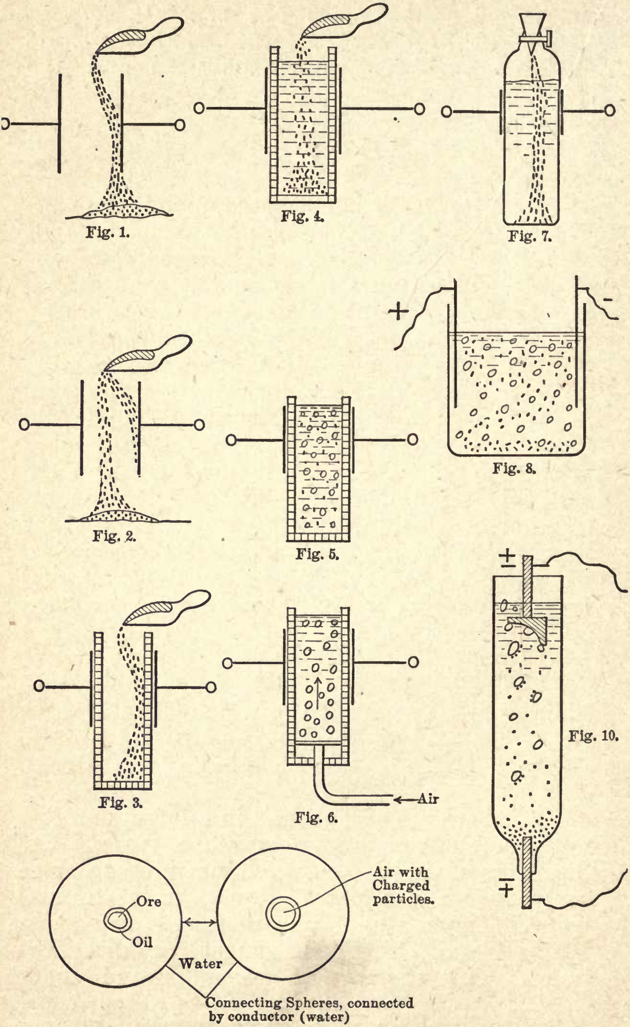

Fig. 1. Fig. 4. Fig. 7. Fig. 8. Fig. 2. Fig. 5. Fig. 10. Fig. 3. Fig. 6.

Fig. 14.

insulating conditions carries a charge and that a particle of this nature, suspended in a non-conductor in an electrostatic field, is attracted.

2. Ore was ground in conducting earthed mortar and poured from earthed spoon. Deflection of only a very few particles was shown. Perhaps the deflected particles were insulated with oil or did not come in contact with earthed surface.

3. Ore treated as in No. 1 and poured between glass sides of a cell. Glass was 1 mm. thick and separated by two centimeters. Potential between plates of machine was 8500 volts. Deflection as shown. The interposition of glass had very little effect.

4. As in No. 3, but the cell was full of water. Used conductivity, tap, and acid water. No deflection. This indicates that particles charged, or otherwise, suspended in a conducting solution (*i.e.*, enclosed within our hypothetical conducting sphere) are not affected by electrostatic forces without.

5. Cell contained ore and nitric acid solution to generate gas. Neither bubble rising nor ore particles dropping showed deflection. Potential, 10,000 volts. The conditions here duplicate those of No. 4.

6. Bubbles blown through canvas into water or acid solution were not deflected. A charge of bubbles flowing in one direction would produce an electric current, and even if they were charged they could not be attracted, as here again the charges are enclosed in a conducting material.

7. Ore poured into cell containing gasoline. There seemed to be a slight deflection. 10,000 volts between plates. Conditions here should not differ greatly from those of No. 3. Solution may not have been sufficiently non-conducting.

8. Solution placed in electrolytic cell, ar-

ranged as shown, gave no deflection of ore or bubble with conducting or non-conducting solution. Both ions and charged colloids are susceptible to this treatment, and no doubt they would move easier than the large body and so lessen the potential on the larger masses.

9. The water itself was electrolyzed to furnish gas. A two-way switch gave either hydrogen or oxygen at the bottom pole, which was covered with a layer of ore. Both gases carried apparently equal amounts of ore with equal readiness. Bubbles in either case, upon striking the upper plate, did not discharge their burden of ore, no matter what the sign of electrode.

10. Set up as in No. 9, except that gas was furnished by action of nitric acid on ore. Changing of sign produced no discernible effect upon bubble or ore or upon bubbles with load when coming in contact with upper electrode plate.

Preferential Flotation

The term " Preferential Flotation " has often been confused with that of " Selective Flotation." " Preferential flotation " is the term applied to that process by which one mineral is separated from another, both being amenable to the flotation treatment. " Selective flotation," on the other hand, means the flotation of a valuable mineral in the presence of waste material. Making a froth concentrate of galena and blende from a lead-zinc ore is a sample of selective flotation, but if two separate concentrates, one containing a high percentage of lead and the other a high percentage of zinc, are made by means of two or more different treatments, the process would be "preferential."[1]

So far the chief methods of preferential flotation can be classified into these three groups: 1. Roasting Methods. 2. The Use of a Chemical Solution. 3. Controlling Flotation.

Roasting Process. — The roasting process was developed chiefly by Wentworth, Ramage, and Horwood. This process really consists in the deadening of certain sulphides by short and slight roasts, while other sulphides, which may be present, remain unaffected by the heat. Ramage terms this "fractional roasting," while Horwood speaks of it as "preferential flotation." The Horwood process of preferential flotation is practically the same as the processes of Wentworth and Ramage.

The Wentworth Process:

"The process consists in the preliminary treatment of ore mixtures containing several sulphides, which converts some of the sulphides, superficially at least, into metallic compounds which are differentiated in their behavior" with respect to flotation processes as commonly practiced. To the words of a later patentee, the surfaces of such minerals as galena, pyrite, and chalcopyrite are "deadened" by a very short and slight roast in a roasting furnace, while the sphalerite is unaffected. Thus the sphalerite can be removed by flotation from such an ore, leaving the other sulphide minerals to be removed by other means. A few minutes heating at a dull-red heat has been found to be sufficient.

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[1] "Advancement and Present Status of Preferential Flotation," by H. J. Stander, *Min. & Eng. World*, Nov. 18, 1916.

The Ramage Process:

" This process has for its object the separation of the valuable minerals from such ore as chalcopyrite, bornite, or erubescite, and mixtures of the same with pyrite, in which ores the copper is in chemical combination with the iron; and also from such ores containing zinc blende. The method is also applicable to compound ores, such as those of the Cobalt district and other sulph-arsenides." " The principle of the process is founded on the combination of fractional roasting with chemical floating." Ramage's introduction of the term " fractional roasting " is particularly felicitous, as it more accurately describes the method than does the term " preferential flotation," used by Horwood.

Ramage described the process by the use of three examples, which are decidedly interesting. The first example is of an ore containing iron pyrite and chalcopyrite, with a content of about 5 per cent copper and 30 to 40 per cent sulphur. The ore is roasted at about a red heat long enough to decompose the pyrite slightly and not affect the chalcopyrite. " The burnt ore is then crushed to at least 15 mesh and passed through a solution of acid sulphate of soda and nitric acid (the solution being formed by adding nitric acid to sulphate of soda), which solution is kept near the boiling point. The copper sulphide immediately rises to the top of the bath and can be skimmed off." The copper dissolved in the bath can be recovered in known ways. This method of flotation (hot acid bath) is not new, having been patented by DeBavay, Potter, Delprat, and others. The fractional roasting had been previously patented by Wentworth, and so the only thing that seems new is the combination of methods.

A second example is that of an ore containing pyrite, chalcopyrite, and zinc blende in quantity. The ore is roasted at a temperature of not over 600° C., so that only the iron pyrite is deadened. The roasted ore is then subjected to the acid sulphate of soda solution for flotation of the unchanged sulphides of zinc and of copper. This product is then roasted at about 700° C., until all of the zinc sulphide is decomposed and the copper sulphide unchanged. This mixture is treated with a solution of dilute sulphuric acid for the dissolution of the zinc, to be recovered from solution by any familiar process, such as electrolysis, the copper sulphides being sent to the copper smelter. There are certainly most interesting facts disclosed in this patent. The great resistance of copper sulphides to the roasting process, as compared with the sulphides of zinc, is something new and will be a most valuable characteristic, if true.

The third example is that of the ores of the Cobalt district, Canada, where cobaltite, niccolite, chalcopyrite, pyrite, and native silver occur. All the sulphide and sulpharsenide minerals are floated, leaving the silver in the gangue. The sulphides are roasted at about 800° C. and everything is decomposed except the copper sulphide, which can be floated from the calcine. Again we have mention of the almost incredible property of copper sulphides to resist roasting.

The next patent was that of H. A. Wentworth, amplifying on this former patent in claiming the chemical change of minerals as a method of separating them preferentially by flotation. He had in mind particularly the treatment of the ore with chlorine, which would sink when subjected to a film-flotation process, while others would have their flotative properties enhanced. As an example, a mixture of zinc and iron sulphides, when treated with chlorine gas in a slightly damp state, is so altered that the blende will float on a film-flotation machine much better than before treatment, while the pyrite has a coating formed over its surface which is much more easily wetted, so that it will sink. Still a further example is the application to the separation of pyrite and chalcopyrite. The latter is attacked much slower than pyrite; hence it can be floated when both are present. A similar behavior of the minerals is observed when they are suspended in water containing dissolved chlorine in the proper concentration, but the best work seems to be done with minerals fed onto one of the film-flotation machines, such as that of H. E. Wood of Denver, although Wentworth gives the design of one of his own in the specification. It is easy to see that with chlorine water and one of the mechanical frothing methods of flotation the soluble coatings that are formed on the surfaces of the minerals would be simply washed off and the preferential part of the flotation lost. Tests in our laboratory seem to show this. So far as is known to me, this process is not being used.

The Horwood Process:

It depends upon the "deadening" of galena and pyrite in a short roasting at 300 to 500° C., whereby the galena is coated with lead sulphate and the pyrite with iron oxide, while the sphalerite is unaltered. This allows a separation of the undesirable zinc from the lead-iron-silver product and allows their separate marketing. This process has received more careful attention than any other process, and reference to original articles is best.[1] According to the data given in

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[1] T. J. Hoover, "Concentrating Ores by Flotation," *Min. & Eng. World*, July 18, 1914; *Eng. & Min. Jour.* (1914), 97, p. 1208; *Min. & Sci. Press*, April 18, 1914, p. 657; *Metal. & Chem. Eng.* (1914), No. 12, pp. 350 and 592.

some of this literature, it appears that it is possible to take a flotation concentrate containing 36 per cent Zn, 15 per cent Pb, and 22 oz. Ag per ton, and divide it into a zinc product running as high as 50 per cent Zn, 7 per cent Pb, and 15 oz. Ag, and a lead product containing 38 per cent Pb, 8 per cent Zn, and 42 oz. Ag per ton. This is of great interest to all producers of "complex sulphide" ores, as the milling of coarsely crystalline material has presented much difficulty in the past for the reason that some finely-divided material (slime) is bound to form in crushing, and while the combined lead and zinc sulphides can be floated nowadays without much difficulty, the mixture is of far less value than the two minerals separated. This is important enough, not to speak of the possibility of treating the microcrystalline sulphide ores and those containing gangue of high specific gravity, such as barite. While flotation has been a boon to the concentration of all sulphide slimes, preferential flotation is much more important for the ores containing undesirable combinations of sulphides. Hence Horwood's work should receive the highest praise.

Another detail, as regards the process, is that 35 lb. of sulphuric acid per ton of ore is necessary and 2 to 3 lb. of oleic acid for the flotation of the unaltered zinc. All of this appeared in Horwood's first patent, No. 1,020,353, of 1912, and he later came out with improvements on the process in patent No. 1,108,440, of 1914. In this later patent he stated that he had found there was a tendency for the silver to follow the zinc, which is undesirable, but that this could be prevented by simply washing away all soluble salts on the concentrate before it was subjected to the deadening roast. This reduces the amount of oxidized zinc formed and lost by solution in the dilute acid in the mill-water as well as allowing the silver to become deadened to a greater extent. He also found that the most successful flotation took place with the pulp at a temperature of about 120° F.

It will be seen that the Horwood process has been applied only to concentrates from previous flotation or from other concentration processes. This is the logical place to apply it, as there is no object in leaving a non-flotative galena or other sulphide mixed with gangue, by using the process on crude ore. The same remark applies to many of the other processes. To be sure, there has been some success in the Australian mills as well as in the United States in the treatment of mixed galena-sphalerite concentrates from flotation machines on concentrating tables. As an example, the Timber Butte mill is treating the flotation concentrate of a zinc ore containing some zinc concentrate carrying 53 per cent Zn, 1.5 per cent Pb, and 4 per cent insoluble. However, this method has not always met with the best results, and where the proportions of lead and zinc in ordinary complex sulphide concentrates are about equal it is quite hard to get two products that are sufficiently pure. Where it can be done, it is certainly more desirable than the more complex fractional roasting and preferential flotation processes of Horwood, Wentworth, and Ramage.

The Use of Chemical Solution. — In the Lyster process the preferential action is brought about by the use of a chemical solution. This process has received some consideration by the Zinc Corporation. The process is as follows:

This process is carried on in neutral or alkaline solutions (never acid) of the sulphates, chlorides, or nitrates of calcium, magnesium, zinc, iron, acid sodium, or sodium-potassium sulphates. Using eucalyptus oil or a similar frothing agent, the agitation of the pulp takes place in centrifugal pumps, throttled to give further agitation, and discharging into spitzkasten with constricted tops. It is said that a galena froth can be collected carrying 55 to 60 per cent lead and that by sending the tailing to a second machine with further addition of oil, the sphalerite can be floated.

It will be noticed that this, with the possible exception of Wentworth's second patent, is one of the first proposals to give a true "preferential" flotation to a mixture of sulphides, as the roasting methods above mentioned involve an actual conversion of some of the minerals, so that sulphide surfaces are no longer presented to the oils and air bubbles in the flotation operation. Lyster's process, however, involves the actual flotation of one mineral in preference to another, unless the chemicals used are chemically altering certain of the sulphides so that they cannot float. Anyone who has worked with mixtures of sulphides has doubtless noticed that greater care is necessary in the flotation of zinc sulphide than in floating galena; in fact, galena is one of the most easily floated minerals outside of molybdenite, and zinc sulphide is considerably more difficult. The fact that a froth running so high in lead, as the Lyster process is reported to give, would also tend to make one suspicious that rather poor flotation conditions are maintained, so that only the most easily floated material (galena), and only the purest of that, is coming up in the first product. This takes place even in the presence of considerable oil, whenever flotation conditions are poor, on almost any type of machine, and while the grade of froth that is obtained is high, the extraction is poor on account of the fact that only the best mineral is floating. It is possible that some such combination of results as this has caused the process not to be considered unfavorably.

Controlling Flotation. — It is a known fact that the percentage of extraction by flotation of a sulphide in an ore depends on such factors as the degree of fineness of the gangue and of the mineral particles and so also do some of the other variables such as the amount and kind of oil or acid used, the time and speed of agitation and the temperature at which the experiment is conducted. And furthermore, we know that one sulphide is more flotative than another, a very important property in this particular phase of flotation.

In 1913 Nutter and Lavers made use of these different behaviors of sulphides under different conditions, and brought out their process for preferential flotation of minerals. It is "a process for concentrating ores which consists in treating the crushed ore by a flotation process, two or more times under different conditions, to obtain froths or scums, having the constituents of each in certain ratios of size, and thereafter subjecting the powdered mixture contained in each froth to a classifying step to separate the constituents." According to the description of their process, the one sulphide can be separated from the other by correctly controlling certain conditions in the flotation plant.

The following is an example cited by the inventors:

> An ore, containing galena, chalcopyrite, and sphalerite, is crushed and admitted to the flotation machine. Using cresylic acid without any mineral acid, it is possible to float most of the chalcopyrite and a small quantity of galena. So, from this first treatment, a chalcopyrite concentrate is obtained, the residue being given a second treatment, and with the help of sulphuric acid, a galena froth concentrate can be produced, most of the sphalerite being left in the tailings, from which it can then be recovered. In case the ore contains only copper and zinc sulphides, a preferential action can be produced by the use of eucalyptus oil or creosol. No mineral acid is necessary, and a concentrate, containing most of the chalcopyrite and very little sphalerite, can be obtained.

In a method where the separation of one mineral from another depends largely on certain conditions, the process becomes somewhat delicate, especially in the case of flotation. Nevertheless it seems as if this is one of the chief ways in which preferential flotation will be successfully developed in the future.

The phenomena in connection with preferential flotation, according to Thomas M. Baines, Jr., furnish new evidence to strengthen the electrical theory. The following interesting material is taken from his article:[1]

> The simplest experiment, demonstrating preferential flotation, may be performed as follows: Upon a 4-in. watch-glass, place a little galena, blende, and quartz of 20 to 30-mesh size. Add dilute nitric acid and place the glass under a microscope. The acid attacks the galena, forming bubbles of H_2S gas that adhere to the galena. The particles of galena are electrified also, as can be seen by the actions of the particles. The blende and quartz are not attacked. If the ore had been finely pulverized and dilute nitric acid added, the bubbles of H_2S would have been sufficient to float the galena, leaving the blende and quartz at the bottom. However, with fine particles, some blende and quartz would have been entrapped, brought to the surface, and held there by surface tension. The bubbles are not sufficient to float the coarse galena, but by a vanning motion of the glass, the galena will collect, being brought and held together by the H_2S bubbles, forming a mat which is lighter than quartz or blende and can, therefore, be panned off, leaving the blende and quartz. This experiment seems to show that the H_2S is charged oppositely to the galena.
>
> If more concentrated nitric acid had been added to the ore, the blende would have been attacked and the process would have been reversed, the blende forming the mat while galena and quartz were left behind. If dilute sulphuric acid, one part of acid to four of water, had been used, then both the blende and galena would

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[1] "The Electrical Theory of Flotation," *Min. & Sci. Press*, December 11, 1915.

have been attacked and if the ore had been finely pulverized, no " preferential " separation would have resulted, both galena and blende finding their way into the float concentrate. However, with coarse material, the blende is much more highly charged than the galena and if the watch-glass be tapped and the contents given a vanning motion, the blende will gather most of the H_2S bubbles and finally float, leaving galena and quartz behind. This shows that the electrification of minerals varies with different acids and also with different strengths of the same. This action of one mineral, " robbing " the others of their bubbles, has not been utilized in practice, as yet, but there is no reason why " preferential " separations could not be made on a large scale, utilizing this principle. Less air or gas would be necessary than in the present type of frothing cells and a clean concentrate would be produced at once. A separation of blende, galena, pyrite, and quartz may be made as follows:

Add dilute sulphuric acid and pan off the blende; then add dilute nitric acid and pan off the galena; then add concentrated sulphuric or nitric acid, which attacks the pyrite so that it may be panned off.

Or the separation may be made with nitric acid alone, varying the strengths; with sulphuric acid, by use of the " robbing " action described above or by use of hydrochloric and other reagents that attack one or another of the minerals more strongly than the others. If galena or blende and magnetite be treated with dilute sulphuric acid, the magnetite will not be acted upon by the acid, but some of the H_2S bubbles generated by the sulphide will attach themselves to the magnetite, provided the bubble is formed near the magnetite. This illustrates the fact that electrical conductors in a conducting liquid attract electrified bubbles. A slight jar, however, will displace these bubbles; or a piece of sulphide in close proximity will rob the magnetite of the bubble, magnetite being a poor conductor.

Referring to the article on page 668 of the *Mining and Scientific Press* of October 30, 1915, describing a patent for preferential flotation of blende, galena, and pyrite, the second paragraph read: "The new process consists of treating ores in a medium (*i.e.*, sulphuric acid and sodium sulphide) that wets the zinc sulphide and which does not wet the lead sulphide or pyrite." This phenomenon brings out nicely the part played in flotation by the "dielectric film." When thiosulphates, sulphites, or bisulphites are acted upon by sulphuric acid, there is more to the phenomenon than formation of SO_2 gas. The following reactions take place when blende and galena are treated with sulphuric acid and sodium sulphide:

$$\mathrm{ZnS+PbS+2\ H_2SO_4 = ZnSO_4 + PbSO_4+2\ H_2S},$$
$$\mathrm{Na_2SO_2+ H_2SO_4 = Ns_2SO_4+H_2O+SO_2},$$
$$\mathrm{2\ H_2S+SO_2 = 2\ H_2O+3S}.$$

This sulphur thus formed is in a very fine state and acts as a dielectric film about the galena, for which it had a great attraction. Therefore, no frothing agent is needed in this case, as the dielectric film about the bubbles is formed by the sulphur similarly to the films of oil formed in the ordinary flotation processes. In the last paragraph of the above-mentioned article on "Preferential Flotation," the statement is made that "the procuring of the effect aimed at, is dependent upon the presence of a frothing agent, only when a reducing gas is introduced into the medium. It is not independent of the presence of a frothing agent in the flotation medium, when a reducing gas is generated in the flotation medium by a reaction of a substance introduced into it." In other words, if sulphur or any other "dielectric" is liberated in a very fine state, by a "reaction of a substance introduced," no frothing agent need be used.

This action may be nicely illustrated by taking 20- to 30-mesh galena and blende and treating them with dilute nitric acid on a watch-glass and observing the result under a microscope. The galena will gather all the H_2S bubbles, when vanned. Now if the sulphuric acid is added and the watch-glass be tapped and the particles moved over one another, the H_2S bubbles on the galena will be robbed by the blende. Sulphur may be seen surrounding the bubbles, the reaction being as follows:

$$ZnS + PbS + 2\,H_2SO_4 = ZnSO_4 + PbSO_4 + 2\,H_2S,$$
$$H_2S + H_2SO_4 = SO_2 + 2\,H_2O + S, \quad (1)$$
$$2\,H_2S + SO_2 = 2\,H_2O + 3\,S. \quad (2)$$

In (1) the sulphur is formed from the decomposition of H_2S; and would be charged oppositely to the sulphur formed by the decomposition of SO_2 gas. In (2) we have both negatively and positively charged sulphur particles.

In conclusion, Mr. Baines states:

It may be well to call attention to the fact that for laboratory experiments in preferential flotation, any one of the sulphides may be separated from the other sulphides, (*a*) by the use of some reagent that attacks this particular sulphide and not the others, (*b*) by the use of a reagent that attacks one sulphide more vigorously than the others (in this case, the vanning motion allows the sulphide more highly charged to gather up the bubbles from the sulphides less highly charged, and if sufficient bubbles are collected, the mass of bubbles and sulphides will float). If not sufficiently buoyed, the mass remains submerged, but it is lighter than the other sulphides of gangue minerals and can be panned off or separated by hydraulic classification.

The second point of interest is the formation of a frothing agent within the pulp, when reactions take place that liberate dielectric substances in a very fine state, electrically charged.

The third point is that laboratory experiments may not work out in practice, due to failure to understand the nature of the electrical charges of the bubbles, dielectrics, and particles of ore. A little stronger reagent or a different way of frictionally electrifying the bubbles and pulp, or too thick a film of dielectric or frothing agent, causes the attraction to cease or change. It is no wonder that great difficulty has been experienced in the practical application of flotation to ores, when such delicate electric forces have to be considered.

CHAPTER IV

THE FLOTATION OF OXIDIZED ORES

Concentration of natural sulphide ores by the flotation process has met with such success that attempts have recently been made to apply the process to the flotation of ores other than natural sulphides.

A recent article by O. C. Ralston and Glen L. Allen[1] covers quite thoroughly the work done on the subject up to date, and what follows is largely taken from their work.

Flotation of oxidized minerals depends upon preliminary "sulphidizing" by any method that will convert at least the surface of the mineral particles to a sulphide of the metal. This step is followed by flotation of the artificial sulphide, which results in a concentration of the valuable metals in the low-grade oxidized ore being treated.

The methods of sulphidizing so far investigated are as follows:

1. By the use of hydrogen sulphide on either the dry or wet crushed ore.

2. By the use of solutions of the various sulphides and sulpho-compounds of sodium.

3. By the use of solutions of the various sulphides and sulpho-compounds of calcium.

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[1] "The Flotation of Oxidized Ores," by O. C. Ralston & Glen L. Allen, *Min. & Sci. Press*, July 29, 1916.

4. By the use of a sulphur vapor.
5. By the use of a sulphuretted oil.
6. With colloidal sulphur.

It has been found that treatment by some of these methods will form a film of sulphide over the surface of the particles of such minerals as lead carbonate or copper carbonate, whereas in the other cases the mineral particles are sulphidized to the core. Other methods failed.

By the Use of Hydrogen Sulphide. — In sulphidizing with hydrogen sulphide gas, as applied to lead-carbonate ores, the best method of applying the hydrogen sulphide gas is in a tumbling barrel with the gas inlet in the end. It is also found that a low extraction and likewise a low-grade concentrate of lead is obtained if an attempt is made to float the blackened sulphide (after treating with H_2S) without previously acidifying the pulp. The concentrate is cleaner but the extraction still low. Only by prolonged treatment by H_2S gas can the extraction of lead be raised to commercial grade.

Hydrogen sulphide can be generated quite cheaply. With iron matte available at $5 to $10 per ton, the cost of the H_2S gas resulting, including labor, etc., is between $30 and $50 per ton. A ton of H_2S gas, if it were not for the fact that the gas attacks the metallic particles of the ore with such avidity that by the time the latter are sulphidized sufficiently to permit of good extraction by flotation, they have been sulphidized to the core, could be made to film many tons of ore.

Owing to the fact that the value of lead concentrate obtained is very low as compared to the amount of H_2S necessary to sulphidize it, this process is not regarded as commercially practicable.

Joseph T. Terry, Jr., states:

That H_2S gas is the most satisfactory reagent and can be cheaply produced without the use of acids by the destructive distillation of numerous organic substances mixed with sulphur, and that the sulphide filming of the carbonate minerals is best accomplished by introducing the gas into the ore pulp crushed to 80 mesh, with a density of 20 per cent solid, kept in motion or agitation in an enclosed agitator, or other suitable apparatus, this paralleling conditions when using a solid sulphide.

By the Use of Solutions of Sulphides and Sulpho-compounds of Sodium and Calcium.— Good results on lead-carbonate ores have been obtained when sulphides of sodium calcium were used for sulphidizing agents; also sodium polysulphides Na_2S_4, and Na_2S_5 and the sulph-hydrates of sodium, calcium, and ammonium. Of these the sulph-hydrates seem to be very effective. Different ores require 10 minutes to 24 hours of contact with the solutions of sodium sulphide, depending upon the properties of the ore and the strength of the solution, 10 to 20 lb. per ton of ore usually being sufficient, and should be applied to pulp containing about one ton of water per ton of ore. When a good black color has developed, and the color has ceased to increase in thickness, the pulp is diluted with water to a 3 : 1 or 4 : 1 mixture and floated in either mechanically agitated or pneumatic machines.

By the Use of Sulphur Vapor. — Sulphidizing with sulphur vapor has been tried with little success, for the reason that it must be applied at a temperature above the boiling point of sulphur in order to prevent condensation of sulphur. This means that the ore must be brought to a temperature above 445° C. Pyrite could be used to furnish the necessary sulphur, for when it is heated in a closed space, it gives up half of its sulphur. Sulphur dioxide gas can be reduced to elemental sulphur by passing it through a heated zone in the presence of a reducing agent.

This method has the disadvantages of having to be applied to dried, heated, and finely divided ores. Although it is stated that sulphur vapor was tested at one of the large plants for flotation of oxidized forms of copper, it gave better results than any other method of sulphidizing.

On oxidized copper ores H_2S seems to be by far the best sulphidizing agent. It is best applied to wet pulp and seems to cause true filming. As little as $\frac{1}{2}$ lb. of sulphur per ton of ore is giving good results in the plant of the Magma Copper Company, at Magma, Arizona.

For oxidized copper ores containing a fraction of 1 per cent[1], 2 to 3 lb. per ton of ore is giving satisfactory results.

Calcium polysulphide has been used for some time in a number of the large copper concen-

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[1] Sulphides are present, of course.

trating mills with indifferent success, and seems to be detrimental in some instances.

By the Use of Sulphuretted Oil. — Much secrecy is observed by a number of plants using sulphuretted oils as to the technical details of this work.

With Colloidal Sulphur. — Oxidized forms of copper, so far as is known, are not floated by colloidal sulphur. Neither have the silicates of copper been floated.

It is a peculiar fact, but repeated attempts to float natural sulphides along with sulphidized minerals have failed, as the sulphidizing agents cause trouble with the flotation of natural sulphides. By careful adjustment this difficulty has been solved in one plant, though the details are not available.

The treatment of zinc ores and carbonates, as a whole, has been unsuccessful. The sulphide film does not adhere very strongly and hence comes off too soon.

So far as the writer is aware, in all of the successful work in floating oxides and carbonates, there has been an alteration of the oxide to sulphide. A number of parties claim to be successful in the flotation of copper carbonates without sulphidizing, and others in the flotation of schulite, fluorite, and magnetite.

The Maurex Magnetic Process. — This process was invented and patented by A. A. Lockwood. Various blendes of crude oils are used in the proportion of 15 to 20 lb. (or $\frac{3}{4}$ to 1 per cent) of oil per ton of ore, to which is added an equal quantity of magnetite, ground to 100 mesh. This mixture of oil and magnetite forms a permanent paint, which, no matter how finely it may be divided or broken up, will always be found to be composed of the two substances in the same ratio. The selective affinity of the oil in the magnetic mixture enables it to adhere to any particle of valuable mineral, either sulphide or oxide, contained in the ore, with which it may come in contact, forming a rich magnetic-oil-mineral mixture containing little or no worthless gangue.

In practice the crushed ore and water, together with a regulated quantity of oil mixture, are fed through a horizontal tube revolving slowly, which contains several hundred pounds of $\frac{1}{4}$-inch rough iron shot. The shot becomes oiled and collects the mineral particles, both fine and coarse, in the form of a paste that adheres. This paste is continuously broken away from the shot by attrition and flows with the pulp through a screen at the opposite end of the agitator tube into a shaking tray which feeds it under a powerful electromagnet. The coated mineral particles are attracted by the magnet from the flowing stream of pulp to the underside of an endless belt traveling under the magnet at right angles to the shaking tray, thereby suspending them until they are carried out of the magnetic field, when they are washed off by a spray of water into the concentrate box provided.

The points of advantages claimed for this process are the following:

1. The ore need only be ground fine enough to free the mineral particles from the gangue, in some cases being only crushed to 5 mm.

2. Both sand and slime are treated together in one operation, so that no classification is necessary.

3. This process is suited to the treatment of practically all the sulphide ore, and also successfully treats lead, copper, and zinc carbonates and oxides, making extractions up to 93 per cent in some cases.

CHAPTER V

OIL AND OTHER REAGENTS IN FLOTATION

Oils Used in Flotation. — The question of what oils to use in flotation has probably given more trouble from a practical standpoint than any other. In some cases the situation has been something like this: The manufacturer or producer of oils cannot get any definite ideas as to what kinds or qualities of oils are needed, so he sends to the plant superintendent products or mixtures marked " 240B " or " 1000A," or whatever he happens to call them, with little information as to their chemical composition or physical qualities. One of these oils is used with good results, although he has no information as to the real composition or the physical qualities that have given him the results obtained. When he needs more oil he naturally asks the purchasing agent for a quantity of " 240B," or whatever he has been using. The purchasing agent then finds in the meantime either " 240B " has trebled in price, or the producer's plant has burned, or he is unable to deliver for some unknown reasons, but that he can get from another producer " 360X," which he is assured is much better and may be cheaper. It is at this point trouble begins.

The following are some of the oils used in the flotation process:[1]

1. Coal-tar Products.
2. Coal-tar Cresols.
3. Fuel-oils.
4. Gas-oil (stove-oil).
5. Crude-oil Turpentine.
6. Pine-oils, Wood-tar Oils, Fir-oils, Wood-creosotes, etc.

Coal-tar Products. — Of the coal-tar products cresylic and carbolic acids are the best known reagents. Commercial cresylic acid is an oily refractive liquid, generally with a red or yellow tinge, has a specific gravity of about 1.044 and consists of approximately 40 per cent metacresylic, 35 per cent orthocresylic, and 25 per cent paracresylic acids, the properties of these three isomers being, according to Lunge and Keane:[2]

Acid.	Boiling-point.	Solubility of 100 parts water at ordinary temperature.
	Degrees.	Volumes.
Orthocresylic	191	2.50
Metacresylic	203	0.53
Paracresylic	202	1.80

This acid is much less soluble in water than its homologue, carbolic acid, and is still more easily broken down by sulphuric, which probably ac-

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[1] "Oils Used in the Flotation Process," by An Occasional Contributor, *Min. & Sci. Press*, May 1, 1915.

[2] "Technical Methods of Chemical Analysis," 1911.

counts for the statement that sulphuric acid may not be used along with either of these weaker acids.

Coal-tar Cresols. — Cresylic acid should be handled carefully, as it gives rise to painful skin wounds, and may easily flash into the operator's eyes. It is well to keep a bottle of olive oil handy as a remedy.

Cresylic acid is an expensive reagent, costing at least $1.25 per gallon delivered at western American mills in time of peace. It comes principally from Germany and England. Crude coal-tar creosote, which is a by-product of gas-works, blast furnaces, and gas producers has shown some promise as a substitute.

Carbolic acid (phenol) is a homologue of cresylic acid. It is difficult to distinguish between them, the smell and color being so much alike. Carbolic acid is easily broken down by H_2SO_4, yielding oxalic acid. It appears to be much less selective than cresylic acid in its action on metallic sulphides, and a slight excess brings over a concentrate high in insoluble matter.

Fuel-oils. — Fuel-oils from various localities have widely different action on any given ore. They are not highly selective like cresylic acid, pine-oils, etc., but are strongly emulsive; they serve the purpose of giving body and mineral-carrying power to the relatively weak but more selective froths; they are cheap, quickly obtainable, and when used in moderation bring over a little gangue.

Gas-oils. — Gas-oil, or stove-oil, a distillation product of crude oil, is a strong emulsifying agent, which is at times most useful. It must be used in very small quantities.

Crude-wood Turpentine. — This is a dark reddish-brown liquid with a pungent smell. On gravity-flow machines it is of little use, as its action in slight excess is to bring over gangue freely. As an emulsifier fuel-oil or tar-oil are preferable. On machines through which the flow of pulp is maintained by mechanical means, it has been found a valuable reagent for the purpose of controlling the levels of pulp, through its physical action on the froth.

Pine-oils, wood-tar oils, fir-oils, wood-creosotes, etc., are the products resulting in a destructive distillation of soft wood.

The Purpose of Oil in Flotation. — The exact function of oil in flotation is a point that has not yet been settled, although it seems obvious enough that we want oil for two main purposes:[1] 1st, to furnish a film around the particle, and, 2d, to act as a means of making a foam or froth.

Oils may be roughly divided into two classes: 1. Collectors or Oilers; 2. Frothers or Foamers.

Oils that are good "collectors" are practically insoluble in water and form a film not easily evaporated, so make persistent bubbles.[2]

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[1] "How Flotation Works," by G. D. Van Arsdale, *Eng. & Min. Jr.*, May 13, 1916.

[2] "Universal Flotation Theory," by C. T. Durell, *Mexican Min. Jr.*, July, 1916.

Good "frothers" are oils more or less soluble and, while they make quantities of bubbles and much froth, evaporate quickly, so that the bubbles burst more readily.

The Qualities of a Flotation Oil. — G. D. Van Arsdale states:[1]

> I think it is safe to say that we want, first, an oil whose viscosity is such as to enable it to be finely divided or extended; second, that it should not emulsify readily; third, that its physical qualities should be such that the resultant of the interfacial tensions between water, oil, and particle should be such as to cause with certainty the entrance of a mineral particle into it and the exclusion of a gangue particle."

The object in the addition of a minute amount of, for example, pine-oil is to change the surface tension and contact angle of the other oil or of a particle coated by it so as to enable it now to float, which it otherwise would not do. Heat apparently acts in the same way, for if we drop some oil on the surface of hot water, it does not film out but assumes the globular form.

It would seem that when two oils are used, one for its filming effect and the other as a frother, they should be used separately in the apparatus, first using the filming oil, thus obtaining a maximum filming-out condition, then followed by the frother.

In general, pine-oil makes a brittle froth, which immediately dies; creosotes make a more elastic froth, the bubbles of which may expand to 3

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[1] "How Flotation Works," *Mexican Min. Jr.*, July, 1916.

inches in diameter or more before rupture. Coal-tar products are poor frothing agents and if used must be aided by either creosote or pine-oil to produce a good froth and insure a high recovery. Oils of a lubricating nature seem to be of little value in flotation, while such light oils as gasoline and naphtha are of value only for thinning the heavy coal and wood-tars. On some ores crude pine-tar will in itself combine both the properties of frothing and collecting. On others, this may have to be enriched by the addition of some one of its more volatile constituents such as refined pine-oil, turpentine, or wood-creosote.

The following examples will illustrate how oils are mixed to give a good flotation oil. At the Inspiration, for instance, the mixture is 80 per cent crude coal-tar, 20 per cent coal-tar creosote; at another plant on similar oil 45 per cent El Paso coal-tar, 40 per cent coal-tar creosote, 10 per cent cresol, and 5 per cent pine-oil; at the Daily-Judge mine 40 per cent crude coal-tar, 40 per cent creosote, and 20 per cent pine-oil; in the Cœur-d'Alene on zinc ore straight wood-creosote was used; on the National Copper ore plain turpentine will work but pine-oil will work better.

In the above examples at the Inspiration, 1½ to 2 lb. of the mixture are used per ton of ore; at the Daily-Judge, 1 to 1½ lb; and at the National $\frac{3}{10}$ lb. oil is sufficient. "The proper kind or kinds of oil and quantity required can only be determined at present by tentative experiments; so far no scientific short-cut is known."

The trend of work to-day seems to be to study flotation from the standpoint of the ore, its electrostatic charge (so-called), etc., and from the standpoint of colloidal chemistry it is believed that, in addition, a study of oils would give a better understanding of the process and of the variables concerned, while also aiding in the solution of certain theories not yet advanced.[1]

Froth and Bubbles. — The idea has been abandoned by most people that a low surface tension is the essential requirement for froth formation. As mentioned by Coghill in a recent writing,[2] "contamination of the liquid with an impurity that will cause a variable surface tension is the real requirement."

A bubble of air is spherical in shape, and this shape can only be maintained if the external pressure exceeds the internal pressure. Since a bubble does not expand *per se,* large bubbles can only be accounted for by heat, coalescence, or electrification. Viscosity is an important factor in froth persistence, as it increases the tendency of the liquid film and thus prevents ready rupture. The rupture or bursting of bubbles is explained thus:[3]

1. Concussion upon a surface film deficient in

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[1] "Oils for Flotation," by Chas. Y. Clayton and C. E. Peterson, *Min. & Sci. Press,* April 22, 1916.

[2] "The Science of a Froth," *Min. & Sci. Press,* February 26, 1916.

[3] "The Flotation of Minerals," by Robt. J. Anderson, *Min. & Sci. Press,* July 8, 1916.

the requisite viscosity and variable surface tension.

2. Relief of pressure — here the gas of the bubble in expanding exerts a pressure exceeding that of the liquid film.

3. Adhesive force of the entrained gas for the atmospheric air.

4. Evaporation of the liquid film.

Flotation bubbles will burst for any one or a combination of these reasons.

Furthermore:[1]

(*a*) Frothing never occurs in pure liquids and is a definite proof that the solute or dispersed phase lowers the surface tension of the solvent.

(*b*) A froth which shows adsorption at the interfacial boundary of solution and gas depends for its persistence on the production of a viscous film at that boundary.

(*c*) These viscous films are the direct result of surface adsorption of the dispersed phase, that is, dissolved contaminant, the amount of which is small — disappearingly so.

The work of Hall and Miss Benson shows that in a foaming liquid the foam is richer in the dissolved contaminant than in the bulk of the liquid.

Froths Formed by Flotation Oils.[2] — The froth produced by various oils differs with the machine in which it is made. For instance, in the

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[1] "The Flotation of Minerals," by Robt. J. Anderson, *Min. & Sci. Press*, July 8, 1916.

[2] "Froths Formed by Flotation Oils," by William A. Mueller, *Eng. & Min. Jr.*, July 1, 1916.

Minerals Separation type of machine, where the froth rides in the spitzkasten for some time before leaving it, there is plenty of time to collect and mat together, and in this case the froth always lies in a " dead " state, only coming off as it is forced out by other froth from the rear. In this case the froth loses its characteristics so far as the bubble itself is concerned.

In the Callow type of machine the froth is always in rapid motion and no dead froth accumulates. It is kept overflowing by the constantly rising bubble column formed. In the Cole-Bergmann and Flynn-Towne types of machines the froth acts as in the Callow type. In these two, however, a deeper froth column is carried and this makes a slight difference in the froth, making the bubbles slightly smaller.

In adding oils for flotation it is of the utmost importance that they be well mixed with the pulp before flotation is attempted. This is usually done by adding the oils in the mills during grinding, and this is the most desirable method. Sometimes where this cannot be done, as is the case where primary slimes are treated by flotation and the oils are not wanted in the rest of the feed, a Pachuca tank is used for the mixing. This works fairly well, although it is not the most desirable way of mixing where the entire pulp is to be treated. If not thoroughly mixed, the oils kill froth rather than produce any. When a machine is in good working order and some raw oil suddenly gets into the pulp, the froth immediately seems to dissolve, leaving the pulp showing through the froth. In these cases the froth rushes back and forth in the machine; the bubbles become very brittle and finally disappear.

Another important feature in adding the flotation oils is that they be fed in some continuous way and not spasmodically, since the latter would entail constant attention at the machine and abnormal conditions at all times. There are several devices for uniform oil addition. One is by a pump in which the stroke of the piston can be varied, thus giving any desired amount of oil, from a drop at a time to a steady stream. Another satisfactory device is a method whereby the oil is taken from the rim of a wheel which operates so that the rim passes through oil contained in a reservoir. A piece of flat metal is then fixed by a set screw and spring to rest against the rim. By adjustment of the screw the piece of metal can be shifted across the rim so as to take in a greater or less area, thereby increasing or diminishing the oil flow. Still a third method consists of a small bucket or two on an endless chain passing over a pulley, much the same as a bucket pump, located above the launder where the oils are to be added and another pulley in a barrel or drum containing the oil mixture below. The bucket carries its small amount of oil up, discharges into the launder, and is refilled again on passing through the barrel, etc.

In making any changes in increasing or decreasing the amount of oil or adding different kinds of oil, make them very gradually. In increasing or diminishing, especially, be careful and only change the rate very slowly, allowing enough time to give the change a chance to show up in the machine. Especially is this important when the oils are added in the mills, as it takes some time for a change in oil to make its appearance, since it is diluted to such an extent and worked over such a comparatively large volume.

The froth characteristics here described apply to live froths such as are formed in the air types of machines. The agitator type, with the exception of the agitator-and-air type combined, usually has a spitzkasten or settling compartment in which the froth congeals and so loses its bubble characteristics. In these machines the froth characteristics are not so noticeable.

Characteristics of Pine-oil

Pine-oil, as a general rule, is a rather poor mineral collector, but a good frothing agent. For this reason it is generally used only as a frother, although there are some cases where it will take the place of a mineral collector as well as the frothing agent. Its action is delicate, and at plants where pine-oil is largely used the machines will require much closer attention. For instance, it is a good mineral collector on ores carrying chalcocite and on some zinc ores. A pine-oil froth, in addition to being brittle, is also watery and at times, when there is too much of it present, it tends to make a dirty froth and low-grade concentrate. When present in these large amounts, the concentrate froth will often carry large particles of silica and gangue material; that is, some that will pass 28-mesh and stay on a 60-mesh screen. The froth, however, does not toughen up because of its excess oiling, and in this way pine-oil differs from most others. The froth will be dirty, as is the case with other oils, and cannot be cleaned, but the latter is due largely to excess froth rather than to the toughness of the froth, as is the case with other oils. By the addition of acid, or sometimes a caustic, its action as a mineral collector can often be increased, but it still retains the same characteristics of brittleness and delicacy.

Next to pine-oil the most important flotation agent is coal-tar. As a general rule the coal-tars are too stiff and thick to be used by themselves and so must often be diluted with some other oil, preferably one in its own class. The oils commonly used for this purpose are coal-tar creosote, cresol, and other coal-tar products. Sometimes, however, wood-creosote, fuel-oil, or others are used.

Coal-tar is a poor frothing agent, but a good mineral collector, and it is seldom used without mixing with some pine-oil or other frothing agent. The bubbles from coal-tar itself are also brittle, but in the presence of mineral it often seems to become tougher, the mineral and oil film apparently mating together. The froth from this oil is always mineralized to a high degree when it is mineralized at all. Coal-tar, with a suitable frothing agent, is adapted to almost any ore. By this statement I mean that it is not adapted to any one mineral, but works as a rule with the minerals of copper, zinc, and some others. The froth does not acquire any great depth unless some other oil is mixed with it. For this reason we seldom see a straight coal-tar froth except in an experimental machine. Coal-tar is hard to mix with the pulp, and it cannot be done well except by grinding. I have seen coal-tar, even when mixed with pine-oil, separate when reaching the machine, although in this case it had been added in a Pachuca tank at the head of the machine. When coal-tar shows up in the machine as raw oil, it has not the strong froth-killing power of the other oils, but lies on the froth in flakes, sometimes deadening the froth in the immediate vicinity and at other times seeming to mate the small bubbles together, forming a sort of hole in the froth, toward which the bubbles in the vicinity have a strong tendency to rush. Arriving, they seem to be swallowed up much as a cork will act when thrown into a whirlpool. Raw coal-tar in the machine is not so detrimental as the other oils, but, nevertheless, it should be avoided. When in great excess, coal-tar has a strong tendency to separate, as has been noted, even when apparently well mixed. Even though it has no strong frothing power, when too much is used it will cause some excess frothing and a dirty froth, though not so easily as other oils.

Coal-tar Creosote

Coal-tar creosote is used mostly as a dilutant for the cheaper coal-tar oil, and for this purpose it is very good. The creosote bubble has a tendency to be rather large, ranging in size from about an inch in diameter to as much as 12 in. and sometimes even more. The bubble has a tendency to be tenacious. It is very tough and in breaking, the bubbles tend to expand rather than be destroyed altogether. With two bubbles side by side, the breaking seems to take place in the film uniting them, so that where there were two bubbles at first, there is only one after bursting. This enlarging of the bubble, of course, has its limit, and we seldom see them much over 12 in. in diameter unless there is a great excess of creosote, when they may get to be of such size as to reach across the machine. On bursting, the mineral burden is drawn by the film to the film of the neighboring bubbles with which they were in contact before bursting. The bubble has good carrying capacity for mineral. When too much oil is present, however, there is the same tendency to carry gangue, and this is usually at the expense of the mineral. The oil mixes rather easily, the action in the Pachuca tank being sufficient, although mixing in the grinding mills is at all times to be recommended.

Wood-creosote Bubbles

Wood-creosote has some of the same characteristics of the coal-tar creosote, but differs widely in others. The toughness of its bubbles is even more marked. The size of the bubble is also somewhat different. The two oils are not interchangeable — that is, the one cannot be used as a substitute for the other, as coal-tar creosote seems to work better on copper-bearing ores than the wood-creosote and the latter seems to work better on zinc ores. Wood-creosote is often used as a dilutant for coal-tar in the flotation of zinc ores. The size of bubbles varies greatly. The characteristic froth shows small ones resembling the pine-oil bubble, together with the larger ones. The froth, like that of coal-tar creosote, is tough, and a small excess of oil makes a dirty and voluminous froth that is hard to break up. The bubble varies from this type when an excess of oil is used, tending to become larger and more elastic.

Turpentine is not used so much at the present time as when flotation first appeared in this country. The turpentine froth is persistent and elastic. It has a tendency to hold everything that comes in contact with it, and for this reason it was formerly used to bring up the middlings and was added after the concentrates were taken off. For this purpose it was good, but the froth is so tough that it is hard to break down, so that cleaning it is difficult. Usually the middling produced by means of the turpentine could not be cleaned to any appreciable extent. The turpentine bubble ranges in size from ½ in. to 2 or 3 in. in diameter.

Cresol, or Cresylic Acid

Cresol, or cresylic acid, formerly was the chief flotation agent used in the flotation of copper minerals, but its use is now limited to small proportions in the mixtures with coal-tar. The cresol bubble is of medium size — that is, from ½ to 2 and 3 in. in diameter — and as a rule the bubble is not too brittle and not too tough, but makes a good froth to handle. The nature of the oil, however, made it disagreeable to handle and also somewhat dangerous; this, together with the bringing out of coal-tar and the advance in price of cresol, gradually brought it to a point where only a comparatively small amount is now used.

The oil was a good frothing agent as well as a good mineral collector, and its use was almost universal a short time ago. The froth is rather easy to break down, and for this reason the concentrate produced is rather easily cleaned. The oil is very slightly soluble in water and mixes rather easily. Violent agitation, as in a Pachuca tank or in the Minerals Separation type of machine, is often enough to give good distribution and a good flotation froth.

The froth produced by fuel-oil is of the same appearance as that of coal-tar creosote as far as the bubbles are concerned, which are nearly the same size, ranging from 2 to 4 and 6 in. in diameter. The froth, however, is very brittle when the right amount of oil is used and is much cleaner than the creosote. In fact, the froth is almost too clean, so that a clean tailing is hard to make with fuel-oil alone. Mixed with some oil like creosote, however, it sometimes does good work. The concentrates from the preliminary treatment often need no further treatment. Where a final product is made as concentrate, the tailings are usually retreated, and in this case the creosote effects seem to carry through to the other treatment, while the fuel often has to be added in the second treatment. Various ores differ slightly on this point. Again, a little fuel-oil in a coal-tar-creosote mixture will sometimes aid in cleaning the froth.

When the fuel-oil is in excess, the froth produced is stringy and the bubbles often get to be of such size as to stretch across the machine. I have seen them over 2 ft. in length. The froth under these conditions is also dirty and will pass through a cleaner with practically no better grade being produced than before entering. Acid is sometimes an aid in the use of fuel-oil, especially when the oil is in excess. The froth from excess fuel-oil is hard to break down.

Pine-tar oil is coming into the limelight more just now as a possible flotation agent for copper carbonates, but I doubt whether it will be useful alone. It is stiff and flows poorly, so that it must be mixed with some other oils in order to make it of such viscosity as to flow so that it may be added steadily and slowly.

The froth resembles that from wood-creosote and pine-oil in appearance of the bubbles, but in texture it is very much more fine-grained than the wood-creosote It is a powerful frothing agent similar to pine-oil. It is easy to flood the plant with froth from this oil. The froth is characterized by being dirty, but, like pine-oil, is capable of holding up considerable coarse mineral as well as gangue. When a flood of this froth reaches the cleaner, it is subjected to very little cleaning, owing to its frothing character. Often the addition of a small amount of fuel-oil will tend to make a cleaner froth, but with the pine-tar oil a very clean froth must not be expected except at the cost of high tailings.

Oleic acid is used at several plants in this country and is confined mostly to zinc ores. The size of bubbles varies with the amount of oil used, but ranging from several inches to a foot in diameter. The froth is very persistent and stringy, and the bubble film is often strong enough to support light objects.

Eucalyptus-oil is used mostly in Australia, although a small amount of it may be encountered in this country at times. Its cost, however, is very much against it here.

Dealers in Flotation Oils.[1] — The following is a list of dealers in different oils who have placed on the market various products. A host of these dealers are prepared to supply these products at any time, of fairly uniform quality.

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[1] "Flotation-oils," by O. C. Ralston, *Min. & Sci. Press*, June 10, 1916.

None of them has been able to exactly duplicate their car-load shipments, so that the general practice is to test each shipment of oil in a laboratory testing device to determine the proper method of using a given shipment of oil. This non-uniformity of shipments will doubtless vanish when the market becomes steady.

Dealers in Flotation Oils

Wood-oils

Pine-oils, Resin-oils, Wood-creosotes, Tar-oils, Turpentines, etc.

1. Pensacola Tar & Turpentine Co., Gull Point, Fla.
2. General Naval Stores Co., New York.
3. Georgia Pine & Turpentine Co., 158 Perry St., New York.
4. Central Distilling Co., Helena, Ark.
5. United Naval Stores Co., New York.
6. American Tar & Turpentine Co., New Orleans, La.
7. Cleveland Cliffs Iron Co., Cleveland, Ohio.
8. Chesapeake Tar & Rosin Co., Baltimore, Md.
9. Custer City Chemical Co., Custer City, Pa.
10. Yaryan Naval Stores Co., Brunswick, Ga.
11. Hussay & O'Connel, Savannah, Ga.
12. Florida Wood Products Co., Jacksonville, Fla.
13. Oregon Wood Distilling Co., Portland, Ore.
14. National Wood Products Co., Wilmington, N. C.
15. Chapman Manufacturing Co., Savannah, Ga.
16. Spiritine Chemical Co., Wilmington, N. C.

Eucalyptus-oil

17. Atkins, Kroll & Co., San Francisco, Cal., and other importers.

Coal-tar, Coal-creosotes, and Aromatic Hydro-carbons.

1. The Barrett Co., New York.
2. F. J. Lewis Manufacturing Co., Chicago, Ill.
3. American Creosoting Co., New Orleans, La.
4. American Tar Products Co., Chicago, Ill., and St. Louis, Mo.
5. Republic Creosoting Co., Indianapolis, Ind., and Minneapolis, Minn.
6. American Coal Refining Co., Denver, Colo.
7. Numerous by-product coke-ovens, such as:
    Pennsylvania Steel Co., Steelton, Pa.
    National Tube Co., Penwood, W. Va.
    Milwaukee Coke & Gas Co., Milwaukee, Wis.
    Pennsylvania Steel Co., Lebanon, Pa.
    Solvay Process Co., Syracuse, N. Y.
    By-products Coke Corporation, South Chicago, Ill.
    Semet-Solvay Co., Detroit, Mich.
    Central Iron & Coal Co., Tuscaloosa, Ala.
    New England Gas & Coke Co., Everett, Mass.
    Illinois Steel Co., Joliet, Ill.
    Maryland Steel Co., Sparrows Point, Md.
8. Numerous municipal and similar coal-gas plants.

Vegetal Oils

1. Cottonseed-oil, etc., Southern Cottonseed Oil Co., New York.
2. Corn-oil, Corn Products Co., New York.
3. Palm-oil, Peter van Schaack & Co., Chicago, Ill.

Animal Oils (Fatty Acids)

1. Oleic acid, Peter van Schaack & Co., Chicago, Ill.
2. Oil-flotation grease emulsion, Mohawk Refining Co., Cleveland, Ohio.

PETROLEUM PRODUCTS

Crude, Asphaltum Base

1. California crude:
   Union Oil Co., Santa Paula, Cal.
   Associated Oil Co., Los Angeles, Cal.
   Standard Oil Co., Richmond, Cal.
2. Road oil No. 80, Harris Oil Co., Los Angeles, Cal.

Reconstructed Petroleum Oils

1. Special mineral separator, Continental Oil Co., Salt Lake City, Utah.
2. Solulene and minolene, Star Lubricating Co., Salt Lake City, Utah.

Refined Petroleum Products

1. Stove-oil, Standard Oil Co., San Francisco, Cal.
2. Stanolind, etc., Continental Oil Co., Salt Lake City, Utah.
3. Flotation-oils, Utah Oil Refining Co., Salt Lake City, Utah.
4. Heavy mineral flotation-oils, Geo. P. Jones & Co., St. Louis, Mo.
5. Refinery acid sludge, any refinery.
6. Lubricating oils, any company.

Special Mixtures of Mineral and Wool Oils

1. Calol-oils, Standard Oil Co., Richmond, Cal.
2. Mine & Smelter Supply Co., Denver, Colo.
3. Hendrie & Bolthoff Manufacturing & Supply Co., Denver, Colo.

The costs of flotation-oils have varied so much, owing to the unsettled market, that it is almost impossible to give an idea of what they should cost. For a rough estimate it is possible to say that crude petroleum will cost the same as for other purposes. Many of the specialized products, such as coal-tar, listed above, will cost about 5¢ or less per gallon. The coal-creosotes and the wood-creosotes cost 15 to 30¢ per gallon; the pine-oils 45 to 60¢, and eucalyptus-oil will cost $1.50 or more per gallon. The effect of the ending of the war as regards coal-tar and creosote in the American market is uncertain, but, so far as known, wood products will not be affected, and petroleum products for flotation will almost certainly be little affected. Flotation men do not like to have their oil costs go over 5¢ per ton of slime treated, and many costs are nearer to 2¢ or possibly even less.

There can be no doubt that the higher-grade pine-oils and other wood-oils are the best adapted to general flotation work, but the question of what is commercially feasible is entirely different. Thus the wood-creosotes are meeting with much favor. Many of the special petroleum products, especially those high in sulphur, are adaptable for rough concentration of copper ores, but the most favored materials for such ores at present seem to be the coal-tar products in combination with topped crude petroleum, oils from which the lighter fractions have been removed by distillation. Coal-tars and creosotes, with a small addition of pine-oils, are being used a great deal in zinc work, and the wood creosotes find favor in the treatment of galena ores. Gold and silver ores seem to require much pine-oil, although the pine-oil can be diluted with some of the coal-creosote oils.

It will be found that there is a considerable number of oils that will give good results on any given ore, if the mechanical treatment is adjusted to suit each given oil.

Following is a table showing the amount of flotation-oils being consumed every month throughout the United States. These figures were collected at the beginning of 1916 by direct communication with the companies.

Type of ore.	Monthly tonnage of ore.		Monthly consumption of flotation-oils, beginning of 1916, pounds. Wood products.				
	Beginning 1916.	End of 1916.					
	Tons.	Tons.	Pine-oil.	Pine-tar oil.	Eucalyptus.	Creosote.	Turpentine.
Copper	1,248,000	1,942,000	59,300	750	....	417,000	1,500
Zinc and complex	248,000	350,000	60,750	667	....	262,500	3,330
Lead	115,000	136,000	3,900	....	216	121,000	......
Gold and silver	45,700	123,000	9,830	750	....	40,250	......
	1,656,700	2,551,000	133,780	2,167	216	840,750	4,830

Type of ore.	Oleic acid.	Monthly consumption of flotation-oils, beginning of 1916, pounds.				
		Coal products.			Petroleum.	
		Tar.	Creosote.	Cresol.	Crude.	Fractions.
Copper	....	677,000	403,000	8340	79,000	1,702,000
Zinc and complex	5830	10,670	46,000	....	157,000	41,000
Lead	....	....	9,250	....	....	660
Lead and zinc	....	27,450	4,920	....	7,090	6,250
	5830	715,120	463,670	8340	243,090	1,749,910

CHAPTER VI

TESTS

The Important Points to Test for. — The amount of work required, in testing any given ore for the flotation process, is considerable, since the proper kind or kinds of oil and quantity and amount of other reagents, acid or alkali, can only be determined at present by tentative experiment; so far no scientific short-cut is known.

The most important points to be tested on a given ore with any given flotation machine are:

1. Method of Grinding.
2. Fineness of Grinding.
3. Kind of Frothing Agent Used.
4. Amount of Frothing Agent.
5. Temperature.
6. Acidity or Alkalinity.
7. The Effect of Varying the Speed of Agitation when Mechanical Agitation is Used.
8. Necessity of Preliminary Agitation.
9. Effect of Addition Agents in Flocculating Gangue-slime.

Preliminary Considerations. — It may be seen that there may be a certain best combination of the above variables; hence the desirability of doing the tests in a small laboratory machine where many trials can be made in a short time.

In attacking refractory ores there are a number of ingenious things that can be done to the pulp both in and out of the machine. The trouble may be due to deleterious substances, which sometimes can be:

1. Washed out.
2. Rendered harmless by boiling.
3. Overcome by acidifying.
4. Met with by making alkaline with lime before entering the machine.
5. Occasionally, the ore will not work well under ordinary conditions, but will yield beautifully after fine grinding.
6. Sometimes extra reagents are necessary, such as powdered charcoal, modified oils, argol, soap, calcium, sulphate, alum, etc.

One can see that a rational method of devising the proper tests in such cases must be based on some theory of flotation. Colloid chemistry is a branch of knowledge that will aid in the intelligent control of such tests.

After the best conditions have seemingly been established, they should be further tried in a larger-sized machine before they are incorporated into the general practice of a mill for laboratory results are somewhat pessimistic as compared to large scale work.

Again when a good set of conditions has been found for flotation treatment of an ore, it is best to recover the water from each test to see what effect a closed circuit of the mill water will have. Some oil and chemicals are thus recovered, cutting down the amounts necessary for operation. In fact, a carboy or two of the water to be used in the large mill should be used to make certain that no deleterious contamination will issue from this source.

Oil samples for test purposes can be obtained from the various wood-distilling companies now advertising in the *Technical Press*, from gas companies, and from petroleum-refining companies.

Finally, it is well to be prodigal in the amount of analytical work connected with flotation testing in order to discover interesting differences in gangue constituents carried into the concentrate, as well as to find the best conditions for leaving out some gangue constituent that is less desirable than the rest. If an experimenter does his own analytical work he can be expected to spend three-fourths of his time analyzing what has been done the other fourth.

Method of Grinding. — As a rule laboratory machinery for the pulverization of an ore is of the dry-grinding type, with the exception of small ball-mills that can crush from 1- to 100-lb. charges in the wet. Consequently, most people start with weighed charges of finely-ground dry ore, a known quantity of water, of oil, and of acid or alkali. Generally most dry-ground ore must be treated in an acidified pulp to get good flotation. Doubtless, the surfaces of sulphide particles become somewhat oxidized in, or shortly after, dry grinding, and the function of the acid would be to clean the slightly oxidized surfaces. Wet grinding usually does not call for so much acid. In nearly all laboratory work finer grinding than is used in practice seems to be necessary. This is probably due to the smaller amounts of froth that are formed. Such small quantities of froth cannot form layers as deep as those made in the large machines. 60 mesh is about the maximum size that can be floated with any chance of getting high recovery, while ore crushed somewhat finer than this gives much more ease and expedition in operation.

Wet grinding is more desirable, as it parallels conditions in practice, where most of the fine grinding of ore is in Chilian, tube, or other mills. However, wet grinding is much harder to manipulate in a small laboratory and requires more time. The dry weight of the feed to the flotation machine must be known; hence a weighed charge of dry ore crushed to 10 mesh can be introduced into a porcelain or iron pebble-mill for fine grinding and ground for a length of time found necessary to reduce the pulp to sufficient fineness — 15 minutes to 24 hours. The charge can be poured and washed through a coarse screen (to retain the bubbles) into a bucket and thence into a flotation machine. The oxidation of sulphide surfaces is thus avoided, but separate grinding of each charge, in order to know its exact weight, is rather tedious and requires a number of small mills if many tests are to be run (Fig. 15) on account of slow speed in grinding. A mill with iron balls rather than pebbles is of greater service. It is possible to introduce the flotation oil before grinding, to be sure that

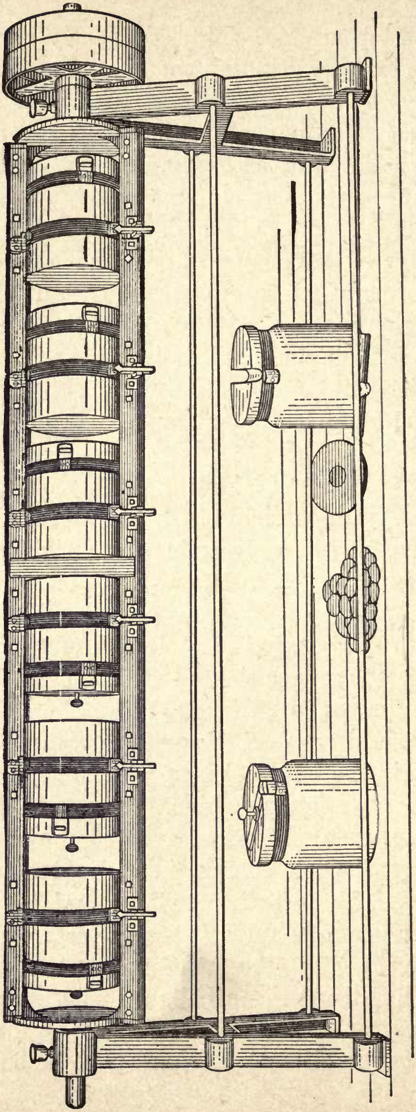


FIG. 15.

it will be thoroughly mixed. For thick viscous oils this is highly beneficial, as a ball mill gives about the best conditions for agitation and mixing. Usually 1- to 2-lb. charges are used and a small laboratory mill of the Abbé type serves well, although a good mill can be made with a 10-in. length, 8-in. iron pipe, and two heavy iron caps for same (Fig. 16).

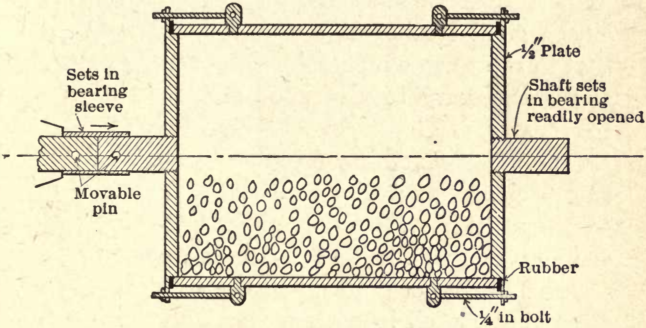


Fig. 16.

Fineness of Grinding. — This would depend to some extent upon the character of the ore. The valuable mineral may be completely liberated at fairly coarse meshes, but it has been found from experience that 60-mesh material is often hard to float with any chance of getting a high extraction, while the operation is performed with much more ease and expedition when the ore is crushed somewhat finer. Some experimenters have claimed that they were able to float even as large as 30-mesh material.

Kind of Frothing Agent Used. — An oil may give a very good percentage of extraction on one ore, whereas it will be an absolute failure when used on another, although both ores chosen are very adaptable to the flotation process.

In some cases a single oil will have both the properties of frothing and collecting, but usually a good frother is not a collecting oil, so that in most cases a combination of two or more oils is necessary to give good results in the recovery.

Amount of Frothing Agent. — In testing for the efficiency of a given oil, it is advisable to tabulate the results obtained with varying percentages of this oil; and it is best to start with about 0.01 per cent of oil in the solution, then increasing the oil in each successive experiment by about 0.02 per cent.

The following forms are convenient for the tabulation of results:

FLOTATION TEST

Ore.. Sample No....................
From... Date..........................

ASSAYS AND ANALYSIS

	Heads.	Concentrates.	Tailings.
Cu	....	....	....
Ag	....	....	....
Au	....	....	....
Pb	....	....	....
Zn	....	....	....
MoS_2	....	....	....
Fe	....	....	....
Insol.	....	....	....

TESTS

Mesh of ore.	Weight of ore.	Oil.	Per cent oil in solution.	Acid.	Per cent acid in solution.	Ratio of amt. of sol. to ore (by weight).	Mineral, per cent in feed.	Per cent extraction.	Remarks on froth.
....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....

Remarks and recommendations..............................

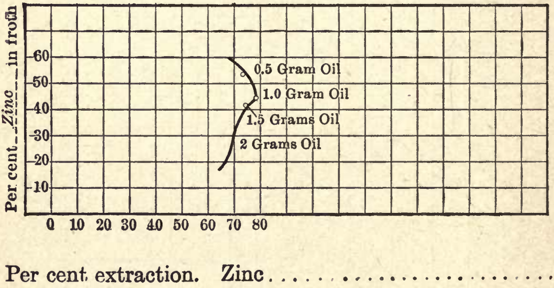
.............*Experimenter.*

To show the effect of variation in quantity. Pine-oil.

Charge.		Variable, grams.	Derived data.			
			Froth.	Assay of con.		Per cent extraction.
				Zn	Pb	
Ore, grams.....	400	...	...	...	...	...
Water, grams...	1200	0.5	29.0	53.2	...	74.6
Acid, H_2SO_4....	2.0	1.0	38.0	43.1	...	79.2
Oil, H_2SO_4......	Variable	1.5	37.0	42.4	...	75.8
Temp. in ° C....	65	2.0	51.0	28.6	...	70.0
Speed, r.p.m....	2000	...	...	...	...	...
Time, minutes..	7	...	...	...	...	...

EFFICIENCY CURVE

Efficiency of pine-oil in terms of frothy assay and extraction.



Acidity or Alkalinity. — The amount of acid or alkali required requires the same manipulation as with oils. The following are some of the probable effects of acid:

1. Prevents emulsification.
2. Prevents deflocculation.
3. Diminishes surface tension of the liquid.

4. Diminishes the gas-liquid contact angle.

5. Increases the viscosity of the gas-liquid surface.

6. From the standpoint of the electrical theory sulphuric acid (as electrolyte) would play a prominent part.

7. Removes surface oxidation and may contribute in the addition of bubbles.

The Effect of Temperature. — In many cases heat is required and in some cases to a high degree. For laboratory work solutions are best heated by introducing steam, generated in a suitable vessel.

Speed of Agitation. — Many reports of flotation test-work with mechanical-agitation machines gives the speed of the rotation of the agitating paddles. In most flotation laboratories it is possible to get much the same work done with quite a variation of speeds, the only effect being to lengthen or shorten the time of treatment. It seems that the importance of this matter is somewhat exaggerated. Some means of speed control is necessary and the speed can be adjusted in each case until the froth presents the proper appearance as to depth, size of bubbles, color, etc. Speeding toward the end of the test is good practice, as it gives a deeper froth with a faint line of concentrate on the top. The speed is better adjusted, for each test, to suit the conditions, rather than running a series of tests with different speeds. Only in the slide machine, where operation of the impeller must be suspended in order to allow froth to collect, is the speed of much importance.

In connection with the electrical theory, Thomas M. Bains, Jr., states:[1]

> The amount of electrification of the bubble will depend on various conditions, such, for example, as the amount of friction produced by the blades of a Minerals Separation machine. Increase the speed and the electrification is greater and the attraction for conductors will increase, reducing the proportion of conductivities in the tailing. Referring to D. G. Campbell's article in the *Mining & Engineering World* of January 17, 1914, the speed of agitation and the percentage of extraction is given as follows:
>
> | Speed of blades, r.p.m. | Extraction, per cent. | Weight of product, grams. |
> |---|---|---|
> | 1800 | 68 | 39 |
> | 1200 | 54 | 32 |
> | 900 | 46 | 26 |
> | 600 | 39 | 18 |
>
> The extraction seems to vary directly as the square root of the increase in speed. But it will be observed that in the increased extraction, the percentage of sulphide in the concentrate decreases, due to the extraction of the small particles of mixed gangue and sulphide. If the bubbles are highly charged, the concentrate will not be as clean in a particular case as if they were less charged.

Effect of Addition Agents in Flocculating Gangue-slime. — The froth of a flotation ma-

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[1] *Min. & Sci. Press,* November 27, 1915.

chine, when viewed in a glass window in the side of the machine, has the appearance of coagules of sulphide, as though the oil or other agent has flocculated the sulphides. The gangue, to sink away from the froth quickly, should also be flocculated. While acids, alkalis, and other addition agents may have other functions, they can easily have a coagulating effect on portions of the ore. A clean flotation concentrate when the gangue is very colloidal is hard to obtain and some method of coagulating the slimes of the gangue is necessary.

The following table, "Effect of Addition Agents" as outlined by O. C. Ralston is of interest.[1]

TABLE II. EFFECT OF ADDITION AGENTS

Inorganic Electrolytes:

Sodium chloride is rarely an effective addition agent for either flocculation or deflocculation of various slimes, and when added to water to any extent demanded by the ore, is likely to increase the viscosity so that the particles will settle slowly in any case.

Ferrous sulphate, the copperas of commerce, is a fairly efficient flocculating agent for negatively-charged particles by virtue of the fact that the heavy bivalent ion of iron is strongly absorbed by the colloid particles. It is a deflocculator of positively-charged particles under some conditions.

Zinc sulphate, copper sulphate, magnesium sulphate, magnesium chloride, calcium chloride, etc., act in the same way as iron sulphate. Magnesium and calcium chlorides are being used for flocculating slimes in the overflow water of many German ore-dressing plants.

Alum and other aluminum and ferric salts containing

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[1] *Engineering & Mining Jr.*, June 3, 1916.

trivalent positive ions are often tremendously effective in the flocculation of negative ore particles.

Sulphuric acid and hydrochloric acid are often effective coagulants of negative colloids owing to the hydrogen ions.

Sodium hydroxide is a most effective deflocculator of negative colloid owing to the strong adsorption of the hydroxyl ions. It will flocculate positive colloids, owing to the same cause.

Sodium carbonate, owing to its alkaline reaction, will generally react in the same way as sodium hydrate.

Sodium Silicate:

This salt hydrolyzes into sodium hydrate and colloidal silicic acid, which carries a negative charge. Both of these products will tend to disperse or deflocculate a negatively-charged ore slime, and hence sodium silicate is one of the most effective agents of this kind, although its full effect is felt rather slowly.

Lime:

The bivalent calcium ion is more strongly adsorbed than the hydroxyl ions and hence lime usually coagulates colloids negatively. It is widely used for that purpose in cyanide mills. Its effect is the opposite of that of sodium hydrate, in which the hydroxyl ion is predominant. The adsorbed ions have been found to be carried down with the precipitated colloids, as has been shown by any number of experimenters.

Organic Electrolytes:

As mentioned in the body of the article, these substances react in many diverse ways. Citric acid and oxalic acid and their sodium salts have been found to deflocculate most ores. Acid tartrates are said to slowly flocculate the negatively-charged slime particles. This field has been almost untouched by metallurgists.

Organic Colloids and Semicolloids:

Tannin seems to deflocculate nearly all ore colloids and is known to affect clays in the same way. Inorganic electrolytes in sufficient amounts will reflocculate the slimes so treated with tannin, but the colloids have been protected by the tannin so that these electrolytes are less effective than on the untreated ore. It produces its maximum effect after standing several hours. It is very deleterious in flotation, although its solutions foam well.

Saponin, the substance used to make beer foam, has an effect similar to tannin.

Albumen, from the white of an egg, is more or less indifferent, but tends to deflocculate most ore slimes.

Ox blood, which contains albumin among other things, is a strong deflocculator and its effects are very hard to counteract.

Soap is an effective flocculating agent with many negative slimes, giving large fast-settling flocks.

Glue tends to flocculate most ore slimes efficiently, especially in the presence of electrolytes, and is known to be bad for flotation.

Gelatin is also an excellent flocculator.

Starch has not been experimented with, but the good effect of flour at Miami is probably due to starch.

Any of the foregoing colloids can be salted out by electrolytes and thereby cause flocculation of the ore slimes in which the process takes place.

Miscellaneous. — The measuring and testing of flotation-oils in the laboratory have been more or less exact. It is common practice to count the number of drops of oil falling from a small piece of glass tubing. A Mohr pipette[1] of 1 cc. total capacity for measurement of the amount

FIG. 17.

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[1] "Testing Ores for the Flotation Process, II," O. C. Ralston & Glen L. Allen, *Min. & Sci. Press*, January 8, 1916.

of oil used in each test is very convenient. Such a pipette is shown in Fig. 17. It will be seen that this pipette allows measurement of the oil to the nearest 0.01 cc., which is close enough for all purposes. If the density of the oil is known, the volume as measured by this method is quickly converted into the weight of oil used.

In the article "Testing Ores for Flotation, Process, II" it is stated:[1]

> The testing of oil samples for flotative power is a matter that needs standardizing. It is desirable to classify oils according to flotative power, but just how to do this is not exactly clear. A unit of "flotativeness" might be established and each oil referred to that unit in terms of percentage. But it has to be remembered that the best oil for one ore may not prove to be the best oil for another, although two such series of oils might roughly parallel each other. For any given ore, it would be permissible to make such a measurement on a series of oils and group them according to some definite standard. A standard oil might be chosen, and the value of a second oil expressed in percentages of the flotative power of the first, as determined by using equal quantities of the two oils in tests on an ore under identical conditions. This test could not be fair for the reason that different amounts of two different oils are necessary to accomplish the same results. Further, the conditions of acidity or alkalinity might favor one oil and handicap another. If we measured the amount of oil necessary to give a fixed percentage of extraction, the first of the

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[1] "Testing Ores for the Flotation Process, II," O. C. Ralston & Glen L. Allen, *Min. & Sci. Press*, January 8, 1916.

above objections would be satisfied, but conditions of acidity or alkalinity could make the test unfair for some oils. Hence the dilemma as to a standardized test of a flotation-oil.

No single test could definitely place an oil in any scheme of classification, and nothing can be done but run a series of tests, using varying amounts of the oil to be tested with varying acidity or alkalinity. The temperature of the pulp must be kept constant, although it has a minor effect.

Considerable work has been done along this line at the Missouri School of Mines and Metallurgy.[1] Their work has been for the purpose of investigating the properties or combination of properties that make oils valuable as flotation agents. They have suggested many points worthy of investigation.

Disposal of the Froth. — The handling of the flotation froth in the laboratory finds difficulties which are reflected in practice. It is often very slow to settle and filters with difficulty. A vacuum filter, connected with a laboratory aspirating pump, is a very convenient method of getting the concentrate out of the froth. A large porcelain Büchner funnel fitted into a filtering flask, as is shown in Fig. 23, is found to be very convenient. A copper vacuum filter is of much the same type, provided with a porous false bottom of acid-proof wire-cloth, resting on a punch plate, as shown in Fig. 32, of the Callow test set. Such a filter can be

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[1] "Oils for Flotation," by Chas. Y. Clayton and C. E. Peterson, *Min. & Sci. Press*, April 22, 1916.

placed under the froth discharge of a flotation machine so that a fairly dry cake of the concentrate is ready for further drying at the end of the flotation test. By loosening the outer rim of filter paper and then turning the funnel upside down over a pan, the filter-paper with the concentrate can be dropped into the dry-pan by gently blowing into the stem of the funnel. This is set aside in a warm place to dry and later weighed against a filter-paper tear. After weighing a numbered tag is put in each pan along with the cake.

The products coming from the flotation machine should be watched closely and occasionally panned or examined with the microscope to see what kind of work is being done. This is fairly easy to determine as the sulphides are most of them distinguished easily from the gangue under the microscope, and likewise gangue particles in the froth concentrate can often be distinguished. A microscope is a most useful adjunct in a flotation laboratory.

Types of Machines and Their Operation

Flotation-test apparatus must necessarily be classified in the same way as large-scale machines, namely: (*a*) film-flotation machines, (*b*) acid-flotation machines and (*c*) froth machines of both pneumatic and mechanically agitated types.

Film Flotation, as exemplified in the Macquisten [1] and in the Wood machines, does not

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[1] *Min. & Sci. Press*, Vol. XCVI, p. 414 (1908).

seem to have the same wide application as does froth flotation; hence little need be said about them.

Macquisten tubes have such a small capacity that a single tube is small enough for test-work on a few pounds of ore at a time (Fig. 18). A small 4-ft. tube is known to give trustworthy results, although a larger one is more desirable.

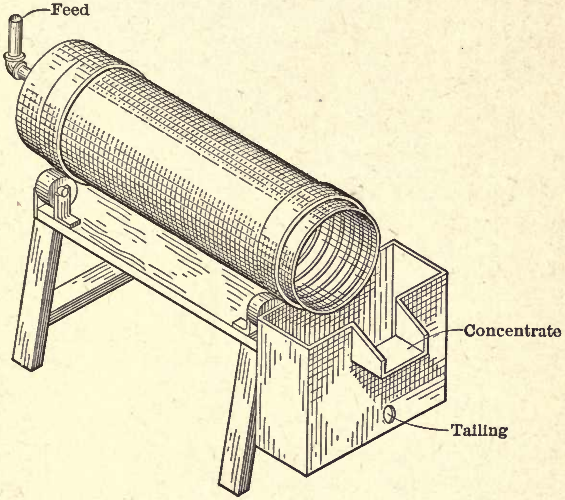

Fig. 18.

The Wood machine can be built in miniature and for several years a small machine of the type shown in Fig. 19 has been used in the plant of the Wood Ore-testing Works at Denver.[1] This machine was about 2 ft. long and 1 ft.

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[1] H. E. Wood, *Trans. A.I.M.E.*, Vol. XLIV, pp. 684–701 (1912).

wide. The method of operation is the same as that of a full-sized machine. As neither of these machines has been much used in practice,

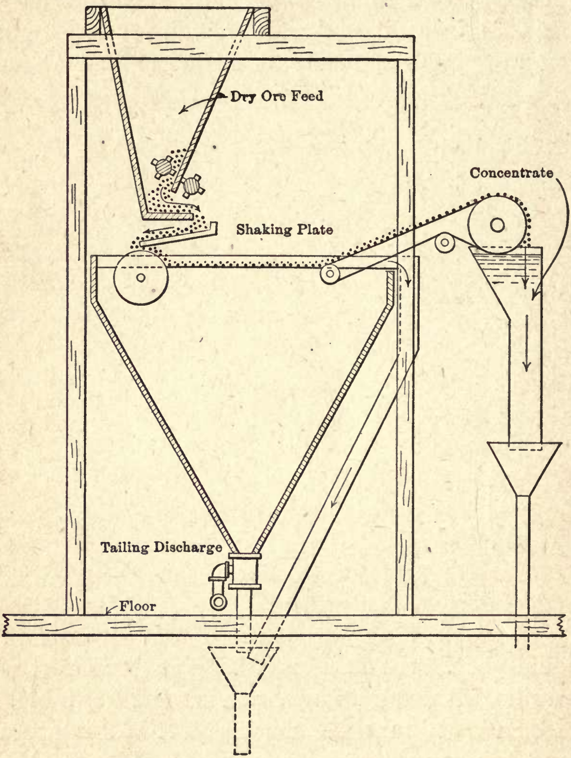

FIG. 19.

they are merely mentioned for the sake of completeness. Hoover[1] has recommended a test on a vanning plaque so that the sulphides will

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[1] "Concentrating Ores by Flotation."

float off onto the surface of the water, but this method is not practical and Hoover has given it merely as a test to illustrate the film processes.

In testing ores for the Potter and the Delprat processes Hoover gives an illustrative test-tube experiment. (See Fig. 20.) Tubes containing 3 per cent H_2SO_4 or acid salt-cake solutions and a little sulphide ore are warmed nearly to the boiling temperature. Bubbles of CO_2 attach themselves to the sulphide, travel to the surface of the solution, discharge into the air, and drop the sulphide into the pocket on the underside of the tube, as shown in the sketch. In another test a 200-cc. beaker is used with 100 cc. of 3 per cent H_2SO_4 and brought to nearly boiling temperature. The ore when introduced into this yields a froth composed of sulphides supported by bubbles of CO_2. In case the ore is deficient in carbonate, an addition of as much as 3 per cent of calcite or siderite is made. The froth is skimmed with a spoon as soon as it forms. The results obtained with

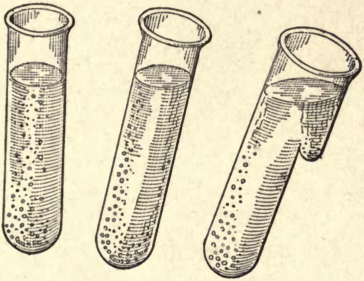

FIG. 20.

these tubes are, however, not reliable as a great deal of the mineral is often lifted partly but never reaches the surface; consequently extractions are low. A better test machine is the small unit shown in Fig. 21.

The acid should be allowed to run down through a section of garden hose to within an inch of the surface of the ore and the ore should be kept stirred with a wooden paddle so that the bubbles of CO_2 generated by the action of the acid can lift the sulphides out of the body of the pulp. The froth formed should be skimmed with the paddle as fast as made, then filtered, dried, weighed, and analyzed. Not many ores yield gracefully to this treatment as slimes give poor extractions. Fines and Wilfley-table middlings are better adapted, and the presence of siderite in the pulp is desirable, as it reacts slowly with

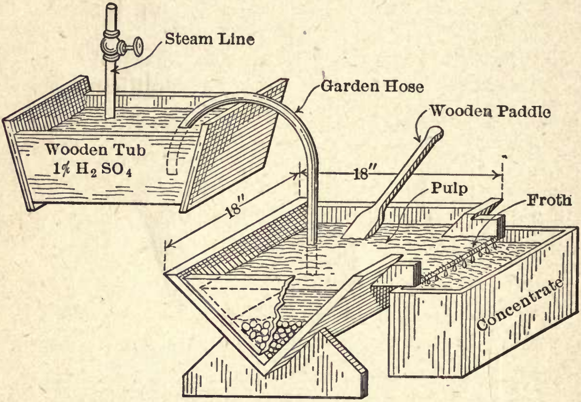

FIG. 21.

dilute acid. From 1 to 3 per cent of H_2SO_4 is best in testing and ½ to 1½ per cent solutions on the large scale will give about the same results. The temperature of the pulp should be maintained at 70° C. by use of a steam jet. The extractions obtained are always lower than in full-sized units. While it is not necessary in this process, it will greatly assist in the flotation, and the addition of a small amount is often of much assistance in test-work.

Mechanical Frothing. — This process, as developed by the Minerals Separation Co., in England and Australia, and modified by others, has been one of the most important methods of flotation, therefore the laboratory machinery that has been developed is at as high a state of perfection as any such machinery now in use.

The Janney machine is probably the best designed machine for getting reliable quantitative results on a small quantity of ore. See photograph and sketch, Figs. 22 and 23. It can be seen that the agitation-compartment is cylindrical in shape and that its top is surrounded by a froth-box, which slopes into a spitzkasten, where the froth can be skimmed. The tailing sinks to a return-hole at the bottom, passing into the agitation-compartment again. To provide good agitation, four vertical baffles are attached to the wall of the agitation-compartment, against which the pulp is swirled by the two impellers. Lining the walls with expanded metal lathing or with a coarse-mesh iron screen adds to the thorough mixing that the pulp must receive. The two impellers are on a common shafting, which enters the machine through a stuffing-box in the bottom of the machine. The lower impeller with four vertical vans is submerged; it agitates and emulsifies the pulp with the upper impeller, likewise, with four vertical vans, acts as a pump to lift the pulp and beat air into it. A pulley and belt connect the shaft with a variable-speed motor.

A dome-shaped lid is used on the machine. A small hole in the top of the dome allows the introduction of oil, acid, water, or other material of the test. The lid is so constructed that it can be turned upside-down with the dome extending down into the froth-box, and in this position it can act as a funnel. The dome rests then on the top of the agitation-compartment and no froth can escape into the froth-box. This allows a period of agitation of the pulp before the dome-top is turned right-side up to allow aeriated pulp to overflow into the froth-box and down into the spitzkasten, where the froth can be removed.

A discharge-plug at the bottom of the machine allows the flushing out of tailing after the test has been completed. So careful has been the design of this test-machine that even this discharge-plug is beveled to fit flush with the bottom of the machine and thus affords no dead space in which the solids might settle.

The spitzkasten is long and narrow, in order to permit a deep froth to be formed and to travel over as long a space as possible, before reaching the discharge. This tends to allow more of the entrained gangue to settle out of a mineral froth. The sides of the spitzkasten are of heavy plate-glass, each fastened to a metal frame by means of screws. The wrought-iron shaft projects through a brass stuffing-box and is supported by a ball-bearing beneath. All the other metal parts are of cast aluminum.

The small variable-speed motor may be of either direct-current or alternating-current type. F. G. Janney recommends the use of a General Electric shunt-wound, direct-current motor for 230 volts, with a rated speed of 1700 r.p.m. and ¼ h.p. The impeller shaft is to be driven at 1900 r.p.m. maximum speed. For speed-control he recommends a General Electric direct-current field rheostat, with an ampere capacity of 1.25 to 0.063 at 250 volts.

The operation of the machine is as follows: It is set up on a bench convenient to the sink and to running water. The motor is set up 1 ft. to the rear with the switch and rheostat placed so that they can be easily reached while standing in front of the machine. A 1¼-in. round-leather sewing-machine belt is used for the drive. The bearings are well oiled, the stuffing-box is properly packed, and some attention should be given to it occasionally in order to see that it is kept screwed tight enough to avoid leakage.

Enough clear water is run into the machine to barely show in the spitzkasten and the motor is started at its lowest speed. A 500-gm.

charge of ore ground to at least 48 mesh is added and the cover placed on the machine in its

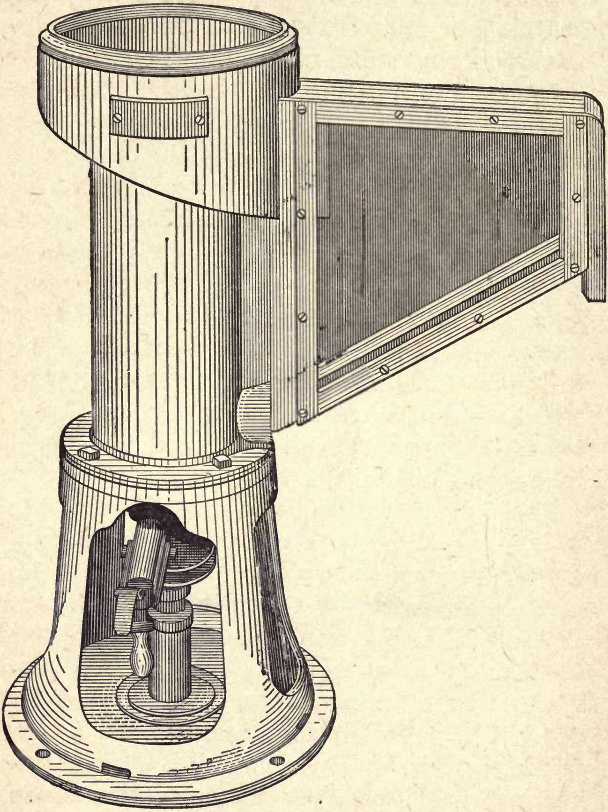

FIG. 22.

inverted position. (See Fig. 22.) This is done to allow thorough mixing without circulation of the pulp. All or part of the oil and other reagents are now added and the motor brought up to full speed for 30 seconds. The speed is again lowered to the minimum and the cover is turned over into its upright position. (See Fig. 23.) The speed is then raised and water is added through the hole in the top of the lid until the froth in the spitzkasten is nearly at the overflow lip. The ultimate speed of the agitator will depend somewhat upon the character of this froth, as some oils will give a deep persistent froth, while other froths are thin and brittle and allow of more water being added to the machine, as well as more violent agitation in order to beat more air into the pulp. The

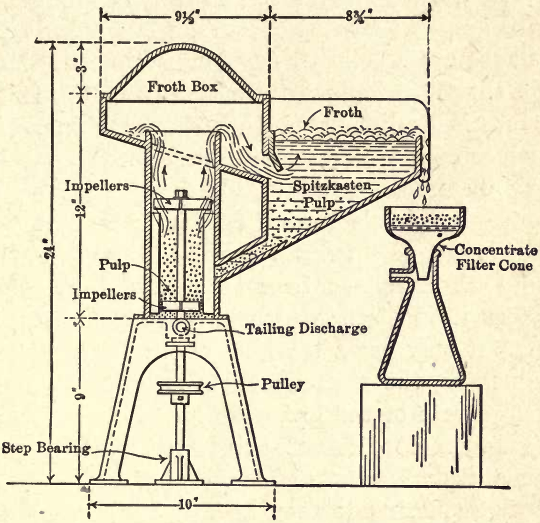

FIG. 23.

froth may either be allowed to flow out of the spitzkasten of its own weight or skimmed with a small wooden paddle. It is a good idea to wet the glass sides of the "spitz" with water while the froth is rising, so that none of the froth will stick to the glass.

The duration of the test is about 5 minutes with an ore that floats easily, while other ores will require a considerably longer time to allow the entrained gangue to settle out of the froth before it is discharged from the machine. In such cases it is best to hold back the froth until its appearance shows it to be fairly clean. Beginners are likely to dilute their froth with too much gangue. In a large-sized machine the froth can travel over from 4 to 8 ft. of spitzkasten before it is discharged, while in this test machine it only has a travel of about 10 in. Consequently, the small machine is liable to yield concentrate of too low a tenor. The same applies to most other machines for making tests on flotation.

The concentrate may be caught in a pan or on a filter. After the test the machine is brought back to low speed and the tailing plug removed, so that the tailing can be caught in a pan or bucket or run to waste.

If it is so desired, this rough concentrate can be put back into the machine and treated in the same way as the original sample, or the concentrates from several tests combined to give enough material for retreatment. If this is done three products are made, namely:

1. A " rougher " tailing to waste.
2. A clean concentrate for shipment.
3. A " cleaner " tailing or middling which in actual practice is returned to the head machine.

When these conditions are observed results only slightly lower than those possible with a big machine can be obtained. A test can be run in from 5 to 30 minutes in such a machine with 500 gm. of ore in anything from a 3 : 1 to a 5 : 1 pulp. The glass sides of the spitzkasten allow close observation of the condition of the froth, and this is a great advantage to the beginner. The small amount of ore necessary for a test is a matter of considerable convenience as fine grinding of the ore in the laboratories is often irksome. The aluminum casting is little corroded by either acid or alkaline electrolytes. The return of pulp from the " spitz " to the agitating compartment allows the material to be treated until all mineral has been removed without stopping the machine, so that a single treatment yields a clean tailing. However, a second treatment of this " rougher-froth " is sometimes necessary in order to get a high-grade concentrate. Clean tailings generally mean only medium-grade concentrates due to entrainment of gangue in the removal of all the mineral.

The stuffing-box in the bottom will probably leak if not watched. However, this driving of the impeller from below, instead of from above, leaves the top of the machine free for the operator and is more convenient in every way. This is of importance in a laboratory machine and will excuse the use of a stuffing-box. In large-scale machines a stuffing-box underneath would not be tolerated and the drive should be from above.

The Hoover Machine. — The so-called Hoover machine was designed after a testing machine described in the second edition of Hoover's book, being copied from one of Lyster's patents, and has been much copied by people wishing to make flotation tests. In general, the machine is not nearly so convenient for making tests as the Janney machine and other recent testing machines on the market. Its cost of construction has been the main point in its favor. The

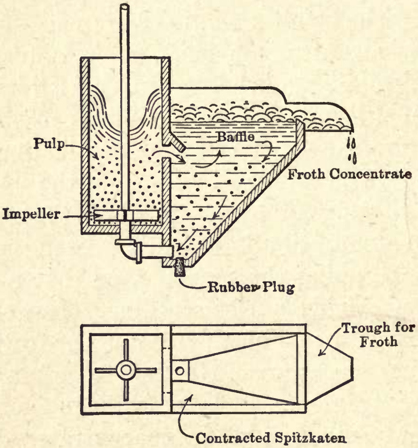

FIG. 24.

Janney machine will cost about $100 while the Hoover machine can be built for a small fraction of this amount. In the agitation-compartment the pulp is swirled into the corners (see Fig. 24) where it is well mixed with air; hence the baffles sketched in the Janney machine are unnecessary. One objection, however, is that unless the agitation-compartment is very tall the pulp being swirled in the corners has a tendency to splash out, and a lid similar to the one on the Janney machine is desirable. However, it is difficult to attach one because the sfirrer shafting is in the way. The operation of this machine is practically the same as that of the Janney, except that without glass sides on the spitzkasten it is hard to get as clean a froth. A charge of 1000 to 2000 gm. was necessary in this machine.

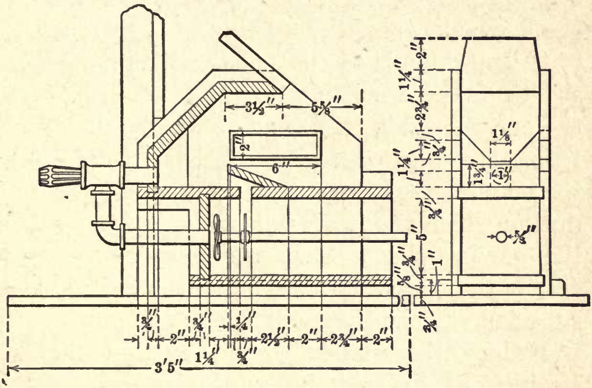

FIG. 25.

Other modified forms of the Hoover machine are shown in Figs. 25 and 26.

The Slide Machine. — This machine as shown in Fig. 27 was designed by Hoover and perfected by many others. In recent practice it is motor driven. Many people favor this apparatus for the reason that they have had little opportunity to use any other design. In this machine the agitator is driven from below through a stuffing-box, as in the Janney, with the consequent freedom of the top of the machine for the convenience of the operator. The top half of the machine is so constructed that it can be slid to one side, cutting off the froth formed in the agitation from the gangue, which is allowed to settle. The operation consists in agitating the oil and other reagents, then a period of quiet during which the froth collects at the top while the gangue sinks. Two windows in the side enable the observer to see when the gangue has subsided sufficiently to allow the top half to be slid along the rubber gasket, cutting off the froth from the remainder of the pulp. The time necessary for the settling of the gangue is sufficient for much of the gangue to separate from the froth, leaving only clean sulphides in the froth. This element of the machine has made it of some value in testing flotation-oils, but in a weak froth much of the sulphide mineral also settles out and is lost, so that the test results with this machine often show unnecessarily low extractions and a high grade of concentrate. On the other hand when con-

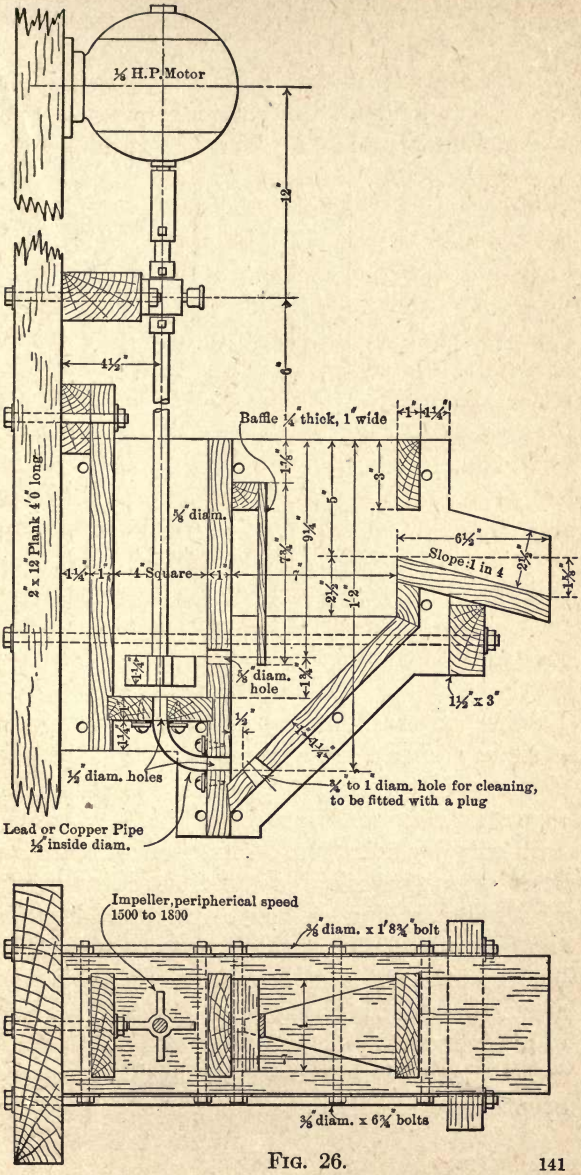
⅛ H.P. Motor
12"
6"
4½"
2" x 12" Plank 4'0" long
Baffle ¼" thick, 1" wide
1" 1¼"
3"
5"
9¼"
7¾"
1⅞"
1'-2"
⅝" diam.
6½"
Slope: 1 in 4
2½"
1⅝"
1¼" 1" 4" Square 1" 7"
2½"
1¼"
⅝" diam. hole
1¾"
1½" x 3"
½"
1" 1¼"
1"
1¼"
½" diam. holes
¾" to 1" diam. hole for cleaning, to be fitted with a plug
Lead or Copper Pipe ½" inside diam.
Impeller, peripherical speed 1500 to 1800
⅜" diam. x 1'8¾" bolt
⅜" diam. x 6¾" bolts

FIG. 26.

ditions are adjusted to give a froth persistent enough to hold all the sulphide mineral, considerable gangue is entrained in the stiff froth.

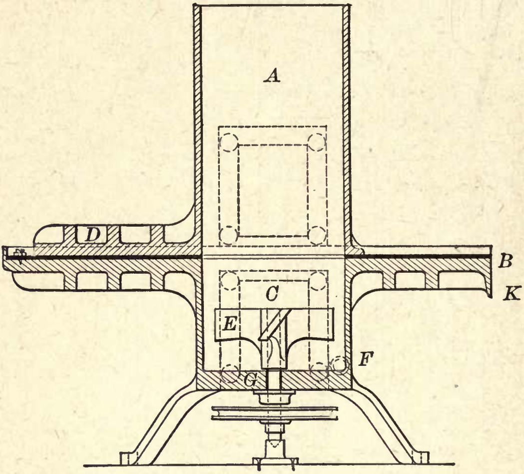

Fig. 27.

Further, after skimming one froth we find it necessary to add more water and start the machine again to make more froth. It is hard to make the slide machines give a high extraction with only one agitation. The intermittent character of such work and the time necessary to wait while settling are disadvantages that make the Janney or Hoover machines of greater utility. The parts are of cast aluminum with a rubber gasket between. A charge of 500 to 1000 gm. of ore is used.

The Case Machine. — This machine consists of a single aluminum casting, comprising the

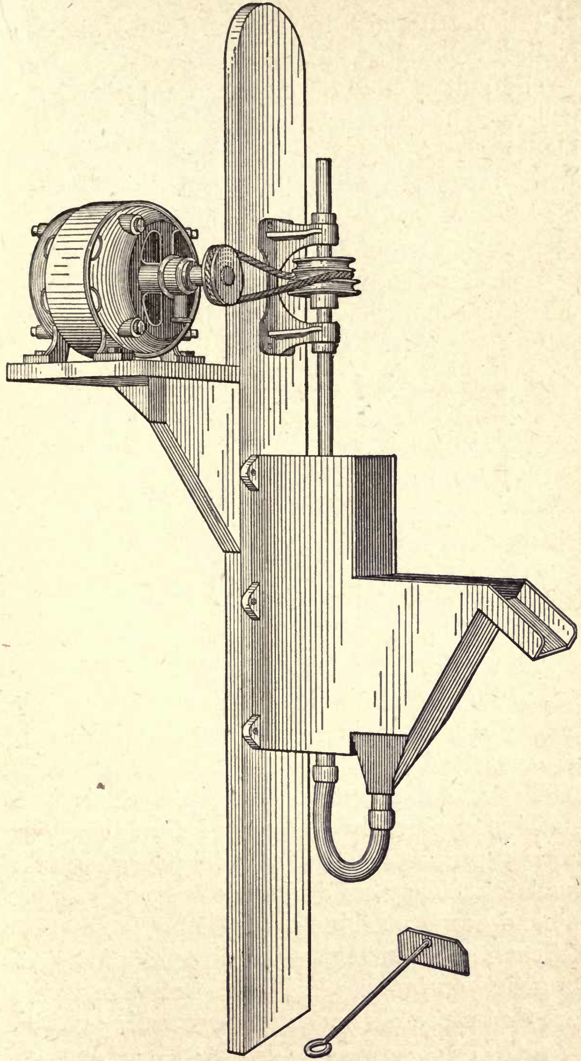

FIG. 29.

agitation cell and a spitzkasten from which the froth is collected.

The agitation cell contains a shaft and impeller. The impeller is provided with four blades set at angles of 90 degrees. The steel shaft is coated with lead and the impeller blades are made of aluminum to resist the corrosive action of acids.

A piece of extra heavy pressure tubing provides for connection between the bottom of the spitz box and the agitation cell. (See Fig. 29.) With this tubing is supplied a strong pinch-cock for the regulation of pulp circulation, the pressure tubing being easily removed for cleaning purposes.

The operation of this machine is practically the same as that of the Janney and the Hoover type. It is apparently a modified Hoover machine, made by the Denver Fire Clay Company, Denver, Colo.

The Roy and Titcomb Machine. — This machine invented and made by Roy and Titcomb, Inc., Nogales, Ariz., is a machine which is self-contained (Fig. 30).

The cells are cast in one piece. This is a machine apparently well suited for laboratory testing purposes, especially if power is not available. They are also made for motor drive. A hand-power machine costs $85.

Separatory Funnels. — During the past year an article on practice in Mexico[1] mentioned the fact that much of the preliminary testing on the

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[1] *Min. & Sci. Press,* July 24, 1915.

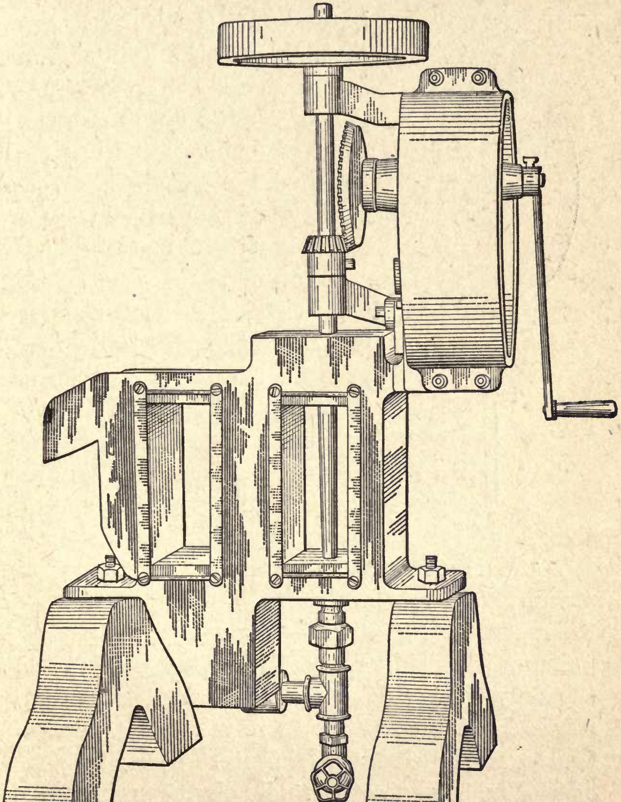

Fig. 30.

ore is done in separatory funnels (Fig. 31) in which the charges of pulp, oil, etc., were shaken, after which the cock at the bottom of the funnel was opened and the tailing run into a second separatory funnel for further flotation tests, the cock being closed in time to catch the froth. The versatility of experiment permissible with the use of such apparatus is commendable. Obviously, this arrangement is open to the same objection as is the slide machine except that separatory funnels are simple and inexpensive.

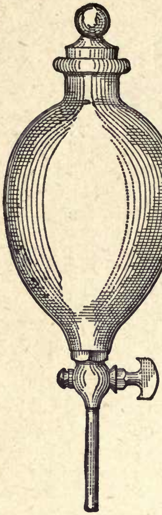

Fig. 31.

In comparison of the above mechanical agitation type of laboratory machine the Janney and Hoover machines are by far the most useful.

Pneumatic Flotation. — Among the different pneumatic machines, the Callow test-machine is the only one of laboratory size that has been much developed. It is merely the commercial Callow machine reduced in size. (See Figs. 32, 33.) Fig. 32 shows the whole plant in miniature as developed in the laboratory of the General Engineering Company in Salt Lake City. It consists of a Pachuca mixer, a roughing cell, cleaning cell, vacuum filter, and sand pump to return middling to Pachuca mixer.

As seen in the drawing, the pulp is mixed with a Pachuca tank of small size overflowing into the rougher flotation-cell. The tailing from this rougher goes to a sand-pump and is returned to the Pachuca. The froth is treated in a second

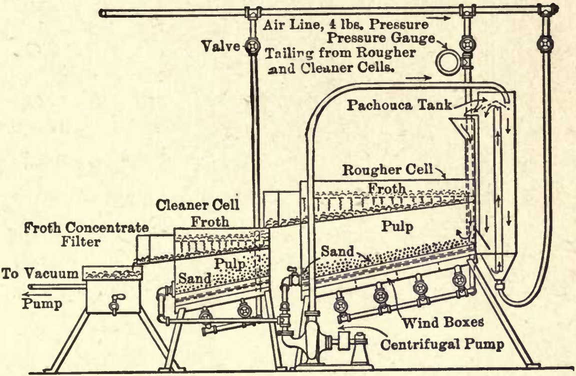

FIG. 32.

and smaller pneumatic-flotation unit, giving a concentrate that overflows into an ordinary laboratory vacuum-filter actuated by a water or aspirating pump. The tailing from the "cleaner cell" consists of a middling that likewise flows to the sand-pump and back to the Pachuca.

A novice will have no small difficulty in operating such an installation, as there are a number of things to be kept in operation at the same time.

The mixture of ore, water, oil, and any other reagent is fed either into the suction of the sand-pump or into the top of Pachuca after air has geen started into the various machines. The overflow from the Pachuca into the rougher cell accumulates until a nice froth is coming up

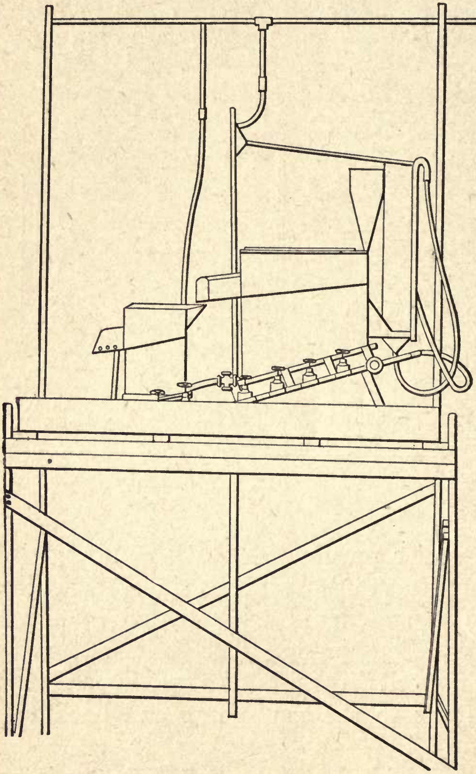

FIG. 33.

and nearly overflowing. Then the tailing-discharge valve is gradually opened and froth allowed to overflow from the cell into the "cleaner cell." It is best to get most of the charge circulating before much concentrate-froth is allowed to overflow, the overflow of froth being controlled by the main air valves leading to each unit. After the valves into the individual wind-boxes beneath the machine have been once adjusted they should never be disturbed, and all control of air supplied should be at the valves in the main pipes. When everything is going well, the air-pressure in the cleaner can be increased until concentrate-froth is overflowing into the vacuum filter. A wooden paddle to stir any settled material in the flotation-cell is of value, as well as a small jet of water from a rubber hose for washing concentrate along the froth-launders and for beating down froth when occasional too-violent rushes of froth from the cells take place. After a test is complete the pulp should be drained completely from all parts of the machine while the air is still blowing, so that solids will not settle in passages or clog the canvas blanket in the cells. Only practice will allow any one to get reliable results with this machine. A watch-glass for catching and panning occasional samples of froth is another necessary auxiliary to this equipment. The cost of installing such a set of apparatus is from $100 to $150. At least 1000 gr. of ore is required for a test and about 30 minutes to 1 hour is spent. It can be seen that nothing but a finished concentrate and a tailing are obtained or a middling product may be left in the cleaner cell. This middling may be assayed as such and calculated into the concentrate and tailing or its sulphides may be panned out and added to the concentrate. The machine is said to give results closely paralleling those obtained with larger-scale apparatus. A source of supply of air at 3 to 5 lb. per square inch is necessary and the main valves on the air-pipe leading to each machine should be some type of needle valve in order to insure exact control.

In connection with this apparatus a qualitative oil-tester should be used. A good tester consists of a glass tube of about 2 in. in diameter and 2 ft. long (Fig. 34). This can be set on end and closed at the bottom with a one-hole rubber stopper through which passes a glass tube into a small canvas bag. The small bubbles of air coming through the canvas are similar to those used in large-scale machines and can be observed through the glass walls of the tube. With some pulp in the tube, oils, acids, salts, etc., may be added in very short tests until the proper appearance is obtained. An overflow lip is provided in case it is desired to examine the mineral in the froth. A slight adjustment of the air will provide an ample overflow of froth.

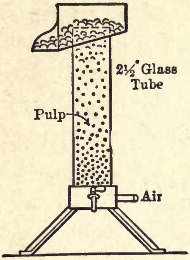

FIG. 34.

CHAPTER VII

THE COST OF FLOTATION

After having determined a satisfactory combination of oils, etc., and in general the ore is found to be amenable to the flotation process, the next important question confronting the flotation engineer is, "How much will a flotation plant of a given required capacity cost?" Or, "How does the cost of flotation compare with that of other methods of concentration?" It is hard to obtain any exact figures that will apply in all cases, but a few average and approximate figures for some of the flotation processes are given below; from these the reader can be able to figure out for himself approximately the cost of any particular kind and size of flotation plant.

For the Callow or Pneumatic agitation process, the following figures are those given by John M. Callow.[1]

Power. — The National Copper Co., which treats 500 tons per day, requires 35 h.p. This means 12.53 tons per horse power, or 1.25 kw-hr. per ton.

A company which treats 2400 tons per day requires 210 h.p., which means 11.45 tons per horse power, or 1.56 kw-hr. per ton.

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[1] Paper as presented by him at annual meeting of Utah section of the A.I.M.E., Salt Lake City, October, 1915.

The former company uses 10 cells and the latter 60, which gives 3.5 horse power per cell in both cases.

He gives the maximum figure as 2.5 kw-hr. per ton of feed, with an air pressure of from 5 to 5.5 lb., the air being generated by a Roots or Connersville positive blower.

Oil, Labor, and Maintenance. — The oil costs from 1¼ to 3¢ per pound, and about 1.5 lb. of oil to the ton of feed is used. This would give an average of 2.5¢ per ton of feed. The average cost of labor and maintenance would be about 1¾¢ per ton of feed.

The following is also given by Mr. Callow, as being an average figure for a 2000-ton plant:

Labor	$0.0125
Oil	0.0250
Maintenance	0.0050
Power	0.0250
Total, per ton of feed	$0.0675

And for a 250-ton plant about 10¢ per ton of feed. As the size of the plant increases, one can, of course, see that the cost per ton of feed will decrease, and in one case a figure as low as $0.061 is given.

The Denver Fire Clay Co., Denver, Colo., gives the cost of a complete flotation plant of 100 tons capacity as ranging from $1500 to $5000. The cost of oil, 7 to 15¢ per ton, cost of acid 10 to 20¢, and the operation and maintenance, from 15 to 25¢ per ton. From these figures the total cost of flotation ranges from

32 to 60¢ per ton of ore, in a process where both oil and acid are used.

In the case of the Potter process, Hoover gives the cost per unit as about $1000, including installation, for the Elmore vacuum machine, about $1750 per unit, a capacity of a unit ranging from 30 to 50 tons per day.

For the various flotation processes in use at Broken Hill, we have an average figure of 3 s. 7 d. or 43¢ per ton of ore. This figure does not include the royalty of 1 shilling per ton of ore treated.

From recent data published, the cost of flotation in a certain mill is 35¢ per ton of crude mill feed, or 60¢ per ton of actually treated; whereas in the same mill the cyanide process costs 80¢ per ton of crude mill feed, or $1.50 per ton of ore actually treated.

At the mill of the Consolidated Copper Co., Miami, Ariz., about 14,500 tons of ore are treated daily by the flotation process. Including royally, the mining and milling costs about $1.00 to $1.15 per ton of ore, which would make the cost of concentration almost corresponding to the cost mentioned above.

At the mill of the Consolidated Arizona Smelting Co., Humboldt, Ariz., the cost of concentration by flotation, including coarse crushing and flotation royalty, is slightly over $1.00 per ton. For a period of six months, the cost of flotation, exclusive of royalty, was 27¢ per ton. The power consumption of the flotation machine is 32.7 kw. per hour.

The royalty charged by process owners for the use of their processes is very high; Hoover gives the average figure as 1 shilling or 25¢ per ton of ore treated. Few companies are willing to pay such a high royalty and this naturally has been one of the chief sources of trouble.

Judging from the figures given, one can see that the cost of flotation for various processes, localities, and ores varies greatly. To get the cost of flotation for any particular ore, Stander gives the following items,[1] which if taken into consideration should give an approximate result: power; oil, acid, or both; royalty, if any; labor; supplies and repair work; heat (if a hot solution is required).

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[1] "The Flotation Process," by Stander, 1916.

CHAPTER VIII

FORMULAS AND TABLES

Estimation of Consumption of Oil and Acid per Ton of Feed

The following is a useful chart whereby the consumption of oil and acid can be estimated per ton of feed.[1]

A concrete example showing how to use the table may not be amiss: Assume that a plant treats 450 tons per 24 hr. and that the consumption of pine-oil is 160 cc. per minute, it is desired to find the consumption of pine-oil in pound per ton of feed.

From the point of intersection of the 100 cc. per minute line and the pine-oil line, follow down and read the figure 2.95, which would be the consumption in pound per ton at 100 cc. per minute, and 100 tons of feed per 24 hr.

Inasmuch as the consumption of oil is greater than 100 cc. per minute and the tonnage treated is greater than 100 tons per 24 hr., we must use the third formula to arrive at our final figure. Thus:

$$\frac{2.95 \times \frac{160}{100}}{\frac{450}{100}} \text{ or } 2.95 \times \frac{169}{100} \times \frac{100}{450} = 1.05 \text{ lb. per ton.}$$

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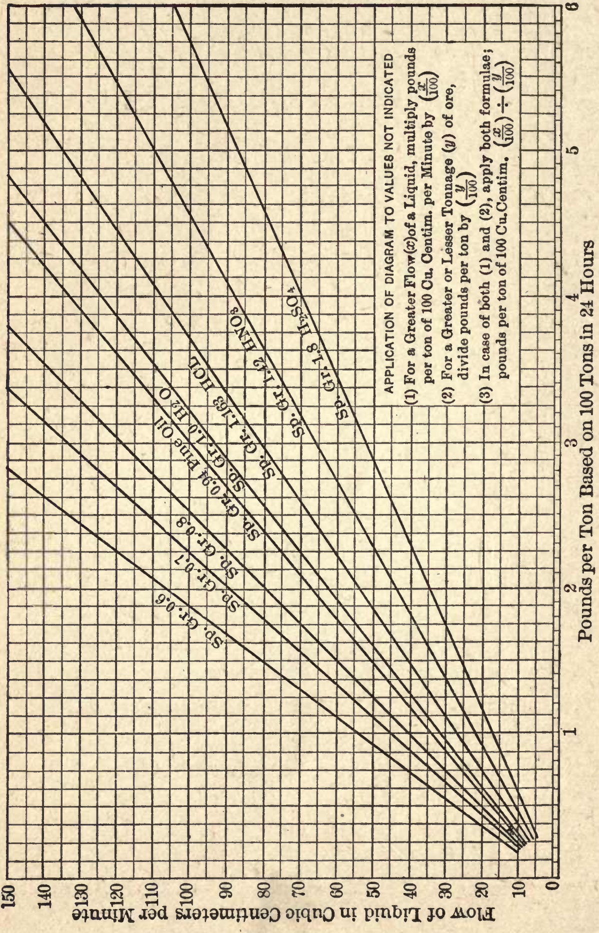
[1] *Min. & Sci. Press*, May 20, 1916.



APPLICATION OF DIAGRAM TO VALUES NOT INDICATED

(1) For a Greater Flow (x) of a Liquid, multiply pounds per ton of 100 Cu. Centim. per Minute by $\left(\frac{x}{100}\right)$

(2) For a Greater or Lesser Tonnage (y) of ore, divide pounds per ton by $\left(\frac{y}{100}\right)$

(3) In case of both (1) and (2), apply both formulae; pounds per ton of 100 Cu. Centim. $\left(\frac{x}{100}\right) \div \left(\frac{y}{100}\right)$

Calculation of Tonnage of Feed to any Particular Unit

For the application of this method the tonnage of either the concentrate or the tailing produced must be known and also the assay of all three — heads, tailings, and concentrate. The basis of the method is the efficiency by assay of the plant.

A concrete example, used in figuring the tonnage to a certain flotation plant, in which both lead and a zinc concentrate were made, will be clearer than the use of formulas and unknowns.

The concentrate tonnage is known and also the assay (in zinc) of the heads, tailing, and concentrate.

Products.	Assay, Zn per cent.	Symbol.
Feed........................	5.7	H
Tailing......................	2.6	T
Concentrate.................	40.4	C

Then:

Ratio of concentration

$$= \frac{C - T}{H - T} = \frac{40.4 - 2.6}{5.7 - 2.6} = 12.1.$$

Efficiency of concentration

$$= \frac{C \times 100}{H \times R} = \frac{40.4 \times 100}{5.7 \times 12.1} = 58.7 \text{ per cent}$$

made 211 tons concentrate of 40.4 zinc, which equals 85.2 tons of metallic zinc.

85.2 tons equals 58.7 per cent of zinc in the original feed.

100 per cent − 58.7 per cent = 41.3 per cent zinc lost in the lead concentrate and tailing, or 59.9 tons metallic zinc.

85.2 + 59.9 = 145.1 tons of metallic zinc in the original feed.

145.1 ÷ 0.57 = 2545.5 tons of feed to the plant.

The tonnage of concentrate or tailing could, by knowing the feed tonnage, be equally well calculated by this method.

SLIME PULP FORMULA (*Caldecott*)

Result sought.	Per cent by weight of dry slime in pulp.	Per cent by weight of solution in pulp.	Ratio by weight of solution to one of dry slime.	Volume in cu. ft. of 1 ton of pulp.	Weight in lb. of 1 cu. ft. of pulp.	Weight in lbs. of dry slime in 1 cu. ft. of pulp.	Volume in cu. ft. of pulp containing 1 ton dry slime.	Weight in tons of dry slime in charge of pulp.
When specific gravity of dry slime = S.	$\frac{100\,S\,(x-1)}{x\,(S-1)}$	$\frac{100\,(S-x)}{x\,(S-1)}$	$\frac{S-x}{S\,(x-1)}$	$\frac{32}{x}$	$\frac{1000\,x}{16}$	$\frac{62.5\,S\,(x-1)}{S-1}$	$\frac{32\,(S-1)}{S\,(x-1)}$	Cu. ft. pulp $\times \frac{S\,(x-1)}{32\,(S-1)}$
When specific gravity of dry slime = 2.7	$\frac{158.824\,(x-1)}{x}$	$\frac{100-58.824\,(x-1)}{x}$	$\frac{1-37\,x}{x-1}$	$\frac{32}{x}$	$62.5\,x$	$99.265\,(x-1)$	$\frac{20.148}{x-1}$	Cu. ft. pulp $\times \frac{x-1}{20.148}$

1. Let S. G. of slime pulp $= x$.
2. Let per cent (by weight) of dry slime in pulp $= y$.
3. One cubic foot of water or solution = 62.5 lbs.
4. One ton of water or solution = 32 cu. ft.
5. Capacity in cubic feet of circular vat. $= (\text{diam. in ft.})^2 \times (\text{depth in feet})^2 \times \frac{11}{14}$.
6. Specific gravity of slime pulp $= \dfrac{\text{Weight of (flask + pulp)} - \text{weight of flask}}{\text{Weight of (flask + water)} - \text{weight of flask}}$.
7. Specific gravity of dry slime $= \dfrac{\text{Weight of dry slime in air}}{\text{Weight of dry slime in air} + \text{weight of (flask + water)} - \text{weight of (flask + slime + water)}} = \dfrac{xy}{xy - 100\,(x-1)}$.
8. One gram per liter = 1 oz. (avoird.) per cubic foot.

NOTE. — In sampling a charge of pulp undergoing agitation, a narrow necked vessel fastened to a rod should be employed, so that the sample may be taken not only from the surface of the charge but also from as far below it as is possible.

A 500-cc. flask is a convenient size to employ in determining the specific gravity of the pulp and the vessel should be well shaken in the intervals of pouring into the flask, so as to prevent settlement of the slime.

Torque units should be distinguished from energy units: Thus, foot-pound and kilogram-meter for energy, and foot-pound and meter-kilogram for torque.

1 ft.-lb.[1] = 13,560,000 ergs = 1.356 joules = 0.3239 g.-cal. = 0.1383 kg.-m. = 0.001285 B.t.u. = 0.0003766 watt-hr. = 0.0000005051 h.p.-hr.

1 kg.-m. = 98,060,000 ergs = 9.806 joules = 7.233 ft.-lb. = 2.34 g.-cal. = 0.009296 B.t.u. = 0.002724 watt-hr. = 0.000003704 h.p.-hr. (metric).

1 B.t.u. = 1055 joules = 778.1 ft.-lb. = 252 g.-cal. = 107.6 kg.-m. = 0.5555 lb.-centigrade heat unit = 0.2930 watt-hr. = 0.252 kg.-cal. = 0.0003984 h.p.-hr. (metric) = 0.0003930 h.p.-hr.

1 watt-hr. = 3600 joules = 2655.4 ft.-lb. = 860 g.-cal. = 367.1 kg.-m. = 3.413 B.t.u. = 0.001341 h.p.-hr.

1 h.p.-hr. = 2,684,000 joules = 1,980,000 ft.-lb. = 273,700 kg.-cm. = 745.6 watt-hr.

1 kw.-hr. = 2,655,000 ft.-lb. = 367,190 kg.-m. = 1.36 h.p.-hr. (metric) = 1.34 h.p.-hr.

POWER

1 g.-cm. per sec. = 0.00009806 watt.

1 ft.-lb. per min. = 0.02260 watt = 0.00003072 h.p. (metric) = 0.00000303 h.p.

1 watt = 44.26 ft.-lb. per min. = 6.119 kg.-m. per min. = 0.001 kilowatt.

1 h.p. = 33,000 ft.-lb. per min. = 745.6 watts = 550 ft.-lb. per sec. = 76.04 kg.-m. per sec. = 1.01387 h.p. (metric).

1 kw. = 44,256.7 ft.-lb. per min. = 101.979 kg.-m. per sec. = 1.3597 h.p. (metric) = 1.341 h.p.

RESISTIVITY

1 ohm per cir. mil-ft. = 0.7854 ohm per sq. mil-ft. = 0.001662 ohm per sq. mm.-m. = 0.0000001657 ohm per cm.^{3} = 0.0000000524 ohm per in.^{3}

1 ohm per sq. mil.-ft. = 1.273 ohms per cir. mil-ft.

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[1] The hyphen (-) as used here means "multiplied by."

= 0.002117 ohm per sq. mm.-m = 0.0000002116 ohm per cm.^{3} = 0.00000008335 ohm per in.^{3}

1 ohm per in.^{3} = 15,280,000 ohms per cir. mil-ft. = 12,000,000 ohms per sq. mil-ft. = 25,400 ohms per sq. mm.-m. = 2.54 ohms per cm.^{3}

CURRENT DENSITY

1 amp. per sq. in. = 0.7854 amp. per cir. in. = 0.1550 amp. per sq. cm. = 1,273,000 cir. mils per amp. = 0.000001 amp. per sq. mil.

1 amp. per sq. cm. = 6.45 amp. per sq. in. = 197,000 cir. mils per amp.

1000 cir. mils per amp. = 1273 amp. per sq. in.

1000 sq. mils per amp. = 1000 amp. per sq. in.

METRIC SYSTEM WITH CONVERSIONS

10 milli- = 1 centi-.
10 centi- = 1 deci-.
10 deci- = 1 (unit).
10 (units) = 1 deca-.
10 deca- = 1 hecto-.
10 hecto- = 1 kilo-.
1 kilo- = 1 myria.

WEIGHT

METRIC UNIT IS GRAM

Gram = weight 1 cubic centimeter of water at 4° C.
Gram = 15.4324 grains.
Gram = .03215 ounce troy.
Gram = .00267923 pound troy.
Gram = .03527 ounce avoirdupois.
Gram = .00220462 pound avoirdupois.
Milligram = .0154324 grain.
Kilo or kilogram = 32.15 ounces troy.
Kilo or kilogram = 2.67923 pounds troy.
Kilo or kilogram = 35.27 ounces avoirdupois.
Kilo or kilogram = 2.20462 pounds avoirdupois.
Metric ton = 1000 kilos or kilograms.
Metric ton = 2204.62 pounds avoirdupois.
Metric ton = 1.10231 United States tons (2000 pounds).
Grain = .0648 gram.
Ounce troy = 31.10348 grams.

Pound troy = .37324 kilo or kilogram.
Pound troy = 373.24 grams.
Ounce avoirdupois = 28.3495 grams.
Pound avoirdupois = .45359 kilo or kilogram.
Pound avoirdupois = 453.59 grams.
Ton (2000 pounds) = .90718 metric ton.
Ton (2000 pounds) = 907.185 kilograms.
Assay ton = 29.1666 grams.
Assay ton = .0377 ounce troy.
Assay ton = .07814 pound troy.
Assay ton = 1.0287 ounces avoirdupois.
Assay ton = .0643 pound avoirdupois.

CAPACITY

Metric Unit is Liter

Liter = 1000 cubic centimeters.
Liter = .26417 gallon (231 cubic inches).
Liter = 1.05668 quarts.
Liter = 33.81 liquid ounces.
Liter = 61.023 cubic inches.
Gallon (231 cubic inches) = 3.78543 liters.
Gallon (231 cubic inches) = 3785.43 cubic centimeters.
Liquid ounce = .029574.

VOLUME

Cubic meter = 35.314 cubic feet.
Cubic meter = 1.3079 cubic yards.
Cubic centimeter = .061 cubic inch.
Cubic foot = .02832 cubic meter.
Cubic yard = .7645 cubic meter.

LENGTH

Metric Unit is Meter

Meter = 39.37 inches.
Meter = 3.280833 feet.
Kilometer = 3280.833 feet.
Kilometer = .62137 mile.
Centimeter = .3937 inch.
Inch = 2.54 centimeters.
Foot = 30.48 centimeters.
Foot = .3048 meter.
Mile = 1.60935 kilometers.
Mile = 1609.347 meters.

AREA

Square meter = 10.764 square feet.
Square meter = 1550.3 square inches.
Hectare or square hectometer = 2.4711 acres.
Square kilometer = 247.1 acres.
Square inch = 6.452 square centimeters.
Square foot = 929 square centimeters.
Square foot = .0929 square meter.
Square mile = 2.59 square kilometers.
Acre = .40469 hectare.
Acre = 4046.9 square meters.

UNITED STATES WEIGHTS AND MEASURES

Avoirdupois Weight

27.34375 grains = 1 dram.
16 drams = 1 ounce (oz.).
437.5 grains = 1 ounce.
16 ounces = 1 pound (lb.).
7000 grains = 1 pound.
100 pounds = 1 hundredweight.
2000 pounds = 1 short ton (usually used).
2240 pounds = 1 long ton (seldom used).

Troy Weight

24 grains = 1 pennyweight (dwt.).
20 pennyweights = 1 ounce (oz.).
480 grains = 1 ounce.
12 ounces = 1 pound (lb.).
5760 grains = 1 pound.

Apothecaries' Weight

20 grains = 1 scruple.
3 scruples = 1 dram.
8 drams = 1 ounce.
480 grains = 1 ounce.
12 ounces = 1 pound.
5760 grains = 1 pound.

Length

12 inches = 1 foot.
3 feet = 1 yard.
5½ yards = 1 rod.
16½ feet = 1 rod.
4 rods = 1 chain.
66 feet = 1 chain.
320 rods = 1 mile.
5280 feet = 1 mile.

Area

144 square inches = 1 square foot.
9 square feet = 1 square yard.
30¼ square yards = 1 square rod.
160 square rods = 1 acre.
640 acres = 1 square mile.

Volume

1728 cubic inches = 1 cubic foot.
27 cubic feet = 1 cubic yard.

Capacity

Liquid

4 gills = 1 pint.
2 pints = 1 quart.
4 quarts = 1 gallon (231 cubic inches).
63 gallons = 1 hogshead.
31½ gallons = 1 barrel

Dry

2 pints = 1 quart.
4 quarts = 1 gallon (268.8025 cubic inches).
2 gallons = 1 peck.
4 pecks = 1 bushel (2150.42 cubic inches).

AVOIRDUPOIS AND TROY CONVERSIONS

Ounce troy = 1.09714 ounces avoirdupois.
Pound troy = 13.166 ounces avoirdupois.
Pound troy = .822857 pound avoirdupois.
Ounce avoirdupois = .91145 ounce troy.
Pound avoirdupois = 14.583 ounces troy.
Pound avoirdupois = 1.21528 pounds troy.

Ton (2000 pounds avoirdupois) = 29,166$\frac{2}{3}$ ounces troy.
Ton (2000 pounds avoirdupois) = 2430.56 pounds troy.

MONEY

English

4 farthings = 1 penny (d).
4 pence = 1 shilling (s).
20 shillings = 1 pound (£).
1 pound = 113.001 grains gold.
1 pound = 7.3224 grams gold.
1 pound = \$4.8665 United States money.

Mexican

100 centavos = 1 peso.
1 peso = 417.74 grains silver.
1 peso = .87 or $\frac{7}{8}$ troy ounce (approximate) silver.
1 peso = 27.073 grams silver.

United States

100 cents = 1 dollar (\$).
1 dollar = 23.22 grains gold.

Value of Gold

1 ounce troy = \$20.67.
1 pennyweight (dwt.) = $\frac{1}{20}$ ounce troy.
1 pennyweight = \$1.03$\frac{7}{20}$.
1 grain = 4.306 cents (United States).
1 gram = \$0.6646.
1 gram = .03215 or $\frac{1}{31}$ (approximate) ounce troy.
1 kilo = \$664.60.
1 kilo = 32.15 ounces troy.

CONVERSION OF THERMOMETER READINGS

	Freezing point.	Boiling point.
	degrees.	degrees.
Fahrenheit	32	212
Centigrade	0	100

To convert Fahrenheit to Centigrade, subtract 32 and multiply by $\frac{5}{9}$.

To convert Centigrade to Fahrenheit, multiply by $\frac{5}{9}$ and add 32.

WEIGHT AND MEASURE OF WATER

1 pound (avoirdupois) water = 27.68122 cubic inches.
1 pound (avoirdupois) water = .0160192 cubic foot.
1 gallon (United States liquid) water = 231 cubic inches.
1 gallon (United States liquid) water = .13368 cubic foot.
1 gallon (United States liquid) water = 3.78543 liters.
1 gallon (United States liquid) water = 8.3389 pounds (avoirdupois).
1 cubic foot water = 62.42 pounds (avoirdupois).
1 cubic foot water = 7.48052 gallons.
1 cubic foot water = 28.318 liters.
1 ton water = 339.84 gallons.
1 ton water = 32.941 cubic feet.
1 ton water = 907.2 liters.
1 liter water = 2.2046 pounds (avoirdupois).

WEIGHT OF ROCK AND SAND

	Cubic feet per ton.	Weight in pounds per cubic foot.
Sulphide ore in place	11–13	182–154
Sulphide ore broken	15–18	133–111
Oxidized ore in place	14–18	143–111
Oxidized ore broken	22–24	91–81
Quartz in place. (Specific gravity, 2.65)	12	165
Quartz broken	21	94
Earth in bank	18	111
Earth, dry and loose	27	74
Clay	17	118
Loose sand	25	80
Mill tailing. (Specific gravity, 2.7)		
Sand collected under water	21.5	93
Transferred sand (before leaching)	26	77
Leached sand (that has been transferred)	24	83.3

INTERNATIONAL ATOMIC WEIGHTS, 1917

Element.	Symbol.	Atomic weight.	Element.	Symbol.	Atomic weight.
Aluminium	Al	27.1	Neodymium	Nd	144.3
Antimony	Sb	120.2	Neon	Ne	20.2
Argon	A	39.88	Nickel	Ni	58.68
Arsenic	As	74.96	Niton (radium emanation)	Nt	222.4
Barium	Ba	137.37			
Bismuth	Bi	208.0	Nitrogen	N	14.01
Boron	B	11.0	Osmium	Os	190.9
Bromine	Br	79.92	Oxygen	O	16.00
Cadmium	Cd	112.40	Palladium	Pd	106.7
Cæsium	Cs	132.81	Phosphorus	P	31.04
Calcium	Ca	40.07	Platinum	Pt	195.2
Carbon	C	12.005	Potassium	K	39.10
Cerium	Ce	140.25	Praseodymium	Pr	140.9
Chlorine	Cl	35.46	Radium	Ra	226.0
Chromium	Cr	52.0	Rhodium	Rh	102.9
Cobalt	Co	58.97	Rubidium	Rb	85.45
Columbium	Cb	93.1	Ruthenium	Ru	101.7
Copper	Cu	63.57	Samarium	Sa	150.4
Dysprosium	Dy	162.5	Scandium	Sc	44.1
Erbium	Er	167.7	Selenium	Se	79.2
Europium	Eu	152.0	Silicon	Si	28.3
Fluorine	F	19.0	Silver	Ag	107.88
Gadolinium	Gd	157.3	Sodium	Na	23.00
Gallium	Ga	69.9	Strontium	Sr	87.63
Germanium	Ge	72.5	Sulphur	S	32 06
Glucinum	Gl	9.1	Tantalum	Ta	181.5
Gold	Au	197.2	Tellurium	Te	127.5
Helium	He	4.00	Terbium	Tb	159.2
Holmium	Ho	163.5	Thallium	Tl	204.0
Hydrogen	H	1.008	Thorium	Th	232.4
Indium	In	114.8	Thulium	Tm	168.5
Iodine	I	126.92	Tin	Sn	118.7
Iridium	Ir	193.1	Titanium	Ti	48 1
Iron	Fe	55.84	Tungsten	W	184.0
Krypton	Kr	82.92	Uranium	U	238.2
Lanthanum	La	139.0	Vanadium	V	51.0
Lead	Pb	207.20	Xenon	Xe	130.2
Lithium	Li	6.94	Ytterbium (Neoytterbium)	Yb	173.5
Lutecium	Lu	175.0			
Magnesium	Mg	24.32	Yttrium	Yt	88.7
Manganese	Mn	54.93	Zinc	Zn	65.37
Mercury	Hg	200.6	Zirconium	Zr	90.6
Molybdenum	Mo	96.0	....	....	......

MAXIMUM SOLUBILITIES

(IN WATER AT ORDINARY TEMPERATURES)

	Parts in water.
Aluminum sulphate ($Al_2(SO_4)_3$)	1 part in 3.
Calcium carbonate ($CaCO_3$)	Insoluble.
Calcium chloride ($CaCl_2$)	1 part in $1\frac{2}{3}$.
Calcium hydroxide (slacked lime —$Ca(OH)_2$)	1 “ 600.
Calcium oxide (unslacked lime — CaO)	1 “ 800.
Calcium sulphate ($CaSO_4$)	1 “ 500.
Calcium sulphite ($CaSO_3$)	Insoluble.
Copper sulphate ($CuSO_4$)	1 part in 4.
Iron oxide, hydroxide, and sulphide	Insoluble.
Iron sulphate (copperas — $FeSO_4$)	1 part in 4.
Lead acetate ($Pb(C_2H_3O_2)_2$)	1 “ 2.
Lead carbonate ($PbCO_3$)	Insoluble.
Lead oxide (litharge — PbO)	“
Lead sulphate ($PbSO_4$)	“
Lead sulphite ($PbSO_3$)	“
Lead chloride ($PbCl_2$)	1 part in 93.
Magnesium sulphate ($MgSO_4$)	1 “ 3.
Mercuric chloride ($HgCl_2$)	1 “ 15.
Oxalic acid ($C_2O_4H_2 \cdot 2\,H_2O$)	1 “ $10\frac{1}{2}$.
Potassium bicarbonate ($KHCO_3$)	1 “ 3.
Potassium carbonate (K_2CO_3)	1 “ 1.
Potassium cyanide (KCN)	1 “ $\frac{5}{6}$ (boiling).
Potassium ferrocyanide ($K_4Fe(CN)_6$)	1 “ $3\frac{1}{2}$.
Potassium hydroxide (KOH)	1 “ 1.
Potassium iodide (KI)	1 “ $\frac{2}{3}$.
Potassium sulphate (K_2SO_4)	1 “ 9.
Silver nitrate ($AgNO_3$)	1 “ $\frac{5}{11}$.
Sodium bicarbonate ($NaHCO_3$)	1 “ 10.
Sodium bisulphate ($NaHSO_4$)	1 “ $3\frac{1}{2}$.
Sodium carbonate (Na_2CO_3)	1 “ 4.
Sodium hydroxide ($NaOH$)	1 “ 1.
Sodium sulphate (Na_2SO_4)	1 “ 4.
Zinc carbonate ($ZnCO_3$)	Insoluble.
Zinc cyanide ($Zn(CN)_2$)	“
Zinc hydroxide ($Zn(OH)_2$)	“
Zinc sulphate ($Zn(SO)_4$)	1 “ $1\frac{3}{5}$.

FORMULAS FOR CIRCLES AND CIRCULAR TANKS

$$\text{Circumference of circle} = \text{diameter} \times 3.1416.$$

$$\text{Area of circle} = \frac{\text{diameter}^2}{2} \times 3.1416.$$

$$\text{Volume of cylindrical tank} = \text{area of bottom} \times \text{height}.$$

$$\text{Volume of cone} = \frac{\text{area of base} \times \text{height}}{2}.$$

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