CHAPTER 18

SLURRIES, SLUDGES, SLIMES AND WATER TREATMENT

By F. P. Lasseter,* G. R. Gardner,† and E. A. Reilly‡

THE methods that may be applied to the treatment of slurries and water, as these are related to practical coal-preparation problems, are concerned essentially with the movements of solids suspended in water. It is assumed that there are no fundamental differences between the principles involved in the treatment of coal slurries and the phenomena encountered in general mineral-dressing practice, and the latter are presented in some detail. Basic principles are correlated with present practice for both the anthracite and the bituminous coal fields, and methods are discussed which are designed to utilize best all the material subjected to treatment and suggest a sound approach to the solution of problems relating to the return of clear water to process or to streams.

In order to approach the practical phases of the subject with sufficient understanding of the basic principles, it is necessary to discuss two types of phenomena that are applicable. The first is flocculation and the second is sedimentation. Descriptive matter is given covering the various methods and types of equipment employed to conduct these operations, with emphasis on their application to water and coal-slurry treatment.

DEFINITION OF TERMS

Definitions of terms are consistent with modern developments, and conform, in general, with their usage in mineral-dressing practice.

Because of variations in coal-preparation methods, it is impossible to define a rigid upper limit of particle size for a coal slurry or sludge which will apply generally. Limits vary somewhat with the particular treatment method employed at a given plant. For purposes of definition, this limit is chosen as the particle size for which preparation methods such as Chance cones and jigs are usually dispensed with, and other methods, such as the Hydrotator, tables, and froth flotation, are employed. Generally the limit will be 10 to 6 mesh.

In assuming this variable upper limit of particle size in a coal slurry, it is recognized that the size ranges discussed will duplicate sizes dealt with

* The Dorr Company, Westport, Connecticut.
† Formerly Chemist, The Pittsburgh Coal Co., Pittsburgh, Pa.
‡ Chemist, The Philadelphia and Reading Coal and Iron Co., Pottsville, Pa.

in other chapters, but this does not mean that treatment methods will be duplicated.

A *coal slurry* is defined as a suspension of fine coal and other assorted material carrying particles ranging in size from the finest clay particles to the upper limit defined. Some of the particles are in the colloidal size range and most of the finer sizes exhibit some of the characteristics of suspensoid colloids. The dilution of the system generally is such that it is in a condition of independent particle subsidence. In some localities a slurry is pictured as a suspension of fine coal and other materials having a dilution that cannot be economically dewatered by filtration. It is not generally economical to dewater by filtration such systems when in independent particle subsidence.

A *coal slime* is a slurry containing particles of such size range that 50 per cent or more (by weight) will pass a 200-mesh sieve. Slime suspensions generally are in independent particle subsidence and as a rule are difficult to handle without special treatment in conventional sedimentation equipment.

A *coal sludge* is defined as a slurry that has been partly dewatered by sedimentation, usually to a dilution that will permit further dewatering by filtration.

Culm and silt are terms characteristic of coal-preparation practice, which should be defined. In anthracite terminology, culm is the waste accumulation of coal, bone and rock from old dry breakers.[1] It has a rather wide range of sizes, some rather coarse, and except to differentiate it from silt the term is of little interest to this discussion. In anthracite terminology, silt is the accumulation of waste fine coal, bone and slate settled out of breaker water.[1] It is made up of particles ranging in size from $\frac{3}{32}$-in. round-opening screen to the finest slime. The material is also called sludge, fines, slush and mud, and it is the partly dewatered solids content of what has been defined above as slurry. In the terminology of bituminous coal preparation, the word culm corresponds to slurry or slime, depending upon the size distribution of the suspended solids. Silt corresponds to sludge as defined. It is also called slush, mud and duff.

Sedimentation has been defined[2] as the movement of solid particles or flocs through a fluid due to an imposed force. The case considered in this discussion includes the sedimentation of fine coal and other small particles or flocs through water due to the force of gravity.

Independent subsidence is defined as the condition in sedimentation in which each floc or particle settles freely; that is, its movement is not influenced in any way by other flocs or particles in suspension. The condition is characterized by no definite line of subsidence, a substantially constant rate of clarification equivalent to the settling velocity of the

[1] References are at the end of the chapter.

smallest particles or flocs present, and further controlled by the shape and effective gravity of the particles and the viscosity of the liquid.

Collective subsidence is defined as that condition in sedimentation in which the particles and flocs are sufficiently close together to retard the coarse fast-settling particles while the slow-settling ones are entrapped and carried down with the mass. The condition is characterized by a definite line of subsidence, a substantially constant settling velocity over some distance and finally a marked decrease at the critical point. The flocs are conceived to be close enough to touch but not sufficiently close to result in compression. The line subsidence rate decreases with decrease in dilution.

Compression subsidence is defined as that condition in sedimentation in which the flocs or particles are conceived to be in close contact, further subsidence occurring as a direct effect of compression resulting in the elimination of water from the flocs and interstitial spaces. The settling velocity decreases with time of settling.

Flocculation is defined as a grouping of dispersed particles into relatively stable clumps. It is primarily a conditioning process and may be treated entirely separately from the sedimentation step. As will be shown later, flocculation may have a marked effect on sedimentation velocity.

FLOCCULATION

Developments in the flocculation and clarification of coal slurries during the last several years have followed the lead of those originating the use of organic flocculants, primarily starch. Owing to the emphasis on this approach to the subject, much of the space devoted to flocculation deals with starch coagulants, their preparation and applications. Since water treatment and coal-slurry treatment generally involve the use of varying but small quantities of inorganic flocculants, and since slimes as defined exhibit many of the properties of colloidal suspensions, the mechanism of the flocculation process as developed in colloid chemistry is presented in sufficient detail to demonstrate its practical significance.

Inorganic Flocculants

Colloids are divided into two major classes, sols and gels. The treatment of slimes is concerned only with sols, which are distinguished from gels primarily by the fact that they are very sensitive to the action of electrolytes while gels are not.

The flocculation of a stable sol (for example, a coal slime) may be assumed broadly to include the following steps:

1. The addition of chemicals generally called electrolytes.
2. Mixing of sufficient intensity to promote rapid dispersion of the electrolyte throughout the system to be treated.

3. Gentle agitation designed to promote a maximum of collisions per unit of time between suspended particles without breaking up already formed flocs.

The first two steps listed are primarily conditioning steps having for their purpose the destruction of the stability of the suspended material so that when individual particles come in contact with each other or with groups of particles they will adhere and thus flocculate. The third step is entirely a physical one of subjecting the system to a treatment that largely increases the number of contacts per unit of time.

The most generally accepted theory explaining the behavior of the sol, or suspensoid type of colloidal system, is based on the concept of an electric double layer by Helmholtz[3] and later modifications of this theory by Gouy[4] and Freundlich.[5] The stable particle is conceived as having charge-carrying ions distributed in the plane of its surface, or embedded in the latter, constituting the inner layer. The ions in this layer are referred to as adsorbed ions and in most cases are negative, although with some substances they are positive. The ions in the outer layer are conceived as distributed over a depth of several monomolecular layers. Some of these counter ions remain in the liquid layer firmly attached to the wall of the particle while others are in the freely movable liquid diffusing to a point where the mean electric charge is zero. The inner and outer layers together constitute the diffuse double layer. Owing to the presence of the charges on the separate particles, the latter tend to repel one another and hence cannot approach close enough to collide and adhere. Add a sufficient quantity of an electrolyte to such a stable sol and the particles adsorb ions of opposite charge that counteract the effect of the stabilizing charges. The electric double layer is destroyed, impacts take place between the particles, and the sol flocculates; the first and second steps outlined above having been satisfied.

As a general rule the sol is most sensitive to flocculation by polyvalent ions carrying a charge opposite to that of the colloid. Anions decrease the potential of positively charged particles while negatively charged particles are primarily influenced by cations. As the valence of the active flocculating ion increases from 1 to 2 to 3, the flocculating power increases markedly and roughly in the ratio of 1 to 100 to 1000, respectively. There are, of course, many exceptions to this rule.

If the sol is a relatively concentrated one, the probability of collision between the particles is high and flocculation is fairly rapid. For dilute sols in which the probability of collision is very low, the flocculation rate can be increased markedly by subjecting the system to the effects of gentle agitation in one of several types of mechanical flocculators available.

For a more detailed discussion and evaluation of theories relating to the mechanism of flocculation reference should be made to "Colloidal Phenomena," by Hanser,[6] or to some other standard treatise on the subject. The mechanism as presented here affords a practical approach to the subject of slime treatment, although it is recognized that the percentage of true colloids in such slimes may be small.[7] It does not, however, cover all the factors involved in the starch coagulation of coal slurries, and this approach to the subject is discussed separately.

The use of various inorganic chemicals to facilitate sedimentation of solids from coal slimes and slurries has been accepted practice for many years. Among the principal chemicals so used have been Ferrisul, sodium aluminate, lime, water-soluble silicates and soda ash. Less frequent use has been made of sulphuric acid, ferric chloride and ferrous chloride. Until the development of starch flocculants these chemicals were used not only to destabilize the colloidal solids present in a slurry, but frequently were added in larger quantities in the hope that this would improve the settling characteristics of the coarser fraction of the suspended solids. Since the colloidal solids present in a slurry behave as the sol type of colloid, very small quantities of electrolyte are required to destroy the diffuse double layer and cause coagulation.

Calcium compounds are good flocculating reagents for clays. This fact and the cheapness and availability of lime suggest its use to coagulate coal slurries. The presence in the slurry of any iron oxide sol would increase the effectiveness of lime as a flocculant, because of adsorption of the hydroxyl ion by the positively charged iron oxide. A mixture of lime and some of the salts mentioned above is also suggested.

It should be noted that there are no established rules to follow in ascertaining in a given case the type and quantity of flocculant to employ. Familiarity with basic principles, a knowledge of the materials constituting the system to be treated and some knowledge of available equipment will suggest a reasonable approach to the solution of the problem, but each problem must be investigated separately in order to determine the most economical treatment.

Organic Flocculants

Organic substances as flocculants or as aids to flocculation have received attention in a number of fields during the past 15 or 20 years, but it is outside the scope of this discussion to evaluate the results of all these investigations. Probably the most active phase of the subject has been the introduction of the use of starch coagulants in the flocculation and clarification of coal slurries, particularly in European practice, and this development is outlined.

R. A. Henry[8] conducted the first important investigations on the use of starch coagulants in the flocculation and clarification of coal slurries and slimes. He developed the Henry process and applied it in Belgian preparation plants. Following this, the practice was introduced into England, where similar processes were developed. Various phases of the problem were investigated by Raybold,[9] Samuel,[10] Wilkins,[11] Needham,[12] Holmes,[13] and Tomalin.[14] In the United States, no doubt, a considerable amount of unpublished data has been obtained on the subject by a number of investigators, but the Pittsburgh Coal Co. seems to have been most active in this work. Gardner and Ray published an outline of part of this work,[15] dealing among other things with investigations relating to the best source of the starch and its preparation to get maximum benefit.

Considerable work has been done in attempting to develop an explanation of the mechanism of the flocculation process using starch. An examination of the various theories submitted leads to the conclusion that flocculation of the slurry takes place in two stages. The first stage is the flocculation of the colloidal constituents of the slime, and this stage follows the mechanism, previously outlined, of charge neutralization and subsequent coagulation by contact. The starch solutions have little or no effect on these dispersed sols, and the flocculation of the latter is generally promoted by the addition of small quantities of a suitable (inorganic) electrolyte.

The starch functions in such a way that the smaller flocs and the particles larger than colloidal sizes are caused to form relatively large and stable groups, which settle rapidly and greatly increase the capacities of ordinary settling tanks. One investigator[14] believes that this stage of the process resembles mechanical sticking; and, indeed, no one seems to have submitted any better explanation. Presumably, the idea is that the starch is adsorbed on the surface of the particle in such concentration that it serves as a bonding material when the particles collide with each other.

Any starch or material high in starch content may be processed into an effective flocculant by either heat-treatment, caustic treatment or a combination of the two. Considering all points of view, however, in the long run either corn or potato starch will be the most economical and easiest to handle. In addition to those mentioned, there are several other processes available for converting starch into the colloidally dispersed state necessary for effective flocculation. At present, information regarding the various factors involved in preparation of a reagent by these processes is limited, therefore their use is not recommended. Brief mention of these will be made later.

The only distinction of a general nature that can be drawn between heat and caustic treatment is that the equipment required for the thermal process is somewhat more expensive than that used in the caustic process. As a rule, however, the method selected will be influenced to a considerable degree by factors other than initial cost. These factors relate to specific conditions at the plant in question. Obviously such a selection of processes must be based on thorough knowledge of plant problems and careful testing of plant slurries involved. This is accomplished best by the plant personnel. There are, however, certain specific conditions that should receive particularly careful consideration. Laboratory data should be obtained regarding these conditions before a final selection is made.

The selection of the process, to a great extent, will be governed by the character of the solids in the plant circuit and the present or proposed method of disposal of these solids. Where these solids contain an appreciable amount of clay or similarly highly hydrated material, and where the complete and continuous removal of all solids is desired, the use of the caustic process may be disadvantageous. The caustic soda introduced with the starch reagent tends to build up in the plant circulating water. Depending on the character and amount of clay material present, there are certain limits within which this condition will not affect the results. Once the NaOH concentration passes this point, however, there is a tendency for the clay to become more highly dispersed. If this condition prevails over a shift's operation, a consistent increase in the ash content of the thickened fines may be evident as the shift progresses. Another frequent result of such a condition may be a very undesirable appearance of the clean coal lump. The finely dispersed clay adheres to the surface of the wet-cleaned lump coal and on drying produces a dull, grayish film. Frequent consumer complaints develop from such a condition. In addition, the accumulation of this material in the plant circuit often necessitates the operation of thickening equipment after the regular shift. No hard and fast rule can be laid down as to the quantity of clay material in the plant circuit that will develop this condition with causticized starch. It appears that the degree of hydration is more important than the amount of such material.

The introduction of a causticized starch to the effluent from a classifier may have an undesirable effect on subsequent thickening. For example, in thickening the effluent from a classifier with the aid of causticized starch, the presence of the caustic may cause radical decreases in the bulk density of the thickener underflow. This again is particularly true when considerable quantities of clay or similar material are present. In addition, some difficulty may be encountered in filtering such an underflow.

It should be emphasized that these difficulties can be overcome in a large measure by decreasing the concentration of caustic used in preparing the starch reagent and using higher temperatures. In some cases it may be necessary to eliminate the caustic altogether and use a heat-treated starch. Any conclusion regarding an individual plant must be based on laboratory tests if it is to have any value.

The optimum amount of starch treatment required for a given slurry may be determined in a settling frame, which presents a sufficiently thin cross section so that the degree of flocculation can be observed. The frame consists of two plates of glass 7 by 19 in., spaced by means of a rubber hose threaded with soldering wire and mounted in a suitable frame. Samples of the slurry should be as fresh as possible and ordinarily should be withdrawn directly from the plant circuit for test purposes. Deviation from this rule may cause considerable error in the results. Changes in settling rate of the solids with any specific treatment will usually indicate a proportional change in capacity of the sedimentation unit with the same treatment.

Changes in characteristics of bulk density of the thickened solids may be measured in 500 or 1000-ml. graduates. Again samples should be withdrawn directly from the plant circuit for test purposes. If the ratio between the rate of feed to the thickener and the volume of the unit is to remain unchanged, there will usually be little change in the bulk-density characteristic. It has been noted, however, that the presence of considerable quantities of clay in the solids may change this picture when causticized starch is used. Measurement of the volume of solids after a period of settlement, in minutes corresponding to the ratio between the thickener volume in gallons and the normal rate of slurry feed in gallons per minute, and comparison with the volume obtained for the same period of time with starch treatment, will give a fairly good prediction on this point. If the purpose of the starch treatment is to increase the thickening capacity, the settlement time for this volume test should be decreased accordingly.

The effect of caustic soda on clarification also may be checked in 500 or 1000-ml. graduates. The slurry should be permitted to settle to about one fourth the volume of the graduate and the top 250 or 500 ml. of water should be decanted. The settling rate of this fine material should be determined at intervals of one hour. Any marked decrease in settling rate of the solids contained in this decanted portion suggests use of less caustic.

In order to facilitate the addition of starch reagents in laboratory-scale tests, it is suggested that such reagents be prepared at specified concentrations and diluted to 0.1 or 0.01 per cent solutions. This permits more accurate measurement and introduces no appreciable error.

In preparing a flocculant from starch by the thermal process, a starch paste of not more than 5 per cent concentration should be heated with agitation to a temperature of 135° to 140°C. This can be accomplished in any suitably constructed pressure-reaction vessel capable of operating at a pressure of 60 lb. per sq. in. A suitable and convenient design is shown in Fig. 1. With this design the starch is mixed in the small side tank at 20 to 25 per cent concentration, stirred to a smooth, uniform consistency with the small mixer, and pumped into the pressure heating vessel with the pressure vent valve open. Additional water is introduced until the starch paste is diluted to 5 per cent concentration. Steam is introduced into a steam jacket until temperature approaches 100°C. The pressure vent valve is then closed and temperature is raised to 135° to 140°C. Steam is shut off and stirring is continued until the temperature drops to 100°C. The pressure vent valve is opened and reagent is pumped back to tank and diluted to a convenient concentration.

Attempts to heat starch pastes at concentrations above 5 per cent will result in a gummy, stringy, gelatinous mixture that may necessitate complete dismantling and cleaning of the reaction vessel. Heating

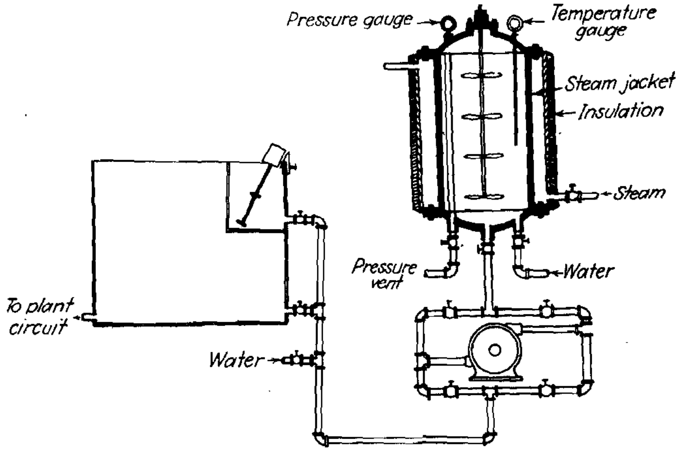

FIG. 1.—EQUIPMENT SKETCH FOR HEAT-TREATED STARCH SOLUTION.

starch pastes above 145°C. will cause degradation of the starch to dextrin and produce an inferior flocculant. The reaction vessel should be thoroughly rinsed with water between batches, since the soluble starch tends to dehydrate to a tough, viscous film that reduces heat transfer to a considerable degree. These ringings should be used in dilution of reagent. If properly prepared, the reagent from the reaction vessel will have a faint opalescent sheen.

TABLE 1.—*Temperature and Strength of Caustic that Should be Observed in Causticizing Starch for Flocculating Purposes*

Reaction Temperature, Deg. C.	Caustic Solution, Per Cent	Reaction Temperature, Deg. C.	Caustic Solution, Per Cent
25	2.5	70	1.7
40	2.2	80	1.5
50	2.0	90	1.3
60	1.8	100	1.0

In preparing flocculants from starch by the caustic process, starch pastes of not more than 5 per cent concentration may be treated with solutions of NaOH from 1 to 2.5 per cent concentration, at temperatures of 100°C. for 1 per cent NaOH down to 25°C. for 2.5 per cent NaOH. The higher the reaction temperature, the lower the concentration of NaOH that may be used. Attempts to heat starch pastes with concentrations of NaOH of less than 1 per cent at temperatures above 100°C. will produce an inferior flocculant. Table 1 lists the temperature-caustic concentrations that should be observed.

The starch gel should be thoroughly agitated for 15 min. at the concentration and temperature required. The mixture may then be diluted to any convenient proportions. Fig. 2 shows a diagrammatical sketch of a convenient mixing unit for preparing causticized starch solutions.

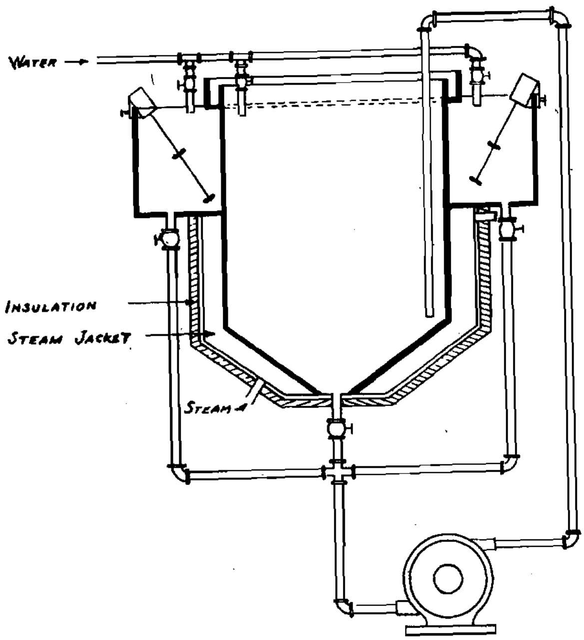

FIG. 2.—EQUIPMENT SKETCH FOR PREPARATION OF CAUSTICIZED STARCH SOLUTION.

Two small side tanks are provided for mixing to uniformity and the two mixtures are pumped simultaneously into the large tank. This provides for rapid mixing of the two, which is extremely desirable in preparing causticized starch solutions. The starch gel in the large tank should be mixed during heating by recirculation with the pump. Regardless of heating, the starch gel should be mixed in this manner for at least 15 minutes.

If possible, the starch reagent should be introduced into the feed to the thickening unit. If practicable, a small mixing chamber of conventional design should be used. This will give a more uniform and better flocculation, and as a rule, better clarification. It should be emphasized, however, that the formation of flocs in a slurry treated with starch flocculant is extremely rapid. Only a few seconds is necessary for floc formation and a mixing period of 15 or 20 sec. is usually ample in treating extremely dilute suspensions. As a result of the short mixing period required, a very much smaller mixing unit may be used with starch flocculants than is required for inorganic reagents.

If it is inadvisable to install a mixing chamber, the starch reagent may be added into the sump preceding the thickener or into the slurry trough feeding the thickener. If necessary to introduce into the trough, several baffle plates should be welded into the trough to provide thorough mixing. In at least one instance the flocculant has been added to the slurry as it passed into the thickener well. By splitting the stream of starch solution into four parts, feeding to the four quadrants of the well, very acceptable results were obtained. At another place the flocculant was added to the water feeding to a jig, with acceptable results.

Regardless of where the reagent is added, it should be added in a continuous manner throughout the shift. Adding large quantities of solution intermittently is never entirely satisfactory and may prove definitely harmful. At least two cases are known where this practice, together with unusually high concentrations of solids, caused such a rapid deposition of solids that the unit was plugged. Once the probable amount of reagent required has been determined from laboratory examination, the total weight of starch plus a safe contingency allowance should be computed for an entire shift. Tank capacity should be provided to handle this amount of starch at such dilution that the rate of flow into the plant circuit shall be reasonably large.

Properly regulating a continuous rate of flow of the starch reagent to less than 5 gal. per hour is impractical. Probably the most practical method of introducing the starch reagent is by the use of a low-pressure centrifugal pump. One pump that has given satisfactory service has a rating of 1 qt. per min. at 14 lb. per sq. in. pressure. The advantage of using a pump is that a positive pressure is available. A by-pass and valve arrangement should be installed around the pump to provide some regulation of the rate of flow of the reagent to the plant circuit. With this system, clogged lines can be easily cleaned. In addition, a pressure gauge installed in the line to the plant circuit gives a ready check at all times as to the rate of delivery of the flocculant.

An alternative method is to feed the reagent into the plant circuit by gravity and regulate the rate of flow by a valve. The disadvantages of this method are variable pressure and the fact that at low pressures the valve clogs easily. Also, the point of addition of the reagent to the plant circuit is often in an inaccessible place and checking the rate of delivery is difficult.

There are several other methods for obtaining flocculants from starch. In view of the limited information available at present regarding these processes, their mention is only of general interest. Among these are a number of flocculants that were available commercially until within recent months. Of these, some are starch products soluble in cold water.

One is a starch derivative marketed under the trade name of Floc-Gel and imported from the Netherlands. The exact process of manufacture remains a trade secret but laboratory-scale tests have indicated the general nature of the process. It is sufficient to say that the process is not suitable for the preparation of flocculating reagents at the average coal-preparation plant. Another is a naturally occurring starch known as Konyaku flour, which comes from Japan. Both of these are excellent flocculants. Other flocculants available commercially are Ogwen powder and Unifloc, both of which have been used in Great Britain and have been imported to a small extent. Although all of these materials are satisfactory for many flocculating purposes, it is felt that their use is somewhat more expensive than reagents prepared from starch by causticizing or heat-treatment.

Comparisons of all these reagents with causticized and heat-treated starch have been published. Some of these comparisons have been unfavorable to the latter and some undoubtedly were of a commercial nature. In addition, there is some question as to the methods used in preparing starch solutions by the caustic or thermal processes that were used in these comparisons. Experience in this country has shown that starch flocculants properly prepared are as effective and efficient as any other material.

Starch may be made soluble to some extent by prolonged grinding of starch pastes. This effect can be improved by use of dilute concentrations of oxidizing agents. Flocculants prepared by this process are very inefficient at present. Treatment of starch pastes with quaternary ammonium compounds shows considerable promise.

SEDIMENTATION

In its broadest sense, sedimentation may represent the gravity settling and thickening of solid particles suspended in a liquid. The primary objective may be: (1) to separate the solids by classification, (2) to obtain a clear liquid, or (3) to dewater the total solids. For the purpose of this discussion the liquid will be water and the solids will be those usually found in coal slurries.

The practical applications of sedimentation to the treatment of coal slurries fall into two groups, one of classification or hydroseparation and the other of clarification and thickening.

In order to obtain best results in classification equipment, making what may be termed fine separation, the suspended particles should be in a well-dispersed state. In general, each particle should behave quite independently of other particles present except as the finer fractions may influence the character or become a part of the medium in which sedimentation takes place. Dispersing reagents are not required for relatively coarse separations in classification.

Classification may be employed in the treatment of coal slurries for either of two objectives: (1) to prepare, from the whole slurry, a relatively low-grade steam fuel; (2) to deslime the slurry so that the slimes and sludges so prepared may be further processed separately. For such separation processes, the laws determining the movement of solid particles in a liquid under the force of gravity are controlling.

The law derived by Stokes[16] applies to the uniform slow motion of a rigid, spherical particle settling independently in a homogeneous, viscous fluid of infinite extent (Eq. 5, chap. 10 of ref. 16). The limitations imposed by the Stokes equation are that the particle is a rigid sphere, the fluid is homogeneous and infinite in extent, and the velocity is uniform and slow. The fluid may be assumed as infinite in extent for commercial installations, but it cannot be assumed that it is homogeneous for these slurry systems having the dilutions usually encountered. Both a density difference factor and a viscosity factor may influence the properties of the system. Much of the material is coarser than 40 microns, but the settling velocity of the coarse particles may be greatly retarded by an increase in the effective density of the medium resulting from the presence of smaller particles of the same material. More notable changes may result from the presence of quantities of finer material of higher specific gravity, and this is the rule rather than the exception with coal slurries. Clay and bone of higher specific gravity than the coarser coal substance constitute a large part of the slimes fraction of the slurry.

TABLE 2.—*Data Correlating Rate of Fall in Water of 1000 One-micron Spheres of Magnesium Hydroxide under Different Conditions of Aggregation*[a]

Packing	Voids, Per Cent	$Mg(OH)_2$, Per Cent by Weight	Average Density	Diameter of Sphere, Microns	Relative Velocity of Fall
Not flocculated	0	100	2.4	1	1
Solid	0	100	2.4	10	100
Hexagonal close	26	87.2	2.04	11	90
Single cubic	47.6	72.5	1.73	12.4	81
	60	61.5	1.56	13.6	74
	70	50.7	1.42	14.9	67
	80	37.5	1.28	17.1	58
	90	21.1	1.14	21.5	46
	95	11.2	1.07	27.0	37
	98	4.7	1.028	37.0	27
	99	2.4	1.014	45.5	22

[a] From a paper by Stewart and Roberts.[2]

An appreciable portion of these clay and bone particles, and also some of the coal particles, are of the size range and behave as true suspensoid colloids. In a dispersed condition these particles would never settle completely, but they may be induced to settle relatively very rapidly by flocculation into groups. Illustrating the marked effect of flocculation on the ultimate velocity of fall of such small particles are the data in Table 2.

No direct comparison can be made between the settling velocities of the finest clay particles in a dispersed state and the material after flocculation, since these dispersed particles are kept in suspension by the so-called Brownian motion. However, the data in Table 2 show that for 2.4-density 1-micron particles in water the settling rate may be increased 22 times by flocculation into clumps having a diameter of 45.5 microns, even with the water in the voids constituting 99 per cent of the volume of the floc. At concentrations sufficient to entrain large grains within the floc structure, the percentage of voids is reduced and the effective density and settling velocity are changed according to whether the entrained substance is lighter or heavier than the floc.

For a given dispersed slurry, the finest particles present would probably behave as though subjected to an effective viscosity equal to that of the pure water or solution. The larger particles undoubtedly would react to a viscosity approximately that of a suspension of the finer material. With a suitable size distribution and high concentration of solids, the effective viscosity might be very different from that of water. Two suspensions having the same viscosity but different size distributions may even permit a given particle to fall at different velocities, owing to their lack of homogeneity.

Flocculent pulps behave as plastic solids rather than true liquids, and the viscosity effects for such systems are more difficult to analyze.[17] Some clays in a flocculated condition exhibit elastic properties, as evidenced by the fact that they will settle quietly to a certain dilution and remain stable. If such clay pulps are gently stirred, the floc stability may be broken down and settling resumed until a much lower dilution is reached.

Although one of the limitations of the Stokes equation is that the particle is a sphere, considerable work has been conducted in which the equation has been applied to the settling of particles of various shapes other than spherical. By adopting the concept of an "equivalent diameter" and employing a modification of the Oden sedimentation analysis method, it was found that carborundum particles smaller than 40 microns settled in water according to the Stokes equation. This was true for concentrations up to 0.2 per cent suspended solids. Above this concentration with the size distribution tested, there appeared to be sufficient particle interference to throw the data out of line. Data obtained by the modified sedimentation method for the minus 40-micron-size fraction of a cement raw mix[1] and screen-size data for the plus 74-micron fraction of the same mix lie on a smooth graph of little curvature, when plotted on logarithmic probability paper. Since testing sieves are not accurate below 74 microns and the sedimentation method cannot be conveniently applied to particles coarser than 40 microns, when using water, the comparison necessarily was indirect. The agreement, however, was very good. Tests at different temperatures have identical size distributions.

Fluid resistance to the settling of particles is generally classified as laminar or turbulent according to the magnitude of the Reynolds number, R (Eq. 11, chap. 10 of ref. 16). As R increases above 1, the settling properties deviate more and more from that represented by Stokes' law.

The effect of the simultaneous movement of many particles in suspension has been studied, both for uniform spheres and for spheres of various sizes. Dispersed systems that, although relatively concentrated, still permit movement of the individual particles must classify under conditions of so-called hindered settling. Particle size, particle density and particle shape are variable factors that must be considered in the applications of hindered-settling phenomena to the treatment of coal slurries. The factor of viscosity, as previously discussed, also enters the picture. For the case of large particles settling in a suspension of fine particles, the latter constitutes the medium. The viscosity and density factors of the medium are not that of water, but they vary within limits with the concentration of these fine particles. Gaudin[18] discusses these factors and submits among other formulas one for determining the hindered-settling ratio between two minerals in suspension in water, the ratio being defined as the ratio of the apparent specific gravities of the mineral (to be separated) against the suspension (of water and fine particles) raised to some power between one-half and unity. The formula may be stated as follows:

$$d_h = \left(\frac{d_1 - d^1}{d_2 - d^1}\right)^m \qquad [1]$$

Where d_h = the hindered-settling ratio,
d_1 = specific gravity of the heavy mineral,
d_2 = specific gravity of the light mineral,
d^1 = specific gravity of the suspensoid (not the liquid)
and (Newton) $1 > m > \frac{1}{2}$ (Stokes)

Table 3 lists the hindered-settling ratios for a slate-bituminous-coal-water system.

The figures in Table 3 were calculated from Eq. 1 and are independent of particle size. The system is assumed as having no plastic properties at any of the concentrations employed in the calculations. The obvious difficulty in applying the hindered-settling principles to coal slurries is the fact that in practice the solids range in specific gravities from 1.3 to 2.7, and the effective hindered-settling ratios between recovered and discarded materials are by no means as large as the calculated values listed in the table.

TABLE 3.—*Calculated Hindered-settling Ratios, System Slate, Bituminous Coal, Water*[a]

Heavy Mineral Out of Total Solids, Per Cent	Percentage Solids by Volume					*m*
	0	10	20	30	40	
0	5.0	5.45	6.0	6.72	7.67	1.0
	3.94	4.23	4.59	5.05	5.56	0.85
	2.85	3.00	3.21	3.45	3.76	0.65
	2.24	2.34	2.45	2.59	2.77	0.50
25	5.0	6.00	7.67	11.00	21.00	1.0
	3.94	4.59	5.65	7.70	13.30	0.85
	2.85	3.21	3.76	4.76	7.25	0.65
	2.24	2.45	2.77	3.31	4.59	0.50
50	5.0	6.72	11.00	41.00	∞	1.0
	3.94	5.05	7.70	23.50	∞	0.85
	2.85	3.45	4.76	11.20	∞	0.65
	2.24	2.59	3.31	6.40	∞	0.50
75	5.0	7.67	21.00	∞	∞	1.0
	3.94	5.65	13.30	∞	∞	0.85
	2.85	3.76	7.25	∞	∞	0.65
	2.24	2.77	4.59	∞	∞	0.50
100	5.0	9.00	∞	∞	∞	1.0
	3.94	6.48	∞	∞	∞	0.85
	2.85	4.17	∞	∞	∞	0.65
	2.24	3.00	∞	∞	∞	0.50

[a] Taken from Principles of Mineral Dressing, by Gaudin.[18]

The treatment of sedimentation described in the foregoing paragraphs has been concerned with dispersed pulps having little or no tendency to flocculate, one objective being that of classification to separate the slime fraction of the coal slurry from the coarser sludge fraction, so that each could be processed separately if desired. When the primary objective is one of clarification and thickening, to recover a relatively dewatered solid and return a clear water to process or to streams, the treatment includes the processing of a suspension in which the solids having the properties of stable suspensoid colloids are rendered sufficiently unstable to promote flocculation. The classification operation discussed may or may not be a necessary preliminary step in the process preceding flocculation and clarification. However, even with the application of starch coagulants, it is probably advisable to classify coal slurries so that a minimum of particles coarser than 100-mesh is left in the slime going to clarification. Classification at 150 mesh would probably be a better figure for anthracite slurries, the ash content of the minus 150-mesh product probably approaching, in most cases, 50 per cent by weight. To separate the so-called slimes from bituminous-coal slurries, the cut should be made at a mesh considerably below that for anthracite. A controlling factor would be the percentage of commercially recoverable fine coal in the slime fraction, assuming the recovery cost could be met by scale of the fine product.

In general, it may be assumed that when one objective of the treatment of a coal slurry is the beneficiation of the coal fraction for commercial use, the classification and other beneficiation steps should precede the flocculation and clarification steps in the process. On the basis of this assumption, these steps may be considered as applicable to the treatment of the refuse from any beneficiation process irrespective of the recoverable fine-coal content of this so-called refuse. Since flocculation principles and practice have already been discussed, it will be further assumed that the refuse suspension is in a flocculated condition and ready to be fed into the clarification apparatus.

Deane[21] outlines a method for observing the mechanics of sedimentation, about as follows: Assume a typical pulp or suspension; for example, a greatly diluted coal or metallurgical slime. This system will contain particles of various sizes ranging from fairly coarse sand to the finest slimes. Pour this pulp into a glass cylinder and allow it to settle. It will be observed that at first a classification takes place in which the coarsest particles settle to the bottom at a relatively rapid rate, the finest particles settle very slowly and remain near the top, and a gradation in sizes develops between these limits. All the particles have free movement and each settles at a constant velocity according, within limits, to Stokes' law. Gradually decrease the dilution of the original pulp and a condition is reached where the solids settle with a distinct line of demarcation between the settling mass and the supernatant clear liquid. In this case, the rate at which the line subsides is probably the average settling velocity of the individual particles composing the pulp in a liquid of specific gravity equivalent to the effective pulp density. The coarse, fast-settling particles are retarded while the slow-settling ones are entrapped and carried down in the mass. Clock the rate at which the line subsides, and it will be found that the rate of subsidence, or, as it is commonly known, the settling rate, is constant. It will be observed that, as the line continues to subside, a concentration is ultimately reached where there is a marked reduction in settling rate. This is called the point of compression, or critical dilution. Upon close observation of the pulp at critical dilution, it will be noted that the particles are much closer together than before reaching this point. The liquid that is being liberated from the lower zones is channeling up through the pulp rather than flowing evenly around each particle as it did before. Under these conditions the particles are resting upon and supporting each other.

Further thickening is due to the compression of the mass by the weight of the overlying particles.

Pulps may be classified as shown in Table 4, dependent upon the method by which they settle.

TABLE 4.—*Character of Subsidence of Different Types of Pulps*

Operation	Type of Pulp	Character of Subsidence	Description
Clarification....	Dilute, Class 1	Independent	Particles or flocs settle independently. No definite line of subsidence. Settling rate dependent upon size and density of particle or floc
	Concentrated, Class 2	Collective	Definite line of subsidence. Settling rate decreases with increasing concentration of solids. Settling rate influenced by particle or floc interference
Thickening. ...	Compact, Class 3	Compression	Flocs and particles in intimate contact. Subsidence due to compression (pressure of particles or flocs upon those below them)

With systems in class 1 the capacity of the settling tank is dependent upon the rate at which the finest particles or flocs will settle to a level below the zone influenced by the overflowing liquid. In other words, with a stream of liquid flowing across a tank, the time required for a particle to travel from the feed inlet to the overflow point must be a little greater than that required for the finest particles or flocs in the feed to settle out of this stream. When there is an effective density differential between feed and effluent, but the suspended materials are still in independent particle subsidence, there is a tendency for the pulp to settle directly to its corresponding density level in the tank. Theoretically, the liquid should then tend to rise at a more or less constant rate throughout the area of the clarifier. Under these conditions, the rising velocity of the water must be less than the settling rate of the finest particles or flocs if complete clarification is to be obtained. Whether or not pulp density has an effect on the process depends upon the nature and concentration of the suspended material.

The general practice now is to provide for flocculation in separate units ahead of clarification or to install combination units that provide for flocculation in separate cells preceding the clarification compartment or compartments. The detention time in the flocculation cell, where no clarification is intended, will be controlled by the time necessary for flocculation to take place under the conditions to which the suspension is subjected in the cell. For such flocculent systems capacity should be based on the behavior of the flocculated material. This applies to both class 1 and class 2 pulps.

The commonest systems of liquid-solid suspensions encountered are those in class 2, where the solids settle with a sharp line. Almost all metallurgical and most chemical pulps fall into this classification. Class 2 pulps may pass through an indeterminate number of concentration zones while settling from the feed dilution to the dilution of discharge. With a feed of 10 to 1 and a discharge of 1 to 1 there will be intermediate zones of 9 to 1, 8 to 1, 7 to 1, and so forth. Some of these zones will have appreciable depths while the depths of others will be infinitesimal. The rate of subsidence is different in the different zones, as is also the quantity of water to be passed through any zone. Consequently, the zone displaying the slowest rate of settlement relative to the amount of water to be separated will be the zone that limits the size of the tank. This is obvious because all the solids must pass through this limiting zone, therefore it will allow only a certain definite quantity of water to be separated. An equation has been developed by Coe and Clevenger[20] for rating the capacity for each zone and thus ascertaining the rate of settlement in the zone limiting the capacity of a tank.

With water as the suspending medium, the equation is usually written as follows:

$$A = \frac{1.333(F - D)}{R} \qquad [2]$$

Where A = square feet of area to be provided per ton solids per 24 hours.
R = the rate of subsidence in feet per hour.
F = the dilution (ratio by weight of tons water to 1 ton solids) of the pulp in the zone giving the rate of settlement R.
D = the dilution of final discharge.

Where the suspending medium has a specific gravity, Sp, greater than 1:

$$A = \frac{1.333(F - D)}{RSp} \qquad [3]$$

Equation 3 is the usual one employed in the analysis of settling-test data. However, it applies only to pulps in collective subsidence, or class 2. If the rate of subsidence is determined for the dilutions representing the various zones between feed and discharge, and these rates are substituted in the equation, various values for A will be obtained. This will give the tank area in square feet required in each zone to handle the water that must pass through it. Obviously the zone of least capacity, or that giving the highest value for A, will control the capacity of the settling tank. When the values for A increase very appreciably, the pulp probably is in compression and other factors are controlling.

As the pulp becomes sufficiently concentrated with respect to the suspended solids to exhibit the characteristics of class 3, further elimination of water depends upon the squeezing action resulting from the weight of the particles in direct contact with each other, and to the action of the thickener rakes, which function in such a way as to enhance this squeezing effect. The extent to which the squeezing action resulting from the weight of the particles is effective is a function, within limits, of the tank depth and of time.

For calculating the capacity in compression, a test is made to determine the time required for a pulp, after it has entered the compression zone, to reach the dilution of discharge desired. Usually this is the point where the sludge reaches its final density, representing the highest possible concentration of solids. Observations are made as to the dilution at various stages during this final settling period. From these, the average dilution in compression is calculated. This value divided by the area required, as indicated by unit-area tests or by the recommended area, gives the depth of pulp in compression that must be maintained in the settling tank.

The equation employed for determining the volume required in compression is as follows:

$$V = \frac{4H(G - Sp)}{3G(S - Sp)} \qquad [4]$$

Where V = the volume of compression pulp required per ton of solids per 24 hours.

S = the average specific gravity of the compression pulp.

Sp = the specific gravity of the suspending medium.

G = the specific gravity of the solids.

H = the hours required for the pulp to settle from the dilution entering compression to the dilution of discharge.

Then: $\frac{V}{A}$ = the depth of the compression zone.

For more detailed information on the theories of slime settlement, reference should be made to papers by Coe and Clevenger[20] and by Deane.[21]

The stirring action of the thickener arms assists in expelling the water entrained in the pulp and thus may lower the final dilution of discharge. With certain materials the effect of the rakes is not sufficient and other means have been tried. It was found that by erecting posts 6 in. apart on the thickener arms, and extending them up through the compression zone, the final dilution can be lowered still further. These posts may function two ways. By their slow movement through the pulp they may tend to compress the material and squeeze out the liquid. Also they may form channels through which the free liquid flows upward to a point above the compression level. Recent installations employ V-shaped posts with the point of the V leading. This construction is known as the type G or "picket thickener" type of unit.[22] The picket thickener construction has been applied in a variety of thickening problems.

The oldest method of sedimentation employs intermittent types of settling tanks of any convenient shape. Means are provided for filling the tank with pulp and allowing it to settle quiet, for removing the clean liquor and for removing the thickened sludge. The clear liquor may be

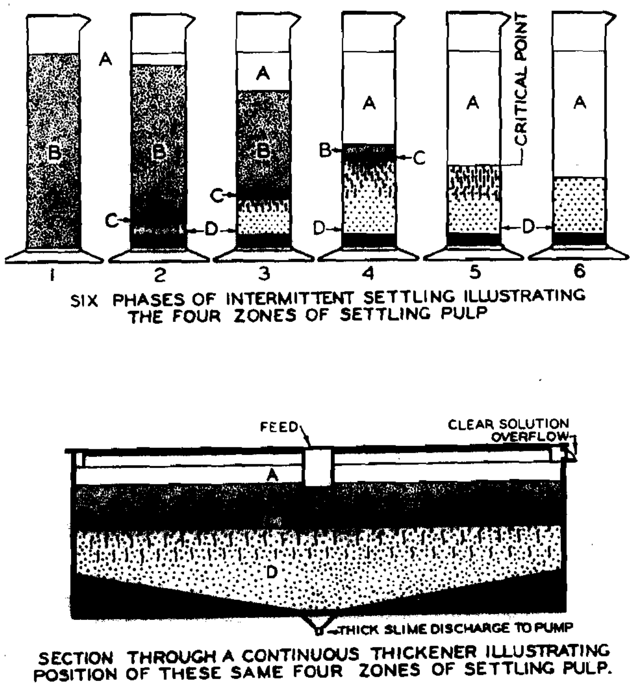

FIG. 3.—SLIME-SETTLING ZONES IN A THICKENER. (*Coe and Clevenger.*[20])
Zone *A*, clear water or solution.
Zone *B*, pulp of feed consistency.
Zone *C*, pulp in transition from *B* to *D* consistency.
Zone *D*, pulp in compression.

drawn off at different elevations, depending upon the time necessary for satisfactory clarification at the drawoff level. The operation necessarily is intermittent but a sufficient number of tanks is employed so that a continuous flow of clear liquor is maintained. These batch tanks have been operated semicontinuously by feeding and overflowing at the same time until filled with settled solids, after which feeding is stopped and the sludge discharged.

Continuous methods for the sedimentation of slimes were developed in the metallurgical industry, especially with the introduction of all-slime treatment of gold and silver ores by cyanide. The continuous operation first employed cones from which settled solids were discharged by gravity at the bottom. Sludge-detention time was controlled by an orifice or valve. Cones cannot be built in large sizes and their use requires a multiplicity of units. Furthermore, most slimes tend to build up on the sides of the cone, causing irregular flow to the apex and making it difficult to maintain a uniform sludge discharge.

Dr. J. V. N. Dorr first conceived the idea of using a flat-bottomed tank equipped with a slowly revolving mechanism having means for moving the settled sludge to a central point of discharge. By using a mechanism of this type, it is possible to go to very large diameters and to obtain a uniformly thick discharge sludge. In order to develop more uniform control of the underflow, sludge pumps were developed for use in place of orifices and valves originally employed.

Fig. 3 is a diagrammatic cross section of a unit-type thickener, illustrating the pulp condition during continuous feed and discharge. Zone *A* is clear liquid, zone *B* is pulp in independent particle subsidence and in collective subsidence, zone *D* is pulp in compression, and *C* is a transition zone between *B* and *D*. Normally zone *B* will be pulp in collective subsidence having the dilution exhibiting the largest area figure for *A* in the equation for unit-area calculations given above. Collective subsidence zones will exist above and below this limiting dilution but they will not occupy any appreciable depth in the thickener. When a thickener is overfed, zone *B* builds up rapidly and zone *A* may disappear. The thickest underflow is obtained with the greatest effective depth of compression pulp. It is customary, therefore, where a thick sludge is required, to carry the pulp line as high as possible. This may be to within 18 to 24 in. of the overflow level.

EQUIPMENT

The importance of proper mixing at the point of flocculant addition to the plant circuit cannot be too strongly emphasized. The objective at this stage of the treatment process is to destroy the stability of the slurry by obtaining a uniform distribution of the flocculant in the shortest possible time. When special mixing devices are employed for this purpose, their strongly agitating effect should cease as soon as uniform distribution is accomplished. That is, the detention time in the continuous mixing chamber should be just sufficient to permit uniformity of distribution of flocculant in the system. The unstable slurry or slime should then be subjected to treatment promoting floc growth. Violent agitation beyond the short time necessary for distribution of flocculant may be harmful.

Several methods and types of apparatus are recommended for the rapid and uniform mixing of the flocculant in the system to be treated. Turbomixers are used to a great extent. Earlier methods employed baffled launders, which are still in fairly general use. Mixers employing paddles are also in use, which serve the double purpose of mixing and agitation to produce flocs.

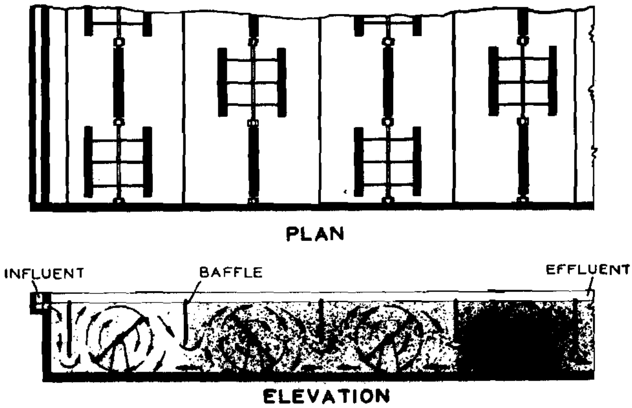

FIG. 4.—PADDLE-TYPE FLOCCULATOR (DORR CO.).

The rate of floc formation is a function of the probability of collision between suspended particles, and with concentrated slurries and slimes

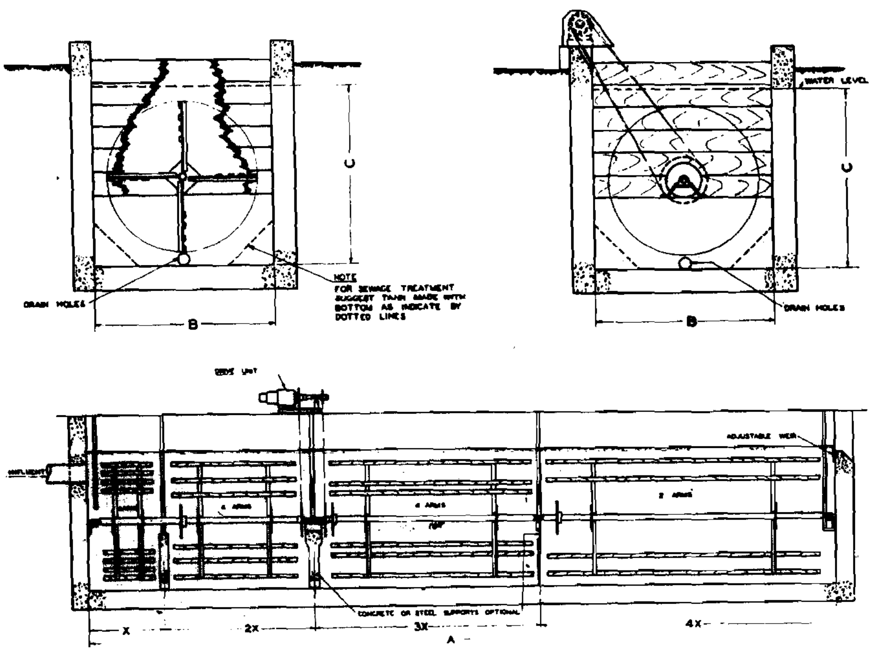

FIG. 5.—PADDLE-TYPE FLOCCULATOR (JEFFREY MANUFACTURING CO.).

the material may be fed directly to clarifiers, since flocculation may take place in a few seconds after they enter the clarification unit. With dilute slurries, the process often may be made economical only by subjecting the material to a gentle agitation step between flocculant mixing and clarification. This is the so-called mechanical flocculation step and is concerned with the probability of collision between units of the suspended

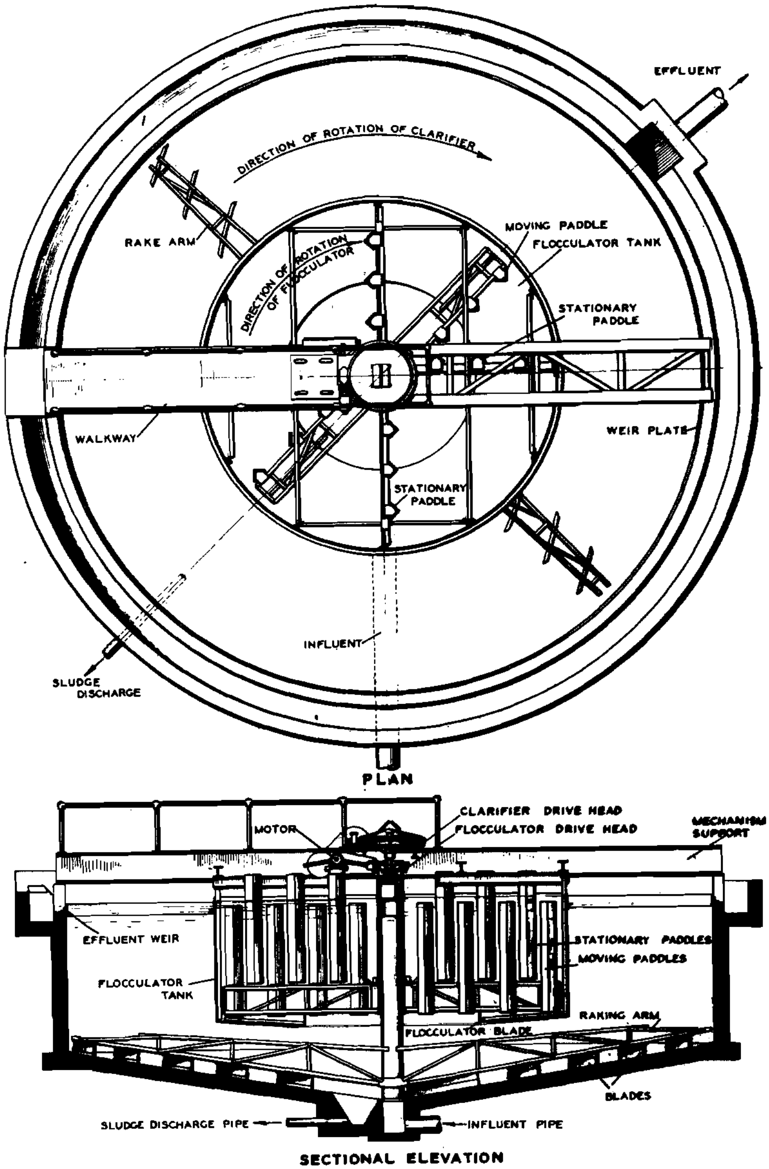

FIG. 6.—COMBINATION MACHINE FOR FLOCCULATION AND CLARIFICATION (DORR CO.).

solids. The slow movement of paddles through the suspension promotes a large increase in the number of collisions per unit of time between the particles and reduces flocculation time accordingly. Figs. 4 and 5 illustrate available units employed for this purpose between the mixing and clarification steps in the treatment process. Fig. 6 illustrates a combination machine designed to carry out two steps in one unit; that is, flocculation followed by sedimentation of the flocculated solids.

The most desirable conditions in classifying a coal slurry or sludge are those which emphasize the effect of differences in specific gravity of the

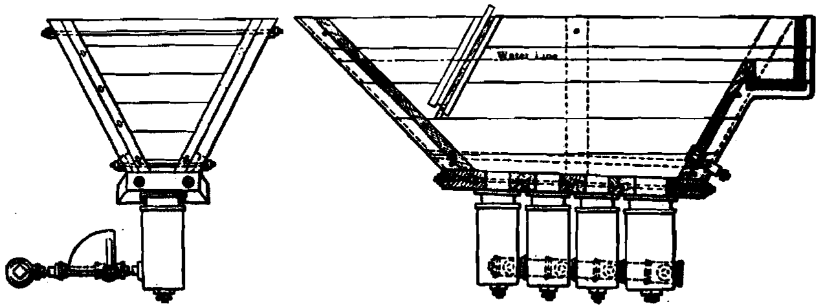

FIG. 7.—RICHARDS HINDERED-SETTLING CLASSIFIER (ALLIS-CHALMERS MANUFACTURING CO.)

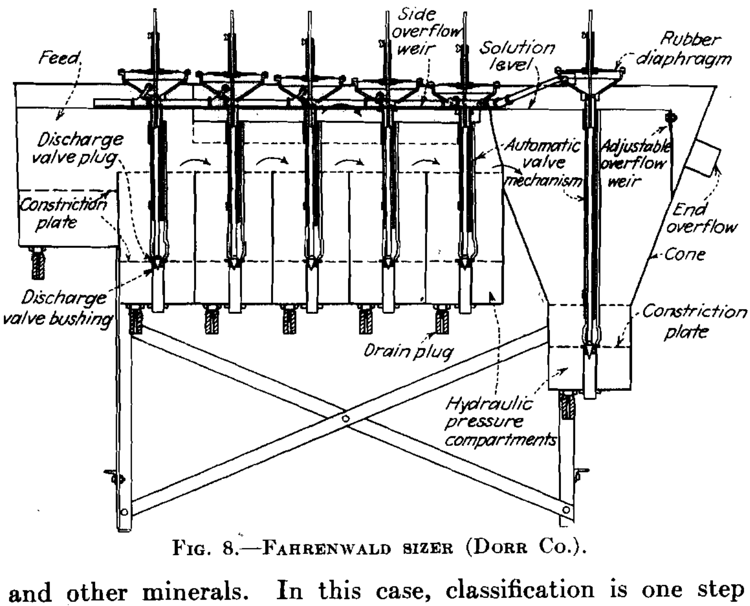

FIG. 8.—FAHRENWALD SIZER (DORR CO.).

coal and other minerals. In this case, classification is one step in a process designed to sort the low-gravity coal substance away from the higher-gravity bone and slate. These conditions may be realized by treating as dense a suspension as possible so that hindered-settling effects rather than independent particle-subsidence effects predominate. Size effects cannot be entirely eliminated, of course.

A number of hindered-settling hydraulic classifiers are available. Representative of the type are the Richards, the Deister, and the Fahren-

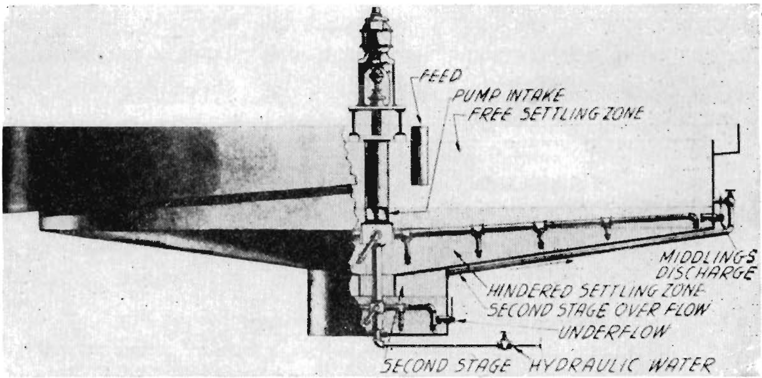

FIG. 9.—HYDROTATOR CLASSIFIER (WILMOT ENGINEERING CO.).

wald. These machines have a series of chambers over which the feed flows. Each chamber is equipped with a source of hydraulic water and a discharge device.

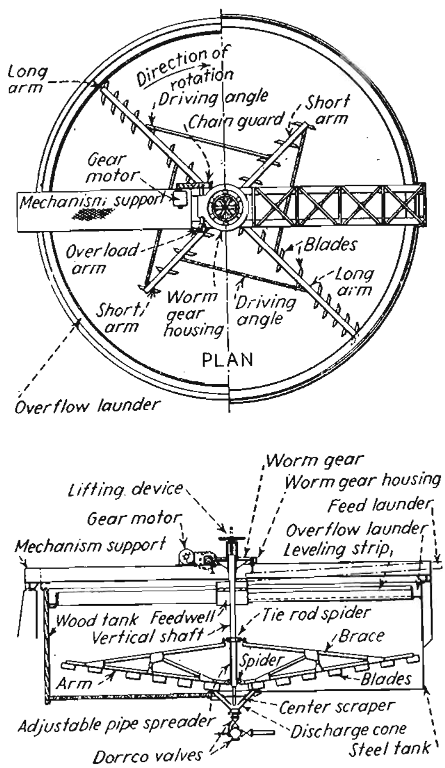

FIG. 10.—HYDROSEPARATOR (DORR CO.).

The Richards classifier (Fig. 7) has cylindrical sorting columns. The hydraulic water is fed from below into the columns and from these into inner conical columns through tangential and radial ports.

The Fahrenwald sizer (Fig. 8) consists of a tank fitted with five rectangular classifying pockets and one cylinder pocket. It has an improved means for spigot discharge, which is entirely automatic. Each pocket yields a spigot product gradually decreasing in size from the first rectangular pocket to the last or the cylindrical pocket.

The Hydrotator classifier (Fig. 9) embodies a hindered-settling zone near the bottom supplemented by a zone at the top in which the particles settle independently. The unit illustrated is designed primarily for coal cleaning.

The problem of preparing a relatively high-grade fine-coal slurry is a complicated one involving both size distribution and gravity distribution.

These variables limit the extent to which the machines illustrated are able to carry the purification process and still obtain a reasonable yield of cleaned product, based on theoretical float-and-sink tests. Recent developments indicate that the best solution to a cleaning problem may be found in methods that practically eliminate the effect of both gravity and size within the size limits defined for a coal slurry,[23] by froth-flotation methods.

If the problem is one of desliming a coal slurry, nonhydraulic or sizing classifiers of various constructions may be employed. In the non-

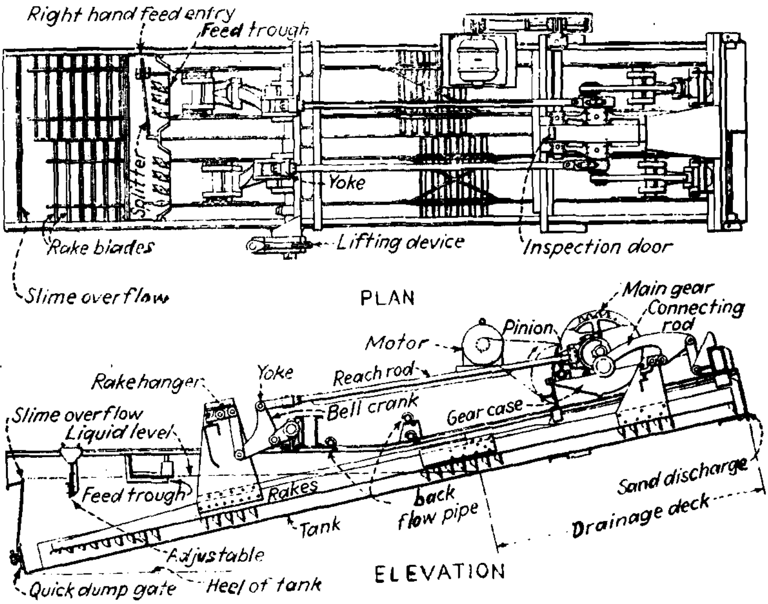

FIG. 11.—DORR RECIPROCATING RAKE CLASSIFIER.

mechanical types the feed flows across the surface, the coarse material settling while the slimes overflow. The settled solids are raked continuously toward a central discharge point, by means of a revolving mechanism. This type, shown in Fig. 10, has been employed rather extensively as one step in treating coal slurry. The nonhydraulic mechanical classifiers have inclined tanks with the upper end open. The settled material is scraped up the sloping bottom by means of reciprocating rakes (Fig. 11), a revolving spiral or helix (Fig. 12), or by drags attached to an endless belt. The machines mentioned constitute only a few of the various types employed in processing suspensions of solids dispersed in water.

When the problem is one of clarification and thickening to overflow clear water and discharge a pulp of high solids content, the practice is first to flocculate the suspended solids. This is accomplished, as previously outlined, by adding suitable flocculants and, where desirable, subjecting the unstable system to gentle agitation. Following this treatment, the flocculated solids are permitted to settle continuously in equipment designed for this purpose. The "clariflocculator" (Fig. 5) is a combination machine, recently developed, which is highly suitable for

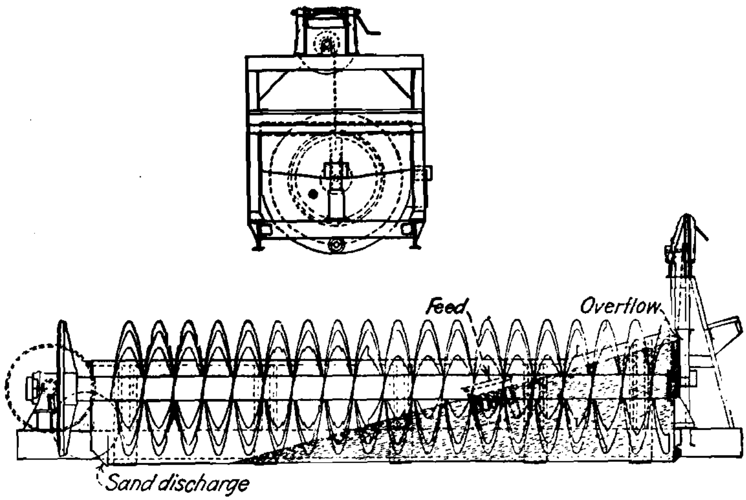

FIG. 12.—AKINS REVOLVING SPIRAL CLASSIFIER (COLORADO IRON WORKS CO.).

application to the problem, both for initial flocculation and final clarification and thickening.

Other thickeners and clarifiers are available. The Dorr traction thickener shown in Fig. 13 is widely used. Multiple tray units are applicable, the "multifeed" tray type constituting the most recently

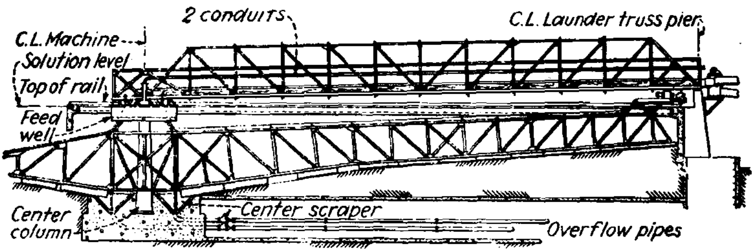

FIG. 13.—TRACTION THICKENER (DORR CO.).

developed machine of this type for treating flocculated suspensions. The latter is so designed that separate channels are provided for feed and thickened pulp, so that no mixing with original feed and resuspension of the thickened solids can take place.

In the operation of the Hydrotator thickener (Fig. 14), the feed enters near the center of the unit. The thickened product is discharged at the bottom and the clarified water is overflowed at the top. At an intermediate level in the tank the pump suction withdraws a portion of the fluid material and reintroduces it through the pipe nozzles at the bottom of the sludge zone. The reactive force of the water through the nozzles causes the supporting arms to rotate so that rising currents are uniformly distributed over the entire tank area. The thickened pulp is maintained in a state of fluid suspension and flows to the discharge point without the aid of mechanical rakes. The clarified water should be overflowed at a rate that will keep the upward current in the clear zone not greater than the settling velocity of the finest particles that are to be removed.

When the feed is delivered as shown, it enters the thickened sludge zone without eddy currents. The thickening process normally delivers the coarsest products to the bottom first with the finest particles toward

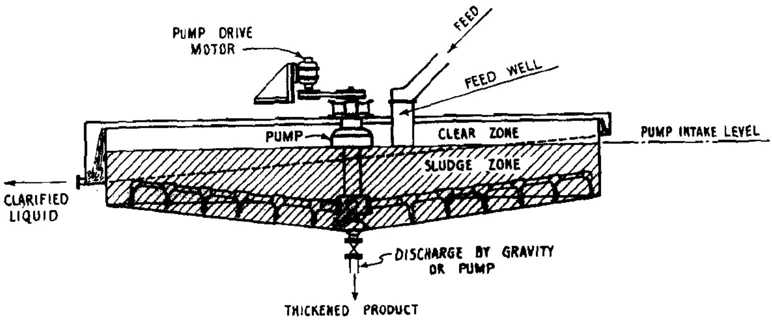

FIG. 14.—HYDROTATOR THICKENER.

the top. The pump suction at the top of the sludge zone gathers the finer particles and they are then delivered at the bottom of the sludge zone to encounter a self-filtering action of the previously thickened material.

After the solids have reached a specific concentration dependent on size and specific gravity of the particles, a "compacted" condition will exist in which classification will cease and the sludge zone will tend to become uniform from top to bottom.

In addition to the references listed, manufacturers' bulletins are available that outline the action and applications of the machines discussed in considerably more detail.

WATER TREATMENT

The basic principles of water treatment are thoroughly embodied in the sections dealing with flocculation and sedimentation. However, for emphasis, the subject of water treatment as related to coal preparation is dealt with separately.

At the present time, and probably to an even greater extent in the future, the mine operator must consider methods of water treatment designed to satisfy two possible objectives: (1) the preparation of a satisfactory water for utilization in the coal-cleaning plant; (2) the treatment of waste water from the plant so that the quality of that discharge to streams will meet certain specifications as to clarity and other properties. Obviously, the more water recirculated in the plant circuit, the less attention necessary to the second objective listed.

Water for coal preparation may be obtained from any or all of the following sources: (1) surface streams, (2) dams or sumps used to collect surface drainage, (3) mine water, (4) deep wells.

Water from deep wells generally requires no special treatment for use in the preparation plant. The extent of the treatment necessary for water from surface streams and surface drainage will be governed by the degree and nature of contamination of such waters. Mine water generally must be treated to neutralize the relatively high acid content developed. The analysis of a typical anthracite water is given in Table 5.

TABLE 5.—*Analysis of Anthracite Mine Water*

Impurity	Parts per Million	Impurity	Parts per Million
Total acidity as H_2SO_4	603	FeO	70
Free H_2SO_4	10	CaO	494
Total solids	3,548	MgO	445
Silica	650	Sulphuric anhydride	1,871
Al_2O_3	115	pH value	4.3
Fe_2O_3	91		

The addition of 4.8 lb. of hydrated lime per 1000 gal. to a water having the analysis given in Table 5 destroys the acidity and renders it suitable for use in a breaker. Aluminum and iron hydroxides and calcium sulphate precipitate and may be removed by flocculation and sedimentation if desired. However, these solids generally are permitted to remain in the plant circuit, constituting a part of the slimes that build up during an operating day.

Good practice in wet cleaning plants, where the pH of make-up water varies from 4.0 to 6.5, is to maintain a pH in the plant circuit of from 8.0 to 8.5. This is accomplished by the use of lime or soda ash, and the quantity of such chemicals required is entirely a function of the acidity of water. It averages about 5 lb. lime, or an equivalent quantity of soda ash, per 1000 gal. of make-up water.

The use of corrosion inhibitors is being investigated and considerable success has been attained. The basis is the tendency of stable oil-in-water emulsions to break at metal surfaces and selectively wet the latter with oil. This is still in the development stage, but successful use of such inhibitors seems assured.

The treatment necessary to satisfy the first objective listed above is primarily one of pH adjustment, and the preparation of a clear water is not an essential part of the process. However, if the objective becomes one of treating breaker water so that all waste water discharged is clear and free from polluting substances, the problem becomes somewhat more complicated. To satisfy this objective, complete treatment is essential and such a process is outlined briefly. It is assumed that no bacteriological treatment is necessary to produce a water suitable for discharge to streams.

The flowsheet of Fig. 15 shows a treatment process taking waste water carrying the slimes from the various preparation steps to a final clear water. The outline is suggestive only, but it includes the principal operations involved. Manufacturers of equipment designed to carry out

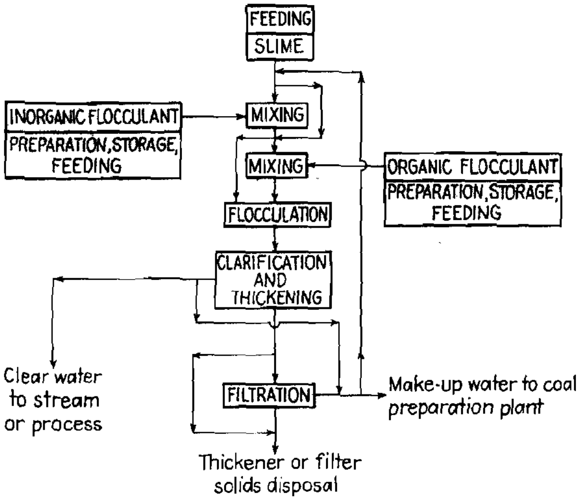

FIG. 15.—WASTE-WATER TREATMENT.

the various steps should be consulted for detailed recommendations. Usually it is necessary to submit adequate and representative samples for special analyses, so that design data may be developed. Information on quantities to be treated and dilutions should accompany the samples.

Inorganic flocculants may be fed as dry salt or in solution of suitable concentration. Organic flocculants are fed as solution prepared according to directions previously outlined. Two coagulant-mixing steps are indicated, but the use of one or two steps would be based upon fluocculation tests.

A filtration step after thickening is indicated. The use of such a step would depend upon the ability to thicken the flocculated slimes and finally dispose of the resultant sludge.

REFERENCES

1. J. D. Sisler, T. Fraser and D. C. Ashmead: Anthracite Culm and Silt. Pennsylvania Geol. Survey, Fourth Series (1928) *Bull.* M-12.
2. R. F. Stewart and E. J. Roberts: The Sedimentation of Fine Particles in Liquids. *Trans.* Inst. Chem. Eng. (1933) **11**, 124–137.

3. H. von Helmholtz: *Wied. Ann.* (1879) **7,** 337.
4. C. Gouy: De la Charge Electrique à la Surface d'un Electrolyte. *Jnl. de Physique* (1910) **9,** 457–468.
5. H. Freundlich: Kapillarchemie, Ed. 4, **1,** 356 ff. Leipzig, 1930. Akad Verlags-Ges.
6. Hanser: Colloid Phenomena. New York, 1939. McGraw-Hill Book Co.
7. E. J. Roberts: Colloidal Chemistry of Pulp Thickening. *Trans.* A.I.M.E. (1934) **112,** 178–188.
8. R. A. Henry: Belgian Patent 351967 (July 31, 1928); U. S. Patent 1862265 (June 7, 1932).
9. W. E. Raybould: The Conditioning of Washery Water: Flocculation. *Trans.* Inst. Min. Engrs. (1934) **88,** 194–229.
10. J. O. Samuel: Some Aspects of Flocculation. *Chem. und Ind.* (1936) **14,** 669–680. Theoretical and Commercial Aspects of Flocculation. *Chem. Age* (London) (1938) **38,** 201–203.
11. E. T. Wilkins: Sensitization and Other Observations on Slurry Flocculation. *Jnl.* Soc. Chem. Ind. (1935) **54,** pt. 1, 391T–393T.
12. L. W. Needham: Settling of Fine Coal in Water. *Coll. Guard.* (1930) **141,** 124–128; Collection and Treatment of Washery Slurry. *Coll. Guard.* (1931) **143,** 2044–2046, 2133–2134. See also *Iron and Coal Trades Rev.* (1931) **123,** 907; .Treatment of Washery Water Practical Aspects of Flocculation. *Coll. Guard* (1936) **153,** 191–197.
13. C. W. H. Holmes: The Clarification of Washery Water. *Coll. Engr.* (1935) **12,** 40–42, 58, 79–82, 133–135; The Riddle of the Slimes. *Coll. Engr.* (1937) **14,** 399–402.
14. E. Tomalin: Flocculation of Coal Slurries. *Jnl.* Soc. Chem. Ind. (1937) **56,** pt. 1, 384T–389T; (1938) **57,** 175–179.
15. G. R. Gardner and K. B. Ray: Flocculation and Clarification of Slimes with Organic Flocculants. *Trans.* A.I.M.E. (1939) **134,** 146–165.
16. Stokes: Mathematical and Physical Papers, **2,** 10; **3,** 56. Cambridge Univ. Press, 1880.
17. Bingham: Fluidity and Plasticity, 55, 216, 231. New York, 1922. McGraw-Hill Book Co.
18. A. M. Gaudin: Principles of Mineral Dressing, 165–198. New York, 1939. McGraw-Hill Book Co.
19. Dodge and Thompson: Fluid Mechanics. New York, 1937. McGraw-Hill Book Co.
20. H. S. Coe and G. H. Clevenger: Methods for Determining the Capacities of Slime-settling Tanks. *Trans.* A.I.M.E. (1916) **55,** 356–384.
21. W. A. Deane: Settling Problems. *Trans.* Amer. Electrochem. Soc. (1920) **37,** 71–100.
22. U. S. Patent 1938894.
23. U. S. Patent 2226170.
24. R. H. Richards and C. Locke: Textbook of Ore Dressing. New York, 1940. McGraw-Hill Book Co.
25. R. H. Richards: Ore Dressing, I to IV. New York. McGraw-Hill Book Co.
26. A. F. Taggart: Handbook of Mineral Dressing. Revised Edition (to be published). New York. John Wiley and Sons.