FINAL REPORT
September 1, 1986 through August 31, 1987

Project Title: Improvements in Fundamental Understanding of Foam and Flotation Separations of Fine and Ultrafine Coals

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Project Coordinator: Professor John C. Slattery, Department of Chemical Engineering, Northwestern University, Evanston, Illinois 60208

Other Investigators: Professor Joseph A. FitzPatrick, Department of Civil Engineering, Northwestern University, Evanston, Illinois 60208

ABSTRACT

Three related tasks were proposed that are relevant to the design of flotation processes for the separation of Illinois coal from ash and pyrite.

We have completed an initial algorithm to be used for the design of staged columns. The analysis has already suggested interesting aspects of staged column operation to obtain high-grade products, but it will require experimental testing. An experimental program has been outlined, and the construction of the required experiments has been initiated. Two alternative experimental devices to determine the complete contact curve have been constructed and testing of these has begun. Plans have commenced to build a multistage column simulator. These experiments will guide further refinement of our approach.

We have completed an initial analysis of bubble-particle interactions, and we have been able to draw several qualitative conclusions regarding stage efficiency and selectivity in staged flotation columns. This portion of the project has been terminated as the result of a lack of funds. A paper describing our results is currently being prepared.

We have completed an initial analysis of the stability and drainage of a foam containing no solids as well as the initial comparisons of this theory with available experimental data. This will form the basis for a new analysis for the drainage and stability of a foam created from a suspension. We hope to use this new theory to simulate the pseudo-equilibrium curves required for the design of staged flotation columns.

EXECUTIVE SUMMARY

We have proposed three tasks that are relevant to the design of flotation processes for improved separation of ash and pyrite from Illinois coals.

TASK 1: A NEW APPROACH TO THE DESIGN OF FLOTATION COLUMNS

We have developed an initial algorithm for the design of staged flotation columns to be used for the separation of ash and pyrite from coal. It allows us to describe the compositions of the coal concentrate and of the tailings as functions of several variables: gas flow rate, feed flow rate, composition of the feed, location of the feed, recycle (rate at which coal concentrate and solution are returned to the top of the column), tray efficiency, and the characteristics of the pseudo-equilibrium relationship.

A major review of the assumptions made in this approach awaits experimental corroboration.

We have designed and begun testing a prototype cell designed to allow us to measure the pseudo-equilibrium curve required for the design of staged flotation columns; redesign and construction of a more appropriate device will follow soon. A series of pseudo-equilibrium experiments using the coal-ash mixture at various solids fractions, pulp volumes, and reagent doses will be performed in a single stage device simulating the conditions to be found on a stage of a flotation column. These tests will yield the desired pseudo-equilibrium curve for that specific coal at given pulp densities and flow rates.

Once a pseudo-equilibrium curve is determined, under certain conditions we may use a graphical analysis (similar to the McCabe-Thiele analysis for binary distillation) for aspects of scaleup and design.

We have examined two aspects of the economics of staged flotation columns compared with standard mechanical cells: the use of reagents and the plan area required for the equipment.

> Staged flotation columns use reagents more efficiently than do standard mechanical cells, since the same reagents pass through each stage. Frequently in applications with standard mechanical cells, reagent is added at each stage.
>
> Compared with standard mechanical cells operated in stages, staged floatation columns make a more effective use of available plan area, when the requirement is to produce a very clean coal concentrate.

TASK 2: ATTACHMENT OF COAL PARTICLES TO AIR BUBBLES

We have completed the initial phase of our analysis of selective coalescence in which we have been extending our prior studies to the case of a thin film formed between a bubble and a much smaller solid particle.

If in these analyses the electrostatic double-layer forces and the London-van der Waals forces in the thin film between the bubble and the solid particle combine to produce a strong positive disjoining pressure, no coalescence will occur and the solid particle will be rejected. This is the desired result with a particle of pyrite or ash.

If the electrostatic double-layer forces are weak but nonzero, they will combine with the London-van der Waals forces to produce a secondary minimum in the potential describing the sum of these forces. Coal particles can be trapped in this secondary minimum without coalescing with the air bubbles. Depending upon the magnitude of this secondary minimum, the resulting attachment may not be sufficiently strong to withstand the turbulent forces in the suspension. It is desirable for a strong negative disjoining pressure to be created in the thin film between an air bubble and a coal particle.

We have been able to draw several qualitative conclusions. In order to enhance the stage efficiency of a flotation column,

> the viscosity of the suspending phase should be as small as possible
>
> the density of the suspending phase should be as small as possible
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> the particle diameter should be as small as possible
>
> the bubble diameter should be as small as possible
>
> turbulence should be minimized consistent with good contact

In order to enhance selectivity in the flotation column,

> any surfactant added to the system should maximize both the negative disjoining pressure between the coal particles and the bubbles and the positive disjoining pressure between the ash particles and the bubbles, while minimizing the reduction in the (liquid-gas) surface tension.

Because of a lack of funds, this work will not be continued under the new contract, but a paper describing our analysis and detailed results is being prepared.

TASK 3: STABILITY OF A FOAM CREATED FROM A SUSPENSION

The complexity of the structure of lamellae draining into Plateau borders in a foam make this a difficult problem. For the case with which we are concerned here, the structure is made all the more complex by having the foam created from a suspension.

Our approach has been to begin by attempting to better understand a foam having no entrained solids. We have completed an initial analysis as well as an initial comparison with available available data. The results are satisfactory, indicating that we have a sufficient basis upon which to construct a new analysis for the stability and drainage of foams created from suspensions.

We hope to use this new analysis to simulate the pseudo-equilibrium curves that we will be measuring as part of Task 1. In this way, we hope to gain a better understanding of the manner in which various parameters affect the stage efficiency of flotation columns.

OBJECTIVES

The objective of this project has been to improve the fundamental understanding of flotation processes, in order that they may be designed and operated to achieve maximum cleaning of fine and ultrafine coals. We have sought both to enhance our understanding and modeling of governing mechanisms and to take advantage of proven concepts for the design of staged columns.

This project has consisted of three related tasks that are relevant to the design of flotation machines for separation of coal from undesirable minerals.

TASK 1: A NEW APPROACH TO THE DESIGN OF FLOTATION COLUMNS

Our first objective has been to extend the traditional methods used in the design, scale-up, and control of distillation, gas adsorption, and liquid-liquid extraction columns to the design, scale-up, and control of staged flotation columns.

TASK 2: ATTACHMENT OF COAL PARTICLES TO AIR BUBBLES

Our second objective has been to study the drainage and stability of the thin films formed between small bubbles and small solid (spherical) particles as they are brought into contact.

TASK 3: STABILITY OF A FOAM CREATED FROM A SUSPENSION

Our third objective has been to discuss the interacting effects of surface tension, the two surface viscosities, bubble size, the strength of the London-van der Waals forces, the strength of the electrostatic forces, bubble diameter, and the densities of the three phases upon the drainage and stability of a foam created from a suspension. The foams created should be neither too stable nor too unstable for the proper operation of staged flotation columns.

INTRODUCTION AND BACKGROUND

Since the background for each of our tasks is somewhat different, they will be discussed separately.

TASK 1: A NEW APPROACH TO THE DESIGN OF FLOTATION COLUMNS

Vertical flotation columns have been proposed and are currently being tested for refining a variety of minerals (Dobby and Finch 1985; Yang 1984; Parkinson 1986). These may be used advantageously in cleaning coal, separating finely ground coal from ash and minerals containing sulfur, since they are reported to be much more efficient than the traditional agitated vessel. Yang (1984) reports that eight traditional stages were required to accomplish the same separation that he was able to achieve with one packed column.

Little has been written about the methods to be used in the design, scale-up, and control of flotation columns (Dobby and Finch 1985; Yang 1984). In Yang's (1986) current work, column scale-up is considered to be direct, because residence times are expected to be nearly those expected in a plug flow. Experience to date suggests that the relatively sophisticated control of these columns is required (Parkinson 1986). Much can be learned from adapting the methods that have been well established for design, scale-up, and control of columns used for distillation, gas adsorption, and liquid-liquid extraction (Sherwood et al. 1975; Coulson et al. 1978; Geankoplis 1978; Treybal 1980; Welty et al. 1984), because there is an important similarity with flotation. Distillation, gas adsorption, and liquid-liquid extraction are used to separate molecular species by concentrating them in separate phases; flotation is used to separate mineral particles by concentrating them with different phases. But there are important differences as well. Until recently, coal and other minerals were typically ground too coarsely to be used in packed or staged columns without serious plugging problems.

Distillation, gas adsorption, and liquid-liquid extraction operations were first conducted in single stages (single contacts in which equilibrium is approached) and later in two or more stages connected counter-currently. These multiple stage operations were gradually replaced by columns, both because columns were easier to control and because columns were cheaper to build.

There are two different types of columns that are used for distillation, gas adsorption, and liquid-liquid extraction: packed columns and staged columns constructed of regularly-spaced slotted trays or trays of bubble-caps. The packing or trays are designed to promote highly agitated, intimate contact of the two phases and to enhance the rate of mass transfer.

Somewhat different approaches are taken in designing these two types of columns (Sherwood et al. 1975; Coulson et al. 1978; Geankoplis 1978; Treybal 1980; Welty et al. 1984). In the design of staged columns, it is assumed that equilibrium is approached in each stage, subject to some empirical efficiency factor that depends upon flow rates, physical properties of the phases, and the particular design and spacing of the trays. In the design of packed columns, there is never equilibrium. The rate of mass transfer at each axial position is the primary concern, and it is described empirically in terms of a mass transfer coefficient.

Historically, staged columns were in common use long before packed columns, in spite of the fact that packed columns are generally cheaper to construct. (Packed flotation columns may be an exception. The stylized packing required to avoid plugging may be comparable in cost to the expense of constructing stages.) At least one reason for this is that staged columns could be largely designed on the basis of bench-scale, equilibrium experiments. Packed column designs require rate data typically obtained in studies of pilot-scale columns.

There are two types of columns that have been proposed for flotation to date: relatively open columns and packed columns (Parkinson 1986). It is possible that staged columns should be considered as well. These three types of columns differ in the manner in which intimate contact between the air and slurry phases is promoted. They also differ in the design methods used.

Dobby and Finch (1985) have given an initial discussion of the scale-up of relatively open flotation columns.

There has been no detailed discussion of the design of packed flotation columns. The scale-up of packed columns proposed by Yang (1984) is semiempirical. This may be attributable to his focus on using regrinding and additional reagents in the reflux streams.

There has been no detailed discussion of the design of staged flotation columns. However, Dell has a patented design for a multistage froth flotation device (Dell and Preece 1980). The method of controlling it is not practical for coal applications.

TASK 2: ATTACHMENT OF COAL PARTICLES TO AIR BUBBLES

A flotation separation of coal from undesirable minerals begins with the coal being finely ground and dispersed in a dilute aqueous solution of surfactant. In a standard flotation cell or open column, a bubble rises through the suspension and is brought into close contact with the particles in the suspension. As a foam rises through a staged flotation column filled with this suspension, it is broken and reformed at each successive stage with fresh bubbles being formed and brought into close contact with the particles. As a foam rises through a packed flotation column, it is continuously being broken and fresh bubbles created. One purpose of the surfactant is to enhance the attachment of coal particles to these fresh bubbles and to retard the attachment of the undesirable minerals. The surfactant is also used to control the stability of the foam. In both staged columns and packed columns, the foam must be sufficiently unstable to permit it to be broken and reformed, but it must be sufficiently stable to transport coal particles up the column to create an enriched product.

Only those particles that by agitation are brought into close proximity of the bubbles for a sufficiently long period of time are eligible for attachment (Schulze 1984; Dobby and Finch 1986a,b,c).

When as the result of mixing a solid particle is brought into close contact with an air bubble for a sufficiently long period of time, a thin film forms between them (Schulze 1984). There may be a combination of electrostatic (short-range, repulsive) forces and London-van der Waals (longer-range, either attractive or repulsive) forces acting between the air bubble and the solid particle.

If the London-van der Waals forces are repulsive, a solid particle will not be attached to the air bubble. Let us therefore assume that the London-van der Waals forces are attractive.

If the balance between the repulsive electrostatic forces and attractive London-van der Waals forces is struck when the thin film is too thick, the solid particle will be easily detached from the air bubble, since the attractive forces will be relative weak.

If the film is sufficiently thin when this balance is struck, the solid particle will be held in close association with the air bubble by the relatively strong, attractive, London-van der Waals forces.

If the electrostatic forces are sufficiently weak or absent, the film will continue to thin, until an instability forms, coalescence occurs, and the solid particles are strongly attached to the air bubbles.

The purpose of the surfactant system is to create relatively strong, repulsive (electrostatic double-layer) forces between the particles of undesirable minerals and the air bubbles and if possible to enhance the attractive (usually London-van der Waals) forces between the coal particles and the air bubbles.

Little attention has been given in the literature to this detailed mechanism for selectivity in flotation processes.

TASK 3: STABILITY OF A FOAM CREATED FROM A SUSPENSION

As a foam rises through a staged flotation column, it must be broken and reformed at each successive stage, creating in this way fresh bubbles. In a packed flotation column, the foam must be continuously broken and reformed. In both cases, if the foam is too stable, fresh bubbles can not be formed. If the foam is too unstable, coal particles will not be transported up the column to produce an enriched product.

When the air bubbles with their associated coal particles reach the surface of the suspension in a flotation column or in a single-stage, agitated, flotation vessel, they create a foam. The foam must be sufficiently stable so as to prevent the loss of cleaned coal to the mixed suspension below.

To our knowledge, there have been no experimental or theoretical studies of the drainage and stability of a foam created from a suspension. Consequently, let us focus for the moment on foams that do not contain solids.

foam structure

There are two limiting classes of foams.

Wet foams consist of spherical gas bubbles that are closely packed in the continuous liquid phase. The liquid volume fraction is greater than 0.26.

Polyhedral or *dry* foams have liquid volume fractions much less than 0.26. They consist of polyhedral bubbles. The films separating the bubbles are known as *lamellae*; the lamellae intersect in *Plateau borders*. A polyhedral foam in a stable structural configuration will consist of Plateau borders formed from three films meeting at angles of 120°.

foam drainage

The foam created by bubbling gas bubbles through a surfactant solution in a column will consist of roughly two regions. In the region adjacent to the liquid pool from which the foam is being created, the foam is wet (a closely packed structure of spherical air bubbles). As the foam moves up the column, gravity causes it to drain. When the foam has moved sufficiently far up the column, it has become polyhedral or dry as the result of drainage.

In this column, liquid is carried up as the result of entrainment with the bubbles, while gravity causes the liquid to drain back into the liquid pool. The relative rates of these two processes determines the liquid volume fraction as a function of distance from the liquid pool.

The drainage in the spherical foam is presumably much like the flow through a bed of packed spheres, in which the sphere walls may be partially mobile, depending upon the local interfacial tension gradients and the interfacial viscosities.

The drainage in a polyhedral foam is more complex. In this case, liquid drains from the lamellae into the Plateau borders.

Film drainage is driven by several forces. During the formation of films when they are relatively thick, gravity is dominant. Once a film has been formed, the curvature of the Plateau border results in a lower pressure in the border than in the relatively flat film. This effect is known as *Plateau border suction*. Later when the films have become sufficiently thin (<1000 Å) as the result of drainage, London-van der

Waals (attractive) and electrostatic double-layer (repulsive) forces become important.

Once the liquid drains into the Plateau border, it drains out of the foam through the network of borders under the influence of gravity. The flow through a Plateau border depends upon its cross-sectional area and the mobility of its walls.

foam stability

As a foam drains in a column, the lamellae become progressively thinner as the result of the forces described above. The films are thickest in the lower portion of the column, where they have had less time to drain, and thinnest in the upper portion of the column, where they have been draining longer.

If electrostatic double-layer forces are dominant, the films will drain to an equilibrium thickness, creating a truly stable foam.

If attractive London-van der Waals forces are dominant, the films will drain to the point of instability and rupture, resulting in an unstable foam. We speak of a foam in which the liquid drains more slowly from the lamellae and Plateau borders as being *more stable* than one in which the liquid drains quickly.

modeling foam drainage and stability

Numerous models have been developed to describe the drainage of foams.

In all of these analyses, any bulk deformation of the foam has been neglected. In many cases, this appears to be a reasonable assumption, because polyhedral foams exhibit relatively large yield stresses and often flow by slipping on a thin film of liquid adjoining the boundary.

Recent analyses have modeled the foams as an assemblage of regular dodecahedrons. This idealization is not entirely realistic, since regular dodecahedrons pack with a 3% void space and because the angles formed by the intersection of three films is approximately 117° rather than the 120° observed in real foams. However, the dodecahedral structure is a reasonable approximation.

Early models were crude, in that they did not take into account the thinning of the films or the variation of liquid volume fraction with position (Leonard and Lemlich 1965; Haas and Johnson 1967). Later film thinning was taken into account and differential mass balances were solved over the length of the foam column to determine the liquid volume fraction as a function of position (Hartland and Barber 1974; Steiner et al. 1977; Desai and Kumar 1983, 1984; Narsimhan and

Ruckenstein 1986a,b).

The models of Desai and Kumar (1983, 1984) and Narsimhan and Ruckenstein (1986a,b) are similar in the sense that they consider mass balances for the films and borders separately. The film balance equations consider the convection of liquid upward with the bulk movement of the foam as well as the loss of liquid due to film thinning. The Plateau border balance equations take into account the convection of liquid upward with the bulk movement of the foam, drainage under the influence of gravity, and addition of liquid due to drainage from the lamellae.

Desai and Kumar (1982) developed an analysis for the velocity distribution in a Plateau border that was adopted by Narsimhan and Ruckenstein (1986a,b). They represented the border as a duct with a triangular cross-section. The walls of the border were taken to be partially mobile interface, for which the interfacial shear viscosity was known. While other analyses for the flow in Plateau borders exist, most of these consider the border walls to be rigid (Haas and Johnson 1967) or the surface mobility to be governed by an adjustable parameter (Steiner et al. 1977). One exception is that of Leonard and Lemlich (1965), who also include the effects of the surface shear viscosity. While Leonard and Lemlich (1965) consider a somewhat more realistic Plateau border configuration than do Desai and Kumar (1982), the improvement seems unlikely to justify the increased difficulty of their approach.

While the models of Desai and Kumar (1983, 1984) and Narsimhan and Ruckenstein (1986a,b) are similar, there are differences. Desai and Kumar (1983, 1984) consider the Plateau borders to be in some average sense either nearly horizontal (72° to the vertical) or nearly vertical (36° to the vertical), with mass balance equations for each type. The liquid from the nearly horizontal Plateau borders is assumed to drain into the nearly vertical Plateau borders; the films drain into both. In contrast, Narsimhan and Ruckenstein (1986a,b) have only one mass balance for the Plateau borders. They calculate the average drainage rate by considering the Plateau borders to be randomly oriented and the average the drainage velocity over all orientations. In some sense, Desai and Kumar (1983, 1984) appear to have done their averaging first, but the manner in which they did it is not clear.

Desai and Kumar (1983, 1984) and Narsimhan and Ruckenstein (1986a,b) also use different expressions for film thinning. Desai and Kumar (1983, 1984) use a film thinning equation developed by Radoev et al. (1969), while Narsimhan and Ruckenstein (1986a,b) employ one presented by Ivanov and Dimitrov (1974). These two analyses differ primarily in the manner in which the mobility of the surface is taken into account. Both of them include Gibbs-Marangoni effects as a mechanism that decreases surface mobility. Ivanov and Dimitrov (1974) also take the effects of the sum of the surface viscosities into account, and they calculate the critical rupture thickness of the film. Because the critical rupture thickness is incorporated in this manner, Narsimhan and Ruckenstein (1986a,b) can calculate a maximum foam height.

The driving force for film thinning is also different in the two models. Both consider Plateau border suction, Narsimhan and Ruckenstein (1986a,b), because they are concerned with film rupture, also include London-van der Waals attractive forces. Because electrostatic forces are not taken into account, Narsimhan and Ruckenstein's (1986a,b) calculation of maximum film height is limited to non-ionic surfactant systems.

The most recent analysis of Narsimhan and Ruckenstein (1986b) is not limited to a uniform bubble size. A population balance equation allows the evolution of the bubble size distribution to be followed in the column. By including non-uniform bubbles, they are able to incorporate inter-bubble gas diffusion through the lamellae, which is another mechanism for bubble coalescence.

Of the two more realistic developments, only Desai and Kumar (1983, 1984) have compared their results with experimental data. Their comparisons are moderately successful.

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PROCEDURES

Our approach to each of these tasks has been as follows.

TASK 1: A NEW APPROACH TO THE DESIGN OF FLOTATION COLUMNS

We have proposed to extend the traditional methods used in the design, scale- up, and control of distillation, gas adsorption, and liquid-liquid extraction columns (Sherwood et al. 1975; Coulson et al. 1978; Geankoplis 1978; Treybal 1980; Welty et al. 1984) to the design, scale-up, and control of staged flotation columns. In our treatment of staged flotation columns, we have focused on the establishment of a **pseudo-equilibrium** that could be expected to be established during the collection of coal, pyrite, and gangue minerals by bubbles in a single stage (or in a perfectly agitated vessel).

We have begun our studies by examining the design of staged flotation columns. The design of these columns is inherently easier than the design of packed columns, because it largely requires only bench-scale, equilibrium experiments. There are basically four steps: 1) the development of the material balances for the column, 2) the design and conduct of experiments to yield the required pseudo-equilibrium data required by this analysis, 3) the design and construction of a bench-scale, staged flotation column, and 4) the test of our design methods using this column.

TASK 2: ATTACHMENT OF COAL PARTICLES TO AIR BUBBLES

We have studied the drainage and stability of the thin films formed between small bubbles and either solid or liquid-gas interfaces (Lin and Slattery 1982a,b; Chen and Slattery 1982; Chen et al. 1984, 1987; Hahn et al. 1985; Hahn and Slattery 1985, 1986; see also Chen 1984), examining the effects of the surface tension, the two surface viscosities, the bubble diameter, the strength of the London-van der Waals forces, the strength of the electrostatic forces, the viscosity of the continuous phase, and the density difference between the liquid and gas phases. Compared with prior work in this area (see Schulze 1984 for a survey), we are the first to derive expressions for the coalescence time (time during which a bubble rests at an interface before coalescence takes place) that accounts for both the dimpling and the stability of the liquid film and that requires only the diameter of the bubble and the physical properties of the system for evaluation. Our results give the best available descriptions of experimental data.

We have proposed to extend these studies to the drainage and stability of the thin films formed between small bubbles and small solid (spherical) particles as they are brought into contact. As the result of these studies, we have hoped to examine selectivity and stage efficiency in staged flotation columns.

TASK 3: STABILITY OF A FOAM CREATED FROM A SUSPENSION

The complexity of the structure of interconnecting thin films in a foam make this a difficult problem. The structure is made all the more complex by having these thin films composed of a suspension. We have recently used the concept of local volume averaging (Anderson and Jackson 1967; Slattery 1967; Whitaker 1967; Slattery 1972) to develop a new theory for the flow of both neutrally-buoyant and non-neutrally buoyant suspensions (Jiang et al. 1987) that describes the flow of suspensions up to 25% solids with no adjustable parameters (Kim et al. 1987). We proposed to do a further local volume average of these equations, in order to be able to discuss the drainage of a foam created from a suspension.

In local volume averaging the equations for the suspension, information about the physical system will be lost, which can be replaced either by empirical data correlations or through the use of an idealized model for the local structure of the flow field. We took this latter approach in our discussion of suspensions (Jiang et al. 1986), and we have proposed to use it again here. Our local structural model will be based upon the drainage and stability of films into a network of plateau borders. It is an idealization of the drainage seen in the interconnecting lamellae of a foam.

We hope in this way to be able to discuss the interacting effects of surface tension, the two surface viscosities, bubble size, the strength of the London-van der Waals forces, the strength of the electrostatic forces, bubble diameter, and the densities of the three phases upon the drainage and stability of a foam created from a suspension. Assuming that we are successful, we expect to be able to use the results to simulate the pseudo equilibrium that would ideally be established on each stage of our flotation column.

RESULTS AND DISCUSSION

TASK 1: A NEW APPROACH TO THE DESIGN OF FLOTATION COLUMNS

We have developed an initial algorithm for the design of staged flotation columns to be used for the separation of ash and pyrite from coal. It allows us to describe the compositions of the coal concentrate and of the tailings as functions of several variables: gas flow rate, feed flow rate, composition of the feed, location of the feed, recycle (rate at which coal concentrate and solution are returned to the top of the column), tray efficiency, and the characteristics of the pseudo-equilibrium relationship.

Our initial analysis has been revised in order to examine a limiting case that can be applied graphically using the complete contact or pseudo-equilibrium curves that we will be measuring. Referring to Figure 1, the enriching operating line is the mass balance in the section of the column above the feed where the coal concentrate being carried by the foam is enriched as it moves up the column. The stripping operating line is the mass balance for that portion of the column below the feed, where the suspension is stripped of coal as it moves down the column. The ideal number of stages (assuming that pseudo-equilibrium is attained on each stage) can be stepped off between the complete contact curve and the operating lines. A major review of the assumptions made in this approach awaits experimental corroboration.

During the last quarter of this project, we have focused on the measurement of this complete contact or pseudo-equilibrium curve. In our prototype cell shown in Figure 2, a pseudo equilibrium is established between the suspension and the foam generated from the suspension. The data required for the complete contact curve shown in Figure 1 is generated by sampling the volume fraction of coal in the suspension associated with the foam as a function of the volume fraction of coal in the suspension from which the foam is generated.

For each Illinois coal to be studied, the first step is the generation the pseudo-equilibrium relationship. For a coal-ash (and subsequently pyrite) system, this means that we must prepare mixtures of coal and ash having different compositions.

A run-of-mine or other coal sample represents only one composition.

Preconcentration by flotation is undesirable, both because residual reagents in the concentrate could distort the results and because the volume of coal to be concentrated would be excessive. Tabling and other methods for concentrating the components are not considered because of cost, of separation efficiency, and of material handling.

An alternative is to generate a "synthetic" coal-ash mixture. This may be accomplished by grinding the feed coal sample to a mean size sufficient to liberate a significant amount of the ash component, most likely be found in the -10 micron size fractions. This ground intermediate will be sieved at a size determined to be optimum for coal-ash separation, the bottom size discarded as waste, and the top size retained as a highly concentrated coal fraction. This coal product can then be ground to a desired size distribution (specifically, a distribution similar to that which will be used as a flotation column feed stock). In other current research at the Northwestern University Coal Research Laboratory

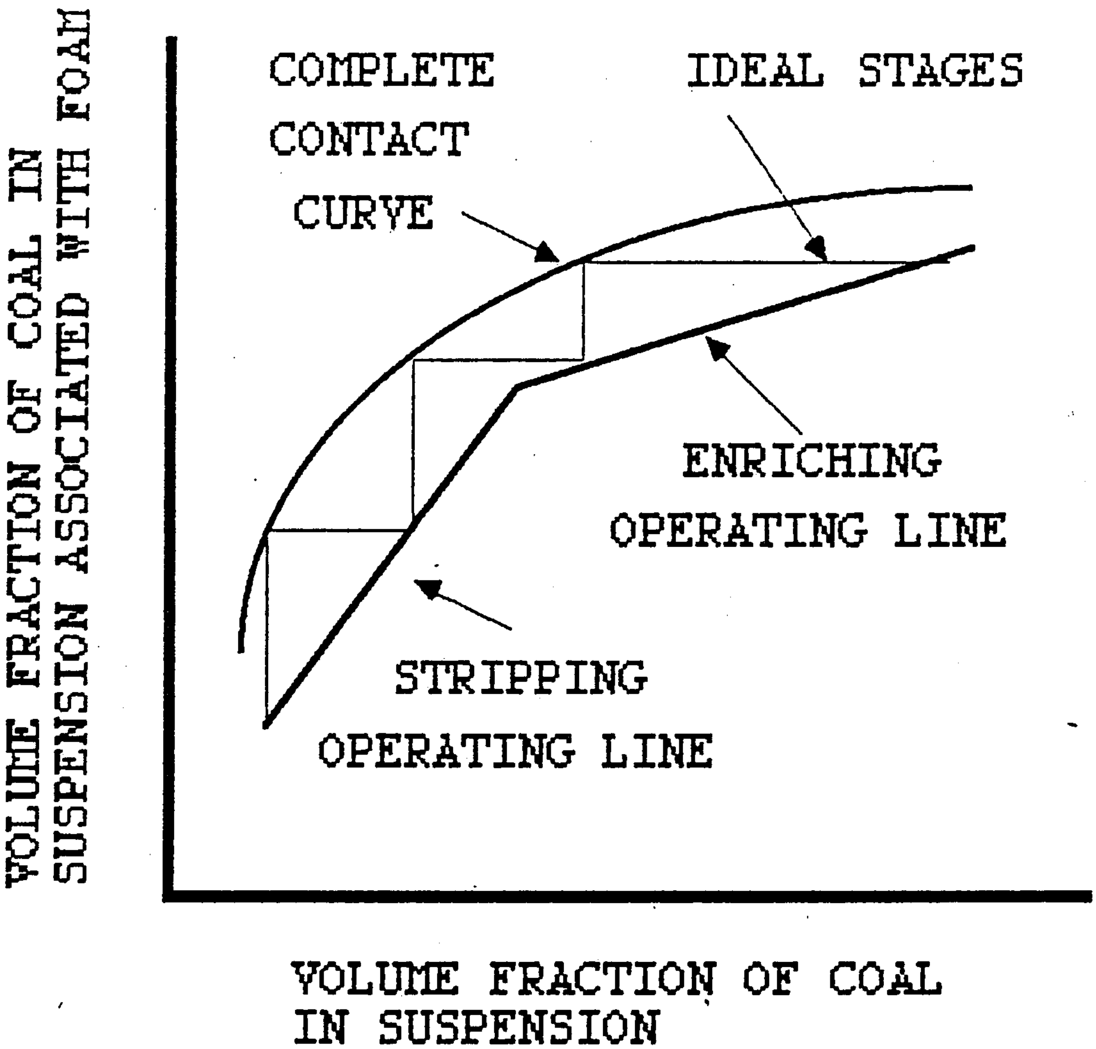

Figure 1: Limiting case algorithm used in stepping off the required number of stages.

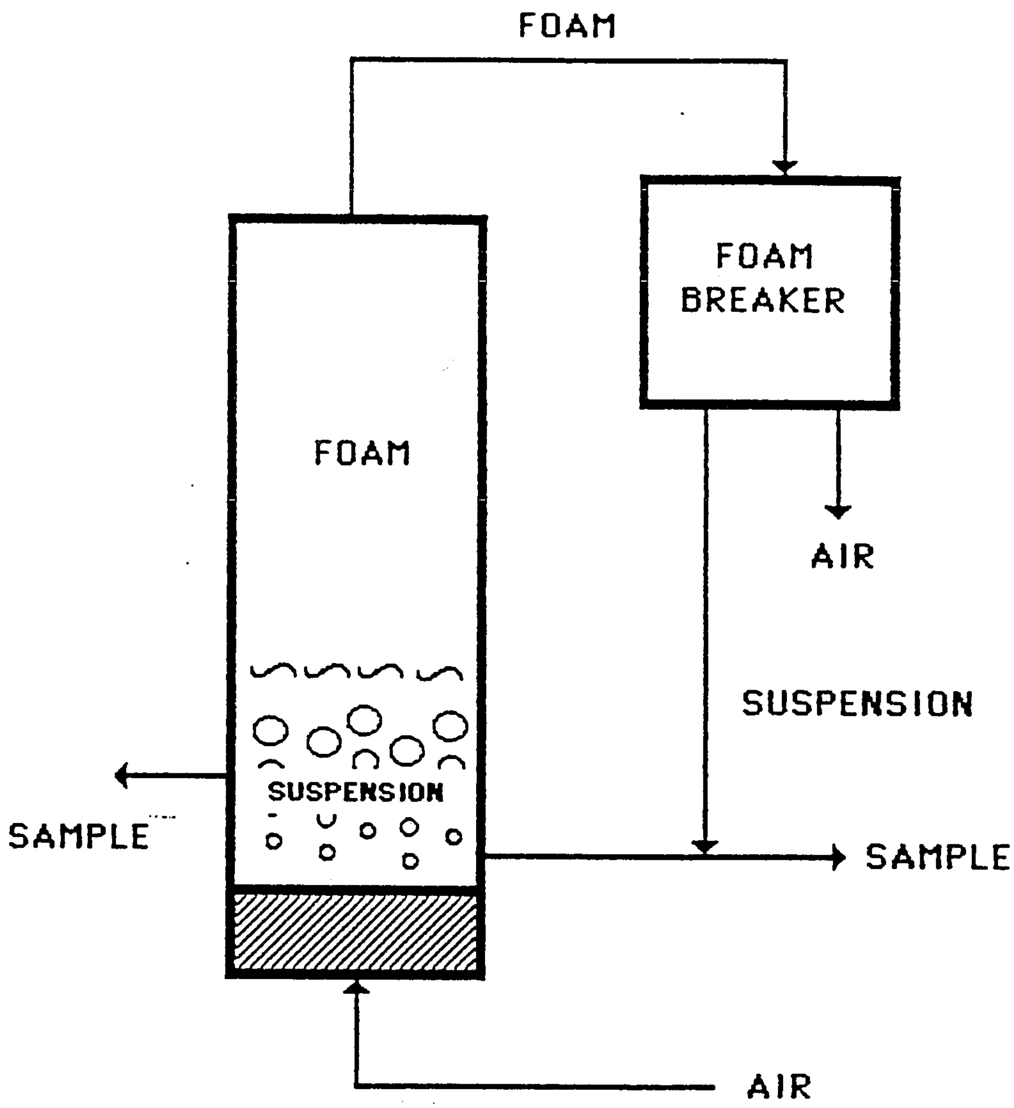

Figure 2: Prototype experiment employed to determine the complete contact or pseudo-equilibrium curve.

(NUCRL), - 400 mesh coal grinds have resulted in ash particles of -10 μ.

In order to simulate the ash fraction (principally clays), an illitic or similar clay in a -10 micron size range may be used. Using the concentrated coal product and clay, a series of compositions could be prepared. It is likely that these "synthetic" mixtures may retain the general floatability characteristics of the feed coal.

A series of pseudo-equilibrium experiments using the coal-ash mixture at various solids fractions, pulp volumes, and reagent doses will be performed in a single stage device simulating the conditions to be found on a stage of a flotation column. These tests will yield the desired pseudo-equilibrium curve for that specific coal at given pulp densities and flow rates.

Once a pseudo-equilibrium curve is determined, under certain conditions we may use a graphical analysis similar to the McCabe-Thiele analysis for binary distillation. The material balance equations are represented as lines on the pulp-froth pseudo-equilibrium diagram. One line represents the material balance for the column below the feed point, the stripping section in which the tailings are stripped of coal; the other denotes the material balance in the column above the feed point, the enriching section in which the desired product is stripped of ash and pyrite. After specifying the recycle and the desired compositions of the tailings and of the coal concentrate, it may be possible to step off the number of ideal stages between the pseudo-equilibrium curve and the operating lines.

In the design of staged columns, it must be remembered that pseudo-equilibrium will not be achieved on each stage. The number of stages required to achieve a specified separation will depend upon the stage efficiency, which can be determined only experimentally. The stage efficiency is anticipated to be a function of the volume fraction solids in the feed suspension, the recycle, the gas flow rate, and the overall froth quality.

We have examined two aspects of the economics of staged flotation columns compared with standard mechanical cells: the use of reagents and the plan area required for the equipment.

Staged flotation columns use reagents more efficiently than do standard mechanical cells, since the same reagents pass through each stage. In the common use of standard mechanical cells, reagent is added at each stage.

Compared with standard mechanical cells operated in stages, staged floatation columns make a more effective use of available plan area, when the requirement is to produce a very clean coal concentrate. In making this comparison, we have asssumed a feed that is 4% solids (coal) by volume and a 100 ton/hour solids capacity.

Staged flotation columns will require about 40% more plan area than a flotation deck with one rougher and three cleaner stages. However the columns could contain as many as eight stages and with the same plan area produce a much cleaner product than four stages of standard mechanical cells.

If we assume that the staged floatation columns produce the same degree of cleaning as eight countercurrent banks of mechanical cells, we find that the staged flotation columns require about 40% less plan area than the standard mechanical cells.

TASK 2: ATTACHMENT OF COAL PARTICLES TO AIR BUBBLES

We have completed the initial phase of our analysis of selective coalescence in which we have been extending our prior studies to the case of a thin film formed between a bubble and a much smaller solid part- icle. To this point, we have included the effects of surface tension, the bubble diameter, the particle diameter, the strength of the London- van der Waals forces, the viscosity of the continuous phase, and the density of the liquid.

If in these analyses the electrostatic double-layer forces and the London-van der Waals forces in the thin film between the bubble and the solid particle combine to produce a strong positive disjoining pressure, no coalescence will occur and the solid particle will be rejected. This is the desired result with a particle of pyrite or ash.

If the electrostatic double-layer forces are weak but nonzero, they will combine with the London-van der Waals forces to produce a secondary minimum in the potential describing the sum of these forces. Coal particles can be trapped in this secondary minimum without coalescing with the air bubbles. Depending upon the magnitude of this secondary minimum, the resulting attachment may not be sufficiently strong to withstand the turbulent forces in the suspension.

It is desirable for a strong negative disjoining pressure to be created in the thin film between an air bubble and a coal particle. Under these circumstances, our analyses predict the coalescence time or rest time, the time that a solid particle appears to rest at the surface of a bubble before coalescence occurs, as a function of surface tension, bubble diameter, particle diameter, strength of the London-van der Waals forces, the viscosity of the continuous phase, the density of the solid particle, and the density of the liquid. During this period, the external forces to which the bubble and particle or subjected fluctuate, alternately acting to force them together or tear them apart. We are continuing to carefully examine the literature in order to determine what might be said about the amplitude and frequency of this force as a function of local turbulence conditions.

With this caveat, we can draw several conclusions. In order to enhance the stage efficiency of a flotation column,

> the viscosity of the suspending phase should be as small as possible
>
> the density of the suspending phase should be as small as possible
>
> the particle diameter should be as small as possible
>
> the bubble diameter should be as small as possible
>
> turbulence should be minimized consistent with good contact

In order to enhance selectivity in the flotation column,

> any surfactant added to the system should maximize both the negative disjoining pressure between the coal particles and the bubbles and the positive disjoining pressure between the ash particles and the bubbles, while minimizing the reduction in the (liquid-gas) surface tension.

Because of a lack of funds, this work will not be continued under the new contract, but a paper describing our analysis and detailed results is being prepared.

TASK 3: STABILITY OF A FOAM CREATED FROM A SUSPENSION

The complexity of the structure of lamellae draining into Plateau borders in a foam make this a difficult problem. For the case with which we are concerned here, the structure is made all the more complex by having the foam created from a suspension. Our approach has been to begin by attempting to better understand a foam having no entrained solids.

We have derived a model for foams using the concept of local volume averaging (Anderson and Jackson 1967; Slattery 1967; Whitaker 1967; Slattery 1972). As the result of local volume averaging, the foam can be described as though it were a single phase. But a price is paid, in the sense that information is lost concerning the local structure of the foam. This information must be replaced either by empirical data correlations or through the use of an idealized model for the local foam structure.

We have taken this latter approach in using a statistical model similar to that employed by Narsimhan and Ruckenstein (1986a; see also Aleman et al. 1987). The result is similar to that of Narsimhan and

Ruckenstein (1986a).

We have completed an initial comparison of our results with available experimental data (Desai and Kumar 1983, 1984) as well as with the results of Desai and Kumar (1983, 1984) and of Narsimhan and Ruckenstein (1986a,b). Although our derivation is different, our results are very similar to those of Narsimhan and Ruckenstein (1986a,b). Our comparisons with experimental data are comparable to those reported by Desai and Kumar (1983, 1984).

In approaching the analysis of the drainage and stability of foams created from suspensions, we will take advantage of our current work on foams having no entrained solids. We will also take advantage of our recent work on suspensions (Jiang et al. 1987; Kim et al. 1987).

We hope in this way to be able to discuss the interacting effects of surface tension, the two surface viscosities, bubble size, the strength of the London-van der Waals forces, the strength of the electrostatic forces, bubble diameter, and the densities of the three phases. Assuming that we are successful, we hope to use these results to simulate the pseudo-equilibrium curves that we will be measuring as part of Task 1. In this way, we hope to better understand how these parameters influence the design of staged flotation columns.

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CONCLUSIONS AND RECOMMENDATIONS

TASK 1: A NEW APPROACH TO THE DESIGN OF FLOTATION COLUMNS

Compared with standard mechanical cells operated in stages, staged floatation columns make a more effective use of reagents and of available plan area, when the requirement is to produce a very clean coal concentrate.

TASK 2: ATTACHMENT OF COAL PARTICLES TO AIR BUBBLES

As noted above, we have been able to draw several conclusions from our analysis of bubble-particle interactions. The most important appear to be these. In order to enhance stage efficiency in flotation columns,

the particle diameter should be as small as possible,

the bubble diameter should be as small as possible,

turbulence should be minimized consistent with good contact.

In order to enhance selectivity,

any surfactant added to the system should maximize both the negative disjoining pressure between the coal particles and the bubbles and the positive disjoining pressure between the ash particles and the bubbles, while minimizing the reduction in the (liquid-gas) surface tension.