AN ANALYSIS OF THE THEORY AND INDUSTRIAL PRACTICE OF FLOTATION: SOME ASPECTS OF THE THEORY AND IT'S APPLICATION TO COAL FLOTATION

By

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An Analysis of the Theory and Industrial Practice
of Flotation: Some Aspects of the Theory
and it's Application to Coal Flotation.

This dissertation, "An Analysis of the Theory and Industrial Practice of Flotation: Some Aspects of the Theory and its Application to Coal Flotation", is hereby approved in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in the field of Metallurgical Engineering.

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ABSTRACT

The flotation process is extremely complex, depending on the interacting influence of many independent variables on physicochemical processes. This complexity minimizes the value of any empirical analysis. Developing a fundamental mechanistic understanding would allow *a priori* consideration of the effects of variables and ensure the process is applied with maximum efficacy. Considerable thought and effort have gone into explaining the general fundamentals of flotation. However, a theory based on the physical mechanisms responsible for separation is unavailable.

One objective of this research was to use experimental results and an analysis of the technical literature to formulate a mechanistic theory. The basis for separation is differential particle transfer from the pulp, through the froth, and into the concentrate launder by two mechanisms: bubble attachment and entrainment. Each phase has an effect on process performance. Both particle size and hydrophobicity have a role in controlling process response by influencing bubble-particle interaction and movement through the pulp and froth phases. Simplification arises because particle behavior can be categorized according to species. Support for this theory is supplied by lab and plant tests on bituminous and anthracite coals directed at correlating mechanisms responsible for separation, process grade-recovery response, species identity, water recovery, and reagent regime.

Another objective was to analyze the influence of reagent regime and particle characteristics on process performance and its optimization. The theory provides a framework for understanding experimental observations, predicting particle behavior, and optimizing circuit performance, e.g.:

1. The mass distribution of particles into species, maximum recovery and rate of recovery for each species, and circuit retention time control process performance.
2. The response of fine ash particles is controlled by entrainment and is therefore controlled by water recovery. Ash in the intermediate and coarse fractions is primarily recovered via flotation of composite particles and is therefore controlled by their behavior.
3. Changing the reagent regime to influence the behavior of one species influences the response of others, perhaps negatively. A technique for optimizing reagent conditions to match feedstock characteristics was developed in this work.
4. Flotation response in plant and laboratory tests differed due to froth phase behavior.

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CHAPTER 1. INTRODUCTION AND STATEMENT OF THE PROBLEM

For many reasons the recovery of fine (minus 600 microns) coal continues to increase in importance, with many new coal preparation plants incorporating flotation into their basic flowsheet. This trend is likely to continue since flotation is currently the most effective and economical method for recovering many types of fine coal. Furthermore, the need for high coal recoveries at increasingly lower ash and sulfur contents necessitates improving flotation process efficiency.

Froth flotation is a physicochemical process that is widely used in mineral beneficiation for separating different types of finely divided ground minerals from their associated gangue particles. The process is based on the contacting of solids with upward moving air bubbles where chemical treatment of the finely divided ore particles in an aqueous pulp is used to create conditions favorable for the attachment of certain mineral particles to air bubbles. The bubble-particle aggregates then carry selected minerals to the surface of the pulp to form a stabilized froth. Most of the unattached particles remain submerged in the pulp, however, water entrains a fraction of all particles present into the froth. Both types of particles are then present in a froth, stabilized by a frother, that is continuously removed from the flotation cell. The froth or cell pulp streams can be valuable or gangue and either recovered, discarded, or reprocessed.

At least two specific steps must occur in order to obtain adherence of the desired mineral particles to air bubbles:

- a hydrophobic surface film must be formed on the particles to be floated along with a hydrophilic film on all other particles; and

- a controlled bubble surface tension must be maintained, allowing for high particle / bubble collision frequency and efficient attachment after collision.

In most applications the above two steps are controlled by chemical reagents. The collector is a chemical that produces a hydrophobic film on the desired mineral particles and is the primary driving force that initiates the flotation process. The frother is a chemical that influences the collision frequency and attachment efficiency of hydrophobic particles and air bubbles. The frother also assists in maintaining a stable froth phase.

As discussed above, particles are transferred from the pulp to the froth by two mechanisms:

bubble attachment and entrainment.

Similarly, particles are lost from the froth to the pulp by the two reverse mechanisms:

bubble detachment and drainage.

Consequently, particle behavior in both the pulp and froth phases is important. Both particle size and wettability play a major role in controlling behavior. In order to take full advantage of the flotation process it is necessary to understand the effect of operating variables with respect to these mechanisms. The analysis presented in this dissertation is a new approach to application, optimization, and control of coal flotation processes. It can also be applied, through logical extrapolation, to any other flotation process. Experimental results are used to demonstrate why the optimal separation of coal from gangue by flotation requires considering both pulp chemistry and froth structure and how to perform the required analysis.

1.1 General Aspects of Coal Preparation

Consider the typical coal processing plant flowsheet shown in Figure 1.1. The raw feed passes through a rotary breaker to remove coarse rock and to reduce the maximum particle size to some acceptable size for processing. The undersize product is sized in a sequence of steps to yield coarse, intermediate, and fine fractions. The coarse and intermediate fractions are generally upgraded by jigging or heavy media processes and the fine fraction (generally minus 600 microns) is the feed to a flotation circuit.

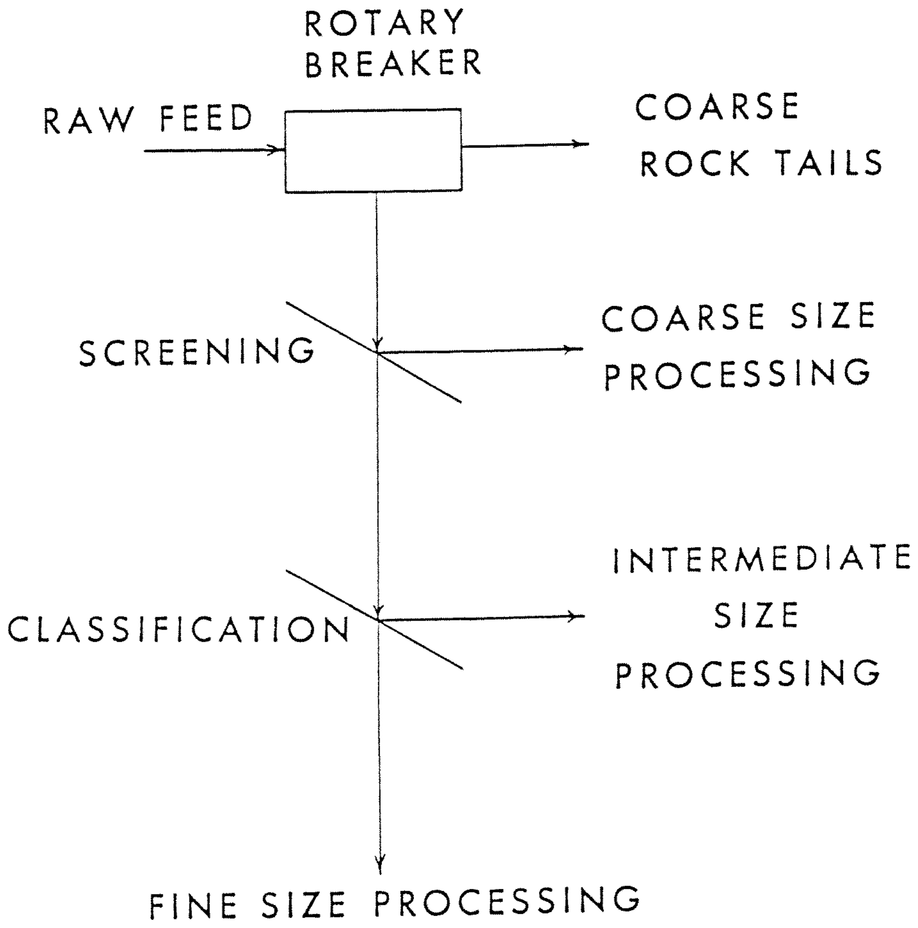


Figure 1.1. General Coal Preparation Plant Flowsheet.

Often there is no size reduction other than breakage that occurs in mining, handling, the rotary breaker, or incidentally in subsequent processing. In other cases, crushing is used to yield a product with a top size of 2 to 6 inches. This is because adequate product quality can usually be achieved through beneficiation at coarse and intermediate sizes. The need for size reduction to achieve liberation is subject to variation from country to country, due to market quality standards and the liberation characteristics of coals being processed.

In most cases, the fraction of natural fines is an economically significantly fraction of the coal being treated. Current coal flotation circuit design and operating practice is to provide, on average, sufficient residence time, acceptable feed percent solids, and sufficient frother and collector addition to recover coal. Plant designs are based on previous experience, lab tests, and flotation cell vendor recommendations.

Operators control recovery in their cells by adjusting the addition rates of frother and collector and sometimes by adjusting air flow (Seitz and Kawatra, 1985). Also, many investigators and plants use a fixed ratio of frother to collector (e.g., Aplan, 1976) rather than separately optimizing each according to coal, ash, and water feed rates, and grade-recovery requirements.

Since most current systems are not automatically controlled, operators typically use enough reagent to "do the job most of the time". Operators make manual adjustments as time and inclination permit. In light of the frequency and magnitude of process disturbances this leads to the circuit operating inefficiently most of the time (Kawatra and Seitz, 1984).

Other operators adjust reagent addition rates to prevent the vacuum disc filters from overflowing or sanding out. Typically, the reagent addition rates are decreased so that the flotation cells and filters operate with minimal operator attention. These poor operational practices lead to the loss of a large amount of fine coal to the tailings ponds and lower grade concentrates are produced. Operators usually do not understand that lowering reagent dosages initially causes reduced coarse particle recovery. This leads to reduced filter capacity because of decreased filtration rates and further reduced recoveries. This neglect goes unnoticed since in many plants only about 5 to 10 percent of the plant feed is processed in the flotation circuit. Maintaining optimum operation of the coarse coal circuits is certainly more important economically than manually fine-tuning the flotation system. However, even a 1 to 5 % yield loss due to poor flotation efficiency coupled with poor product quality is appreciable for many, if not most, plants.

Changes in methods of mining coal and emphasis on increased production have caused many plants to exceed the design capacity in the fine coal recovery circuit. Operators have little flexibility other than adjusting reagent addition levels or pre-treatment of the feed before it enters the flotation cell. This places additional pressure on the system. In all of the above cases, flotation operations might be better optimized through developing an understanding of the effects of variables on the mechanisms responsible for flotation behavior.

1.2 The Mechanisms of Particle Recovery in Flotation

There are two primary mechanisms by which particles are transported from the pulp into the concentrate:

1. Bubble-particle attachment, which operates on particles with hydrophobic surfaces.

2. Particle entrainment, which affects all particles but is relatively more important for hydrophilic and fine particles.

Bubble-particle attachment requires the formation of a stable bubble-particle aggregate that moves to the froth / pulp interface by buoyancy and then up into the froth due to the crowding force exerted by more aggregates moving upward to the froth / pulp interface. Entrainment is the result of bubble-particle aggregates moving up into the froth and carrying with them the pulp in the upper levels of the flotation cell.

After particles have been transported into the froth, there are two primary mechanisms by which they may be transported back into the pulp:

1. Bubble coalescence and particle detachment, followed by particle drainage. This affects particles recovered by bubble-particle attachment.
2. Drainage of entrained particles from the froth, this affects particles recovered by entrainment.

These drainage mechanisms are responsible for a secondary concentration effect in the froth.

Accordingly, although behavior in the pulp controls the flow of hydrophobic and hydrophilic particles and water into the froth, behavior in the froth controls the flow of these species into the concentrate or back into the pulp. Thus, both the pulp phase and froth phase exert a significant effect on selective particle separation by flotation. These mechanisms have been extensively discussed in the literature (Klassen and Mokrousov, 1963; Mika and Fuerstenau, 1968; Moys, 1978; Cutting et al., 1981, 1983; Lynch et al., 1981; Bascur and Herbst, 1982; Seitz and Kawatra, 1985).

Investigations into the turbulent environment in the cell provide knowledge about the mechanisms of particle recovery (Schubert, 1979): bubble-particle contact, attachment and detachment, and bubble-particle aggregate movement in the pulp and froth. The study of flotation kinetics has been primarily concentrated on the development and analysis of overall cell macrokinetics. However, using the results from both macro and micro level studies will permit the development of a better understanding of the mechanisms of particle recovery in flotation.

The optimization and control of coal flotation circuit performance is based on controlling these mechanisms. Thus, the relationships between these mechanisms and process variables must be determined. This necessitates understanding the interconnecting role that water recovery plays in flotation, which is discussed below. However, it is first necessary to consider the mechanisms responsible for particle behavior in the pulp.

1.2.1 The Pulp Phase

The particles to be separated are suspended in a flotation cell by establishing a suitably turbulent hydrodynamic flow regime through the use of mechanical or air agitation. The chemical environment in the cell results in each particle having a degree of wettability that depends on the chemical nature of its surface. As air bubbles move up through the suspended particles in the pulp phase, they interact; the turbulence in the cell has a great influence on this behavior (Arbiter and Steininger, 1964; Schubert, 1979). Bubble-particle interaction that leads to the formation of a stable bubble-particle aggregate is responsible for the selective separation of particles by flotation.

At the present time the following mechanistic model of particle captive is generally accepted (Derjaguin and Dukhin, 1961; Anfruns and Kitchener, 1976; Jameson et al., 1977):

1. The particle must make a hydrodynamic collision with the bubble.
2. During the brief collision period (a few milliseconds) the thin film between particle and bubble spontaneously ruptures. Its instability arises from the hydrophobicity of the collector coated particle. The complexity of bubble-particle interaction and attachment or repulsion involves the following three forces in a manner described by DLVO theory (Blake and Kitchener, 1972; Laskowski, 1974):

- Coulombic forces, that arise from electrical double layers and are generally repulsive in nature and operate at a film thickness of 2000 A;
- Dispersion forces, involving London-van der Waals attractive forces, which generally predominate over distances of 50 - 1000 A and have a second order dependence on separation distance; and
- Structural forces, which arise due to specific effects of the solid on the water molecule, through hydrogen bonding or hydration effects, and operate at separation distances of 100 A and are an exponential function of separation distance.

These forces determine the hydrophobic character of the surface; including both the rate of and equilibrium position for bubble attachment. In emulsion flotation, the complexity is even greater, since a fourth phase, the nonpolar oil, must be considered.

1. The contact meniscus must expand rapidly over the particle and resist displacement, otherwise the particle is subsequently liable to be detached by collisions.

Bubble-particle aggregates move upward until they reach the pulp / froth interface, where they begin to crowd together and interact. At any time during these processes the reverse mechanisms can occur, with consequent loss of the particle back into the pulp phase.

1.2.2 The Froth Phase

The following description of mechanisms operating in the froth phase is based on the work of Moys (1978), Cutting et al. (1981), Kawatra and Seitz (1984), Kawatra et al. (1984), and Seitz and Kawatra (1985 a, b).

The flow of bubble-particle aggregates upward into the froth phase results in the net upward movement of water into the froth, as associated with each aggregate is an envelope of slurry containing a pulp sample representative of the upper portion of the pulp phase. Entrained particles will either drain back into the pulp due to their greater specific gravity or be carried along with the water due to their fine size. Their relative velocity is determined by the spatial distribution of bubbles in the froth; the size, shape and density of the particles; and the net upward velocity of water in the froth. The velocity differential between the water and bubbles results in a steady decrease in the slurry volume fraction with height, so the bubbles crowd more closely together to form first a foam and then a true froth consisting of polyhedral bubbles separated by thin films with Plateau's borders at the intersections of these films. Water and particles continue to drain from these films into the Plateau's borders and downward along the bubbles.

Bubbles coalesce at a rate dependent on many factors; thus, bubble surface area per froth volume decreases with height. Consequently, the properties of the froth change continuously with height, due to drainage and coalescence. Also, the froth is removed from the top of the froth phase by various methods that may themselves cause an increased rate of bubble coalescence and hence reduce recovery. The work of Malysa et al. (1981 a, b) suggests that the properties of bubbles in the upper layers of the froth are extremely important in controlling froth stability.

The processes occurring in the froth may help or hinder the secondary cleaning mechanisms that generally occur. Froth drainage removes particles that are not strongly attached to bubble surfaces, generally gangue particles, while froth coalescence introduces shocks and reduces the bubble surface area, resulting in particle detachment from the films and the loss of valuable particles. If no reattachment of strongly hydrophobic particles occurs lower down in the froth phase, coalescence will not improve the grade of the froth but will only reduce the recovery of hydrophobic particles. If the preferential reattachment of hydrophobic particles does occur, the froth grade will increase and regulation of coalescence becomes a potential control action by using reagent concentration, froth residence time, or froth removal systems. Mixing in the froth phase decreases froth grade, but mixing results from the need for transverse motion of the froth across the cell surfaces so that it can flow into a removal launder.

The state of the froth phase at any particular time controls its capacity for transporting particles from the pulp / froth interface into the concentrate. Particles in the froth coexist with various degrees of crowding and interaction, depending on how loaded the froth is. The mechanisms that establish and control the froth place an upper limit on its particle-carrying capacity. When a particular froth reaches its maximum carrying capacity under given conditions an overloading effect results. This is a condition of reduced froth mobility and increased froth residence time. The result is increased particle drainage from the froth back into the pulp phase and, consequently, a severely reduced rate of particle transfer from the pulp to the concentrate launder. It occurs due to:

- the high rate of flotation of mineral species,
- recovery of the bulk of the circuit feed in the concentrate (Tomlinson and Fleming, 1963), or
- froth characteristics that reflect both of these factors and the reagent regime.

Accordingly, this limit is particularly important in coal flotation, where a high rate of recovery is planned for and the bulk of the feed particles must be transported through the froth in order to report to the concentrate.

The loss in recovery due to froth overloading cannot be entirely regained when retention time is limited. Sun (1952, 1952/53) observed significant effects of various frothers and oils on froth stability. However, the effect of frothers and nonpolar oil collectors on the transport capacity of the froth has not been investigated.

1.3 The Effect of Particle Size

Particle size is one of the most important variables in flotation and one of the major problems in coal flotation is the relatively poor response in many cases of the coarse and very fine particles. Many of the effects of particle size on flotation have long been known (e.g., Gaudin, Groh, and Henderson, 1931; Sun and Zimmerman, 1950). However, until recently there has been little acknowledgment of the value of size-by-size assessment of flotation performance either in research or in industrial practice, nor has there been any significant effort to use this knowledge in the design, optimization, or control of flotation circuits.

Although particle size effects in coal flotation were known and discussed, their significance was ignored by numerous investigators over a period of many years (e.g., Brown, 1962; Aplan, 1976). However, these effects have been studied in some detail for metallic mineral systems. Over the last fifteen years, detailed size-by-size assessments of various mineral flotation systems have been used as a valuable aid for understanding and solving flotation problems. A paper by Trahar (1981) covers this subject in detail and many of the conclusions from that work apply as much to coal as to any other mineral system.

In mineral flotation, recovery-size curves generally have a characteristic inverted U-shape (similar to Figure 1.2), with recovery falling slowly below approximately 10 microns and rapidly above approximately 100 microns (Trahar, 1981). The lower recovery of fine particles has been attributed to a lower probability of particle capture by air bubbles, because of hydrodynamic and inertial effects (Flint and Howarth, 1971; Jameson et al., 1977); and the lower recovery of coarse particles has been attributed to an increased probability of detachment of particles from bubbles in the turbulent zones of a flotation cell (Morris, 1950; Schulze, 1977; Jowett, 1980). Thus, these recovery-size curves may be divided conveniently, but arbitrarily, into three regions:

fine, intermediate, and coarse particles.

(Note that these size regions are different from those referred to in Section 1.1).

As a first approximation, it might be expected that recovery-size curves for coal would be similar in shape to those for minerals, for similar reasons, but with a shift in the size range of good flotation to larger sizes, reflecting the lower density of coal. However, there has been little agreement between researchers on the form of the relationship

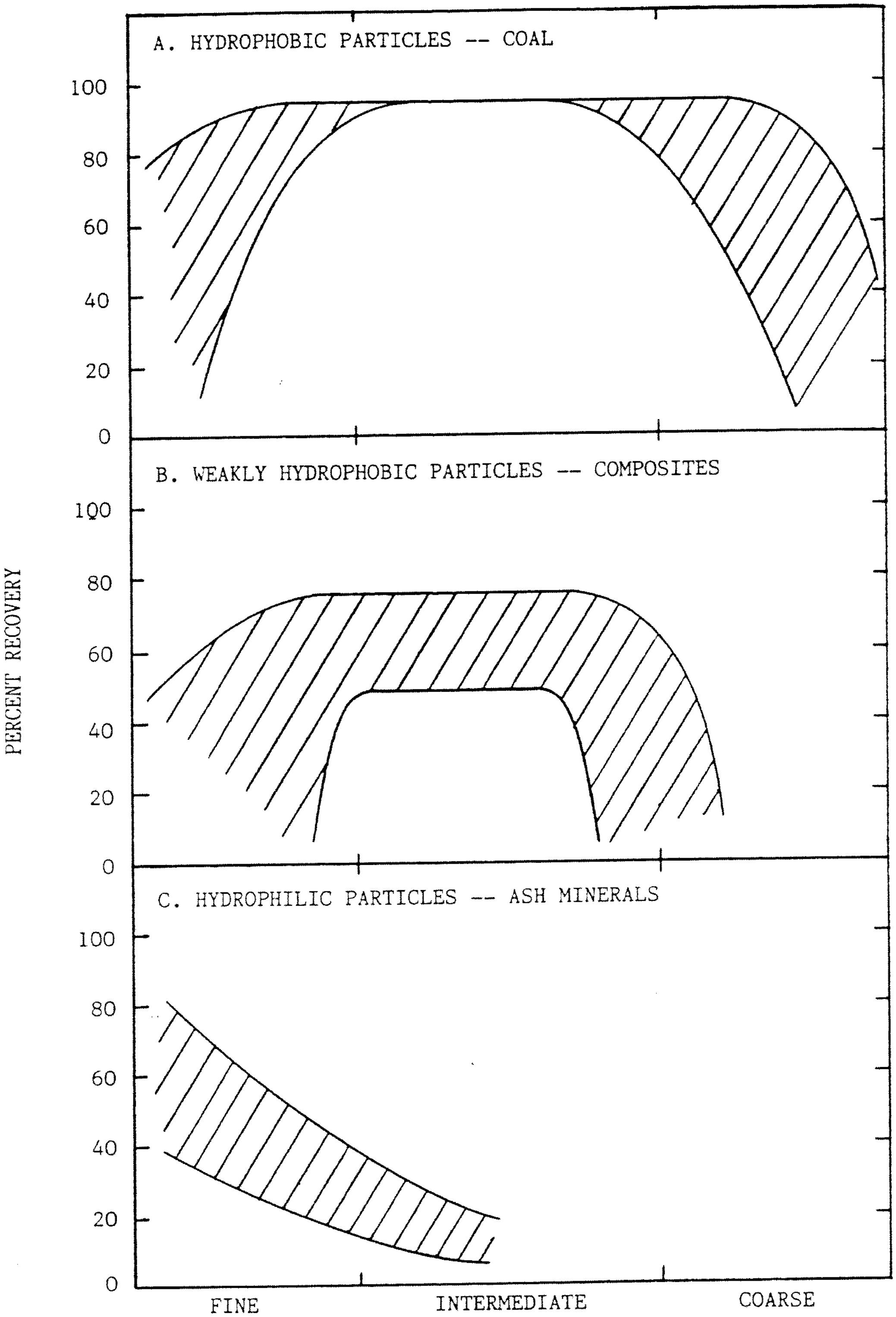


Figure 1.2. Recovery – Size Response for Particles in Flotation.

between recovery and particle size. Allowing for the fact that some researchers have measured flotation rate constants using different kinetic models, while others have measured recovery-size curves at a given flotation time, and also allowing for different reagent regimes and flotation machines, it appears that, as seen in Figure 2.1 and elsewhere in the technical literature, the recovery and / or rate of recovery either increases with decreasing size below approximately 800 um (e.g., Brown and Smith, 1953-54; Banerjee et al., 1962; Miller et al., 1967; Pooley, 1967; Firth et al., 1978; Bustamante and Warren, 1984) or is greatest in some intermediate size range (e.g., Zimmerman, 1948; Sun and Zimmerman, 1950; Safvi, 1959; Burdon, 1962; Lynch et al., 1981; Kawatra and Seitz, 1984; Bustamante and Warren, 1984). In the former case, the lack of a size analysis of ultrafine particles or the tendency for the fuel oil collector to flocculate fine particles (Seitz, 1979) may be responsible for the failure to notice any drop-off for the finer sizes.

The overall picture that emerges from published data is that, in a coal flotation system that is operating under conditions not too far removed from optimum (i.e., pulp density, reagent additions, impeller speed, aeration rate, etc.):

- intermediate sizes (approximately 300 x 74 um) will float quickly;
- fine particles (minus approximately 74 um) are more difficult to float and selectively separate; and
- the region between approximately 300 um and below some more or less undefined upper limit is the coarse particle region, where flotation may be easy or difficult depending on the coal and operating conditions.

Because the boundaries between these three regions are frequently ill-defined and their locations vary widely, it is more convenient to refer to fine, intermediate, and coarse particle behavior than to specify sizes. The precise size ranges are very dependent on coal rank and type and other variables. It is inadvisable to generalize and important in connection with plant design and operation to make appropriate flotation rate measurements on any specific coal.

Figure 1.2 shows the approximate shape of the recovery-size curve for a typical coal floated with a range of reagent regimes. It also shows typical recovery-size curves for flotable gangue (e.g., composite particles and pyrite) and nonflotable gangue (e.g., silicates, etc.). With most materials it is possible to construct these curves, from which the relative flotation responses of the major constituents of an ore can be studied in detail. This can be done through a sufficiently detailed chemical analysis of the system, which is quite routine with modern analytical equipment. It is more difficult to produce a comparable suite of curves for a coal flotation system; where, in a simple case, hydrophobic valuables can be equated to macerals, weakly hydrophobic gangue to miscellaneous ill-defined, high ash, carbonaceous materials and perhaps pyrite, and hydrophilic gangue to a host of silicates (e.g., clays and quartz). In practice one usually gets only ash and total sulfur contents, preferable on a dry, mineral matter free basis (DMMF) but sometimes on an as received basis. Therefore, as discussed in Section 1.4, particles with similar rates of recovery and mechanisms responsible for their recovery must be considered as individual species for purposes of analysis.

Recovery-size curves are usually fairly stable in shape for a given set of flotation conditions. Data from both plant and laboratory batch tests indicates that the curve shape is reasonably independent of moderate variations in particle size distribution, valuable mineral content, and pulp density (Trahar, 1981). Such behavior is to be expected from any flotation system with non-interacting components and first order kinetics describing the rate of recovery of each component (Harris and Cuadros-Paz, 1978). However, interference between sizes may occur in pulps with high solids contents, or of floating minerals, or in which mutual interactions between particles, such as slime coatings, are possible. In such cases, the shape of the recovery-size curve may then depend on the feed size distribution or composition (Trahar, 1981). Additionally, it is necessary that a sufficient number of particles are present in any size range for their recoveries to be statistically meaningful.

The behavior of both liberated and composite particles must be considered. The principal recovery mechanisms are presumed to be flotation by bubble attachment and levitation and entrainment. It should be noted that although entrainment can in some respects be studied separately from flotation, the converse is not true; for the recovery of minerals in a conventional flotation cell is always a combination of true flotation and entrainment. Separation of the individual contributions is possible only to a limited extent. One aim of this dissertation is to identify the essential effects of particle size, to resolve some of the uncertainties associated with the influence of particle size, and to discuss its implications in coal flotation.

An important aspect of recovery-size analysis is the potential for quantifying the extent to which different mechanisms are contributing to the overall result. Methods of improving performance may become apparent from this analysis. In Figure 1.2, the hydrophobic and weakly hydrophobic particles are primarily recovered by bubble attachment, while the hydrophilic particles are recovered by entrainment. Significant recovery of gangue minerals at coarse sizes is indicative of an intergrowth / liberation problem. Such a conclusion from recovery-size analysis considerably improves the potential for selection of correct remedial action. In the case of coal, the scope for such analysis is limited by the scarcity of analytical information. There is also the problem of the "inherent" ash present in all macerals. This can represent a considerable fraction of the total ash recovered and is usually enough to complicate any useful diagnosis relating to intergrowth. However, one major benefit of studying the coal flotation system is the potential for heavy liquid analysis with relatively nontoxic fluids as discussed in Chapter 2.

The recovery-size behavior of coal in flotation is examined in this dissertation with the background discussed above. Particular emphasis is placed on aspects of carbonaceous material and mineral matter (primarily reported as ash) recovery and the selectivity of their separation. In general, flotation cannot be regarded as a precise separating process where coal is concerned. The absence of a comminution stage to liberate individual components, or indeed even the possibility of such liberation, results in a mixture of petrographic components, including different coal macerals and carbonaceous shale with a wide range of ash contents, which often creates a severe selectivity problem. The importance of particle size effects is discussed throughout this dissertation and aspects of its influence are examined by reference to experimental study of the effects of reagent regime on fine, intermediate, and coarse particles.

1.4 The Theory of Flotation Process Analysis

Based on the experimental work presented in Chapter 2 and a review of the literature (e.g., Trahar, 1981, Seitz and Kawatra, 1985) it appears that the recovery or rate of recovery versus size behavior in coal flotation for particles of differing hydrophobicity is as shown in Figure 1.2. Apparently, two factors are of primary significance: size and particle hydrophobicity. There are three general particle size ranges: coarse, intermediate, and fine; and three general ranges of particle wettability present: coal, composites, and gangue.

The concept of a particle species is useful in the subsequent discussion: a particle species is a group of particles that are recovered via the same mechanism at a similar rate of recovery and to the same extent of recovery. There are a plethora of species present in coal flotation ranging from hydrophilic to hydrophobic and a few to hundreds of microns in size. However, for purposes of conceptual development and testing of a theory of flotation process analysis only nine species need be considered as follows:

	Relative Hydrophobicity		
Size	**Coal**	**Composites**	**Ash**
Coarse	1	4	7
Intermediate	2	5	8
Fine	3	6	9

This roughly corresponds to the mechanisms responsible for particle recovery and their dependence on particle size. The behavior of all particles can generally be considered to fall into one of these nine species.

Developing the theory presented above leads to a hypothesis that flotation problems arise for different reasons in each of the three size classes:

1. Coarse Size Particles - Low recovery occurs because it is difficult to achieve the hydrophobicity necessary to overcome hydrodynamic forces, maintain stable bubble-particle aggregates, and float coarse particles. Grade becomes a problem only if significant locking of gangue with coarse particles occurs, since minimal to no entrainment exists.
2. Intermediate Size Particles - Recovery should not be a problem since hydrophobicity requirements are not as great as for coarse particles. Grade should not be a problem, unless significant amounts of composite particles are present, since entrainment only becomes significant at the lower end of this size range.
3. Fine Size Particles - Grade problems occur because of gangue particle entrainment and flotation of composite particles. Poor recovery of fine coal is often observed due to problems associated with bubble-particle aggregate formation.

Solutions to each of these problems can be found in either of two realms:

1. The physical, by using different cell types or operating conditions to alter hydrodynamics in the pulp and froth, e.g., use of mechanical vs. column cells.
2. The chemical, by altering particle hydrophobicity in the pulp or water behavior in the froth.

Of course, all nine of the general particle species are usually present in a feedstock and we cannot consider only the behavior of one size or surface wettability class at a time. However, by considering the relative abundance of each species it is possible to rationally select desirable alternatives prior to test work rather than using an entirely empirical approach.

Thousands of research papers and books have been published on the surface chemistry and general recovery or rate-of-recovery aspects of flotation behavior. The reference list only hints at this vast number. The mechanisms responsible for particle behavior are well identified in that work. However, many of the significant and useful implications of particle behavior are ignored or misunderstood because of a failure to consider them in the requisite detail. For example, there are several excellent reviews covering particular aspects of flotation behavior such as general surface chemistry and recovery aspects (Brown, 1962; Aplan, 1976; Fuerstenau et al., 1983); and Klimpel and co-workers (Klimpel, 1984; Klimpel and Hansen, 1987) discussed the fundamentals of general recovery and rate-of-recovery aspects of flotation process analysis.

It is particularly unfortunate that these scientists failed to comprehend the relative significance of physical mechanisms controlling flotation behavior. This led them to ignore the important role that particle size plays in flotation, regardless of the mechanism responsible for particle recovery. Consequently, although an unbelievable amount of time and effort has gone into coal flotation research, as evidenced by the literature, it is still difficult to use this knowledge to apply, optimize, and control coal flotation industrially, because a useful and comprehensive theory does not exist.

1.5 Statement of the Problem

Considerable thought and effort have gone into developing an explanation for the behavior of coal in flotation. However, although the general principles have been described, a theory correlating the mechanisms of particle behavior and process variables has not been developed. Thus, it is still difficult to apply, optimize, and control the process. A fundamentally based understanding is required because coals are heterogeneous in composition and in their response to flotation

Many variables influence flotation process performance [e.g., system chemistry, equipment design and operating variables, and particle characteristics (both physical and chemical)]. The variables in Table 1.1 and Figure 1.3 are classified either as independent or dependent. The former are either controlled variables or disturbances (that enter the circuit because of the heterogeneous nature of the feed or plant operating problems). The latter are responses of potential interest. The main objective of flotation process analysis lies in determining the effects of independent variables on the grade-recovery performance of a coal flotation circuit.

It is apparent from the discussion presented above that the two dependent variables, i.e., grade and recovery, are macro-level manifestations of the fundamental micro-level mechanisms responsible for particle behavior in flotation. Consequently, developing a comprehensive understanding of the flotation process means that the effects of independent variables should be assessed by considering, as much as possible, the following two levels of effects:

1. The macro-level effects of variables on the maximum recovery and rate-of-recovery of particle species.
2. The micro-level effects of variables on the physicochemical hydrodynamics of particle - bubble - water interaction in the pulp and froth phases responsible for the macro-level changes in the recovery and rate-of-recovery.

. Although it may seem simple, this type of analysis has not been used previously, largely because its significance and necessity has been overlooked. However, such an

Table 1.1. The Variables of Coal Flotation (after Sutherland and Wark, 1955, 13 - 23; Thorne et al., 1976).

Independent Variables		
Disturbance Variables		Coal Rank and Type
		Coal Oxidation
		Feed Size Distribution
		Presence of Clay Slimes
		Water Chemistry (pH, Water Hardness)
		Feedrate
		Feed Percent Solids
Control (Manipulated) Variables		
	Chemical	Frother Type and Dosage
		Collector Type and Dosage
		Modifier Type(s) and Dosage(s)
		Reagent Addition Points
	Physical (Mechanical)	Aeration
		Conditioning Time
		Impeller Speed
		Pulp Level
	Circuit Variables	Cell Configuration
		Cell Size and Type
		Number of Cells
Dependent (Measured) Variables		
		Composition (% Ash, % Fe)
		Flowrate
		Pulp Percent Solids
		Pulp Level
		Froth Thickness
		Power Input
		Recovery
		Circulating Loads

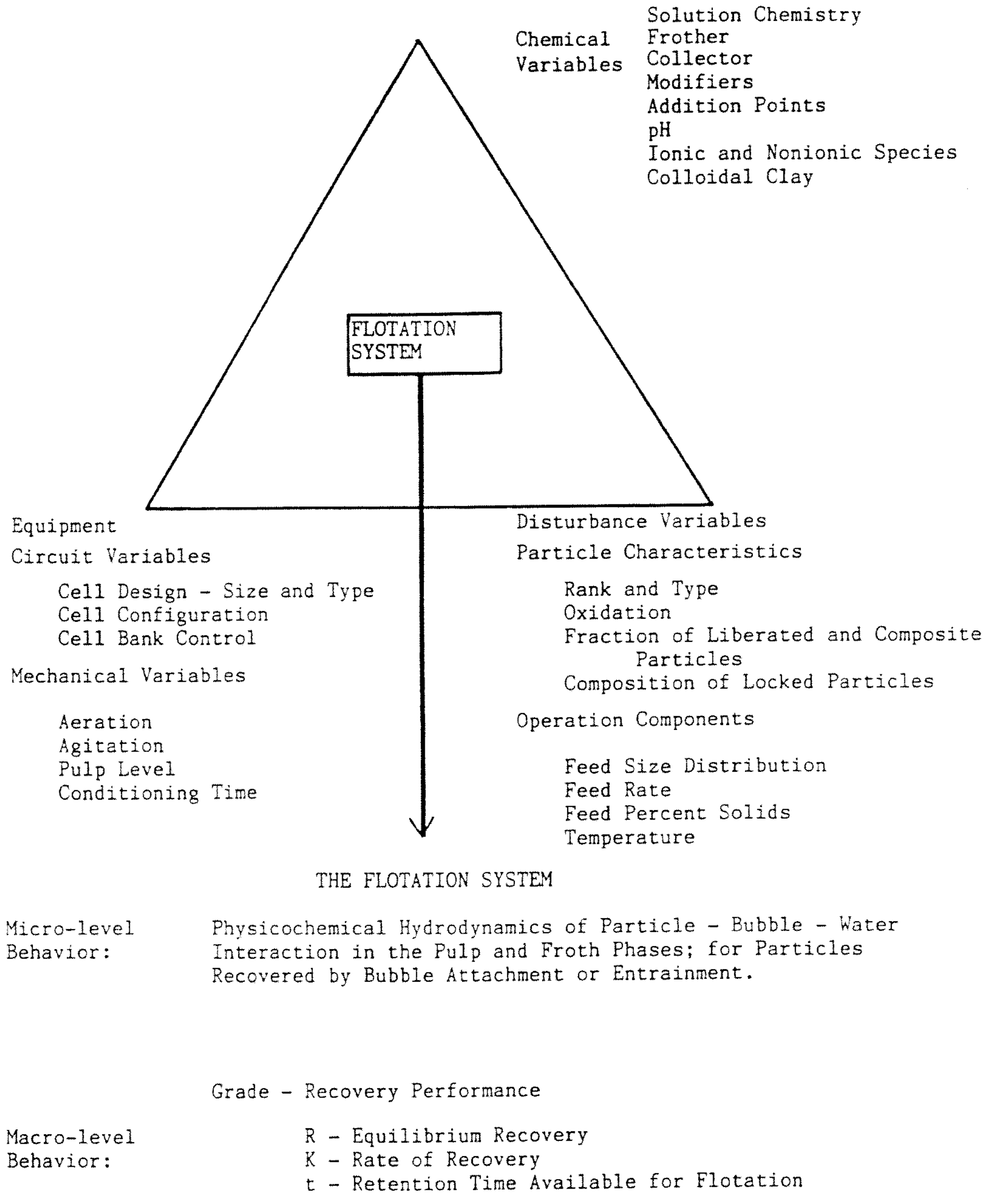


Figure 1.3. An Outline of the General Relationship Between Fundamental Physicochemical Phenomena, Independent Process Variables, and Grade - Recovery Performance in Flotation (Seitz and Kawatra, 1985a; Klimpel, 1985).

understanding of the effects of process variables would lead to improved application of the process by allowing engineers to move from the realm of "best engineering guesses" to scientific engineering prediction.

The objective of this dissertation was to take an initial step by developing a qualitative understanding of the effect of reagent regime on particle behavior from a mechanistic viewpoint based on considering a combination of chemical and hydrodynamic phenomena. This objective was addressed using the following approach:

A. Results from experimental test work and the literature were combined and used to formulate a theory explaining particle behavior based on:

1. Particle recovery occurring by either bubble attachment or entrainment as the basis for selectivity in separation.
2. Analysis indicating that particle behavior rather neatly, and mechanistically, falls into general categories according to particle size and composition, i.e., according to species. The correlation between mechanisms responsible for separation, species identity, and the effects of reagent regime provides a framework for understanding and predicting particle behavior.
3. Understanding how to control these mechanisms provides a rational basis for optimizing and controlling circuit performance.

B. Concurrent with the development of a qualitative, mechanistic model of particle behavior, some aspects were experimentally investigated and clarified by analyzing the response of particle species to variations in the reagent regime. Both lab and plant tests were performed on an anthracite coal (Panther Valley) and a bituminous coal (Kitt Mine).

. These studies were directed at correlating process grade-recovery response, particle size and composition, water recovery, and the critical role of the reagent regime. In particular, the effect of frother and collector dosages on grade-recovery response as a function of size was studied in the lab (Kitt Mine coal) and both sets of plant tests. The effect of particle composition was studied in lab tests (Kitt Mine coal). The effect of reagent regime on process kinetics was studied in select lab tests (Panther Valley coal) and both sets of plant tests. The relationships between particle and water recovery was also studied in both sets of plant tests, with particular attention paid to the control of fine particle entrainment by water recovery.

CHAPTER 2. EXPERIMENTAL WORK AND RESULTS

Experiments were designed to elucidate the behavior of particles in coal flotation and the effects of reagent regime on process behavior. They were also used to provide a basis for hypothesizing about the mechanisms responsible for particle separation by flotation. This necessitated both laboratory and plant scale tests, which were performed on:

A. An anthracite coal from the Mammoth seam, Southern Anthracite Coal Field, PA. (Panther Valley Mine).

B. A bituminous coal from the Lower Kittanning seam, PA. (Kitt Mine).

Detailed test procedures and results are described in later sections. The general objectives for each series of tests are summarized below for clarification.

A. Panther Valley Mine -- Plant Tests.

- Grade-recovery response as a function of size and reagent regime.
- Froth percent solids as a function of reagent regime.
- Kinetic and steady state selectivity (coal vs. ash) as a function of size and reagent regime.
- Comparison of plant and laboratory steady state recovery response as a function of size.

B. Panther Valley Mine -- Laboratory Tests.

- Grade-recovery response as a function of frother type, reagent regime, and time.
- Kinetic and steady state selectivity (coal vs. ash) as a function of frother type and reagent regime.

C. Kitt Mine -- Plant Tests.

- Grade-recovery response as a function of size and reagent regime.
- Rate of coal and ash recovery as a function of size and reagent regime.
- Steady state coal and ash recovery as a function of size and reagent regime.
- Correlation between recovery of water, coal and ash particles of various sizes, and reagent regime.
- Comparison of plant and laboratory steady state recovery as a function of size.

D. Kitt Mine -- Laboratory Tests.

- Grade-recovery response as a function of reagent regime.
- Grade-recovery response for selected size and density classes as a function of reagent regime. This was an examination of the behavior of composite particles.

Data was analyzed using a combination of grade-recovery analysis, as a function of time in some cases, and kinetic, recovery-time profile analysis for particle species. This approach was designed to illustrate the complementary nature of both forms of data analysis. It should be understood that profile analysis is useful for preliminary analysis and observing general trends. However, it is an additional step away from the raw data and, depending on the error present in fitting a first order model to a particular data set, a detailed analysis of the grade-recovery behavior may be necessary for verifying the fit and observing any fine trends present in the data.

The recovery-time response for particles recovered in flotation follows the characteristic profiles shown in Figure 3.3. This follows from the general first order rate of particle recovery. Having an equation to characterize this type of data is useful for both analysis and comparison purposes. A host of alternative equations have been developed for this purpose (e.g., see Dowling et al., 1984) and the question of which to use has been discussed in great detail by numerous researchers. For both theoretical and experimental reasons, the relationship between noise in response data and the resulting noise in fitted parameters must be considered prior to selecting a model (Reich, 1981). For example, Klimpel and co-workers (Klimpel, 1984; Dowling et al., 1984) used several detailed statistical model discrimination studies to show that typical recovery-time data can only support two parameter models. Of the two parameter models they tested, the one offering the most consistent flexibility and reliability was:

$$r = R \{ 1 - (1/Kt) [1 - \exp(-Kt)] \} \tag{2-1}$$

where r is the cumulative recovery of a given species; t is the time from initiation of the process; R is the maximum achievable recovery; and K is a first order rate constant. Consequently, Equation (2-1) was used, as required, for some of the analysis of species behavior in coal flotation reported herein. This nonlinear model arises from the occurrence of multiple first order components within a defined particle species, as shown by Klimpel (1980). The more commonly observed equation:

$$r = R [1 - \exp(-Kt)] \tag{2-2}$$

arises when all of the particles in a species have the same kinetic and equilibrium recovery characteristics. Models with different forms and/or more parameters can only be used in those cases where theoretical reasons and a statistical basis supporting their use exist.

Problems with model fit were observed for both the Kitt Mine plant data (Section 2.1.2.1) and Panther Valley lab data (Section 2.2.2.3). In both cases, R values greater than 100 were routinely obtained. This reflects the fact that most of the data was collected at low recovery, short times and only a limited amount of the data was collected at high recovery, long times. Accordingly, it was difficult to obtain good estimates of R, however, the R values should be comparable because of general similarities in the data sets. The K estimates are based on the initial portion of the curve and they should be reasonably good estimates of true values. The comparisons are further supported because similar conclusions were reached via use of both the grade-recovery vs. time and rate of recovery / maximum recovery (K / R) analyses. The term $r^{max.obs.}$ is used in this dissertation to describe the maximum observed recovery as opposed to R as defined for Equation (2-1). The two values should converge on the same value for long recovery times. In addition, the term reagent regime is used to describe different combinations of frother and fuel oil used as frother and collector, respectively.

Equation (2-1) can be applied to the recovery of different species (separate size and wettability fractions) or to the overall results of testing as follows:

1. To determine whether grade-recovery changes are due to kinetic or steady state effects. The significance of this difference is discussed below.
2. R and K data can be used to develop grade-recovery response curves for the system being studied, for different times, t; or to determine the effects of changing system variables which control R and K on grade-recovery response.

2.1 Plant Tests

2.1.1 Anthracite Coal

These tests were run at the Panther Valley Mine, Bethlehem Mines Corporation, Tamaqua, PA. This was an open pit mine recovering coal from the Mammoth, Forty-foot, Primrose, Orchard, and Buck Mountain seams in the Southern Anthracite Coal Field. The various seams treated at this operation are known to respond differently to flotation. Fortunately for testing purposes, most of the feed came from the Mammoth seam. The balance of the feed was comprised of innumerable blends of coals from all mined seams. Accordingly, only tests performed solely on Mammoth seam coal were subjected to a detailed analysis.

This coal preparation plant treated approximately 600 TPH in a combination heavy media bath / water separator / flotation circuit as follows:

Particle Size	**Process Circuit**	**Feedrate (TPH)**
6” X 9/16”	Heavy Media Drum	240
9/16” X 3/32”	Heavy Media Cone	180
3/32” X 3/64”	Hydrotator	40
3/64” X 28 Mesh	Hydroclassifier	50
28 X 200 Mesh	Flotation	40
- 200 Mesh	Slimes - to waste	50

The nominally minus 28 Mesh coal from DSM screens in the heavy media feed preparation circuit was deslimed in cyclones at approximately 200 Mesh. The 28 X 200 Mesh fraction was sent to flotation and the minus 200 Mesh fraction was rejected as tailings. The typical by-size weight and ash distribution for the flotation feed is given in Table 2.1.

Table 2.1. Typical Flotation Circuit Feed Analysis at the Panther Valley Mine.

Size		Weight %	% Ash
Mesh	Microns		
+ 14	+ 1180	0.62	9.54
14 X 28	1180 X 600	7.50	9.98
28 X 48	600 X 300	22.60	15.85
48 X 65	300 X 212	13.16	18.36
65 X 100	212 X 150	14.80	18.91
100 X 200	150 X 74	28.16	19.86
- 200	- 74	13.16	44.87

It is apparent that a significant fraction of the feed was actually outside the design limits of 28 and 200 Mesh. This reflects inefficient sizing at the plant level, a common occurrence in industrial operations.

The flotation circuit consisted of three rougher banks, each comprised of three 150 cubic feet WEMCO flotation cells. Each bank treated approximately 10 to 15 TPH of feed. The concentrate was dewatered using Bird centrifuges and tailings were pumped to a dewatering thickener.

In this study, a series of tests were run at frother and collector addition levels above and below the standard plant operating conditions of 0.4 lb./ton frother (PPG-200, a polypropylene glycol ether with a molecular weight of approximately 200) and 1.0 lb./ton No. 2 fuel oil. Three frother levels and two collector levels were used. All six possible combinations were tested as follows:

No. 2 Fuel Oil	Frother Dosage

Dosage (lb. / ton)	(lb. / ton)		
	0.2	0.4	0.6
0.7	X	X	X
1.4	X	X	X

Tests were run in a random order and each one was repeated several times.

The plant operated only one shift per day. Test work started each morning after the plant flows were stabilized. The volumetric feed rate of pulp and pulp percent solids were monitored for stability before and throughout each test period using an on-line ultrasonic flowmeter and density gauge combination. For each test, the reagent feeders were set at the appropriate level and a period of 60 minutes (i.e., several bank residence times) was allowed for the circuit to reach steady state. Then the following samples were collected at minute 60, 90, and 120:

1. flotation feed,
2. concentrate from each cell, and
3. pulp from each cell.

A test was rejected if the plant failed to maintain stable feed flowrates during the test period. In addition, operating feed records were studied after each day of testing. Only if all the plant feed during a shift was from the Mammoth seam were the samples analyzed further.

Samples from each selected test were analyzed for the following:

1. percent solids,
2. size distribution, and
3. ash content for the 14 x 28, 48 x 65, and -200 Mesh fractions.

This procedure was repeated for each test. The choice of sizes (14 x 28, 48 x 65, and - 200 Mesh) for these fractions was arbitrary, but designed to permit analysis of the three significant particle size ranges; i.e. coarse, intermediate, and fine.

2.1.1.1 Results

Due to the criteria for test acceptance or rejection that was discussed above, only seventeen of the fifty tests actually performed (34 %) yielded usable results. The grade-recovery behavior for individual size fractions in each test was calculated from the raw data. Then, this calculated data and the froth percent solids for all tests run under the same operating conditions were averaged. Those results are given in Appendix I. The most interesting responses are shown in Figures 2.1 - 2.6. A preliminary review of observations pertaining to each figure is presented below and a detailed discussion based on results from all of the plant and lab test work is given in Chapter 3:

1. Figure 2.1 (curve C): Coal recovery increased dramatically with decreasing size from 840 to 212 um, then leveled off from 212 to 74 um. Ash recovery also increased with decreasing size from 840 to 212 um, but decreased in going from the intermediate to fine size.
2. Figure 2.2: The change in frother and collector dosages (i.e., the reagent regime) had no effect on the grade-recovery curve for the 14 X 28 and 48 X 65 Mesh particles.
3. Figure 2.3: Increasing the frother dosage moved the grade-recovery curve for - 200 Mesh particles far to the right, i.e., the ash content for a given coal recovery increased by 10 to 15 percent. However, increasing the fuel oil dosage moved the grade-recovery curve only slightly to the right.

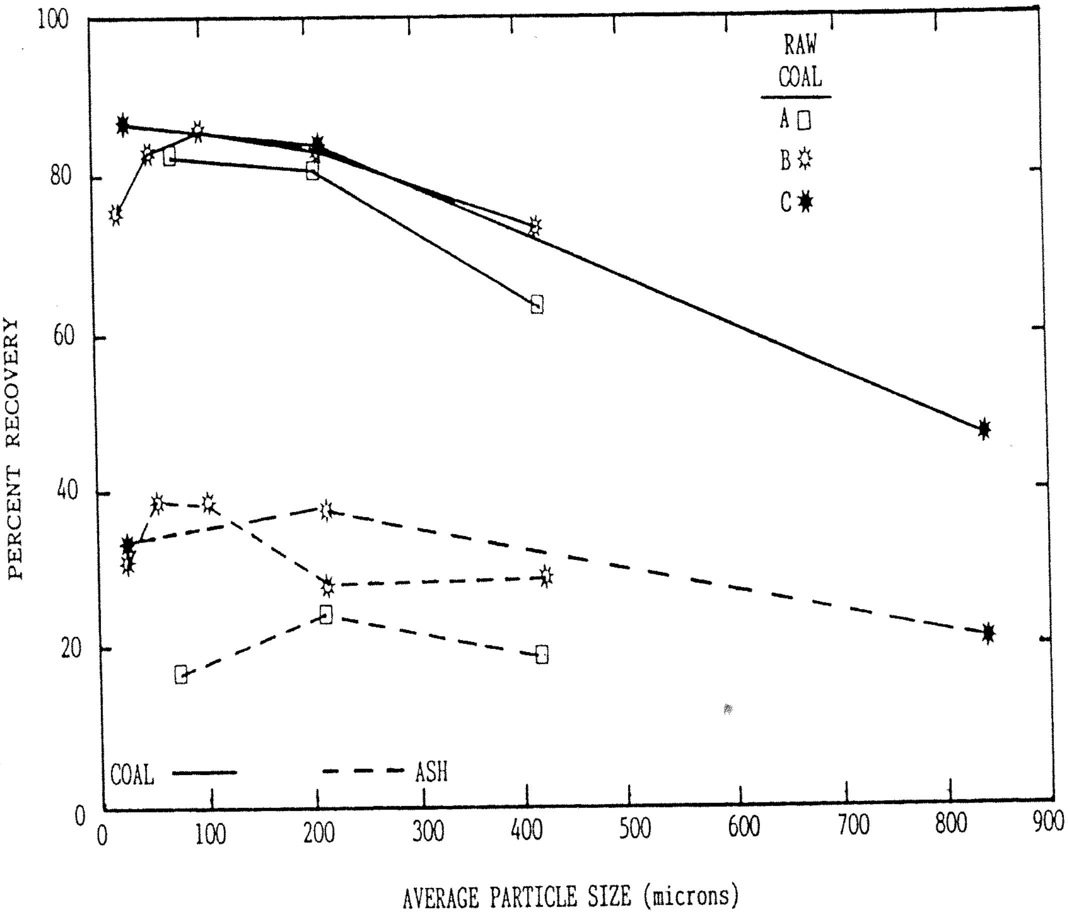


Figure 2.1. **The Recovery – Size Behavior of Coal and Ash in Three Industrial Coal Flotation Circuits: A. Lower Kittanning Seam Coal (Kitt Mine – see Appendix II), B. Blend of Lower Kittanning and Upper Freeport Seam Coals (Canturbury Mine), and C. Mammoth Seam Coal (Panther Valley Mine (see Appendix I). Data from this dissertation and Kawatra, Seitz, and Suardini (1984).**

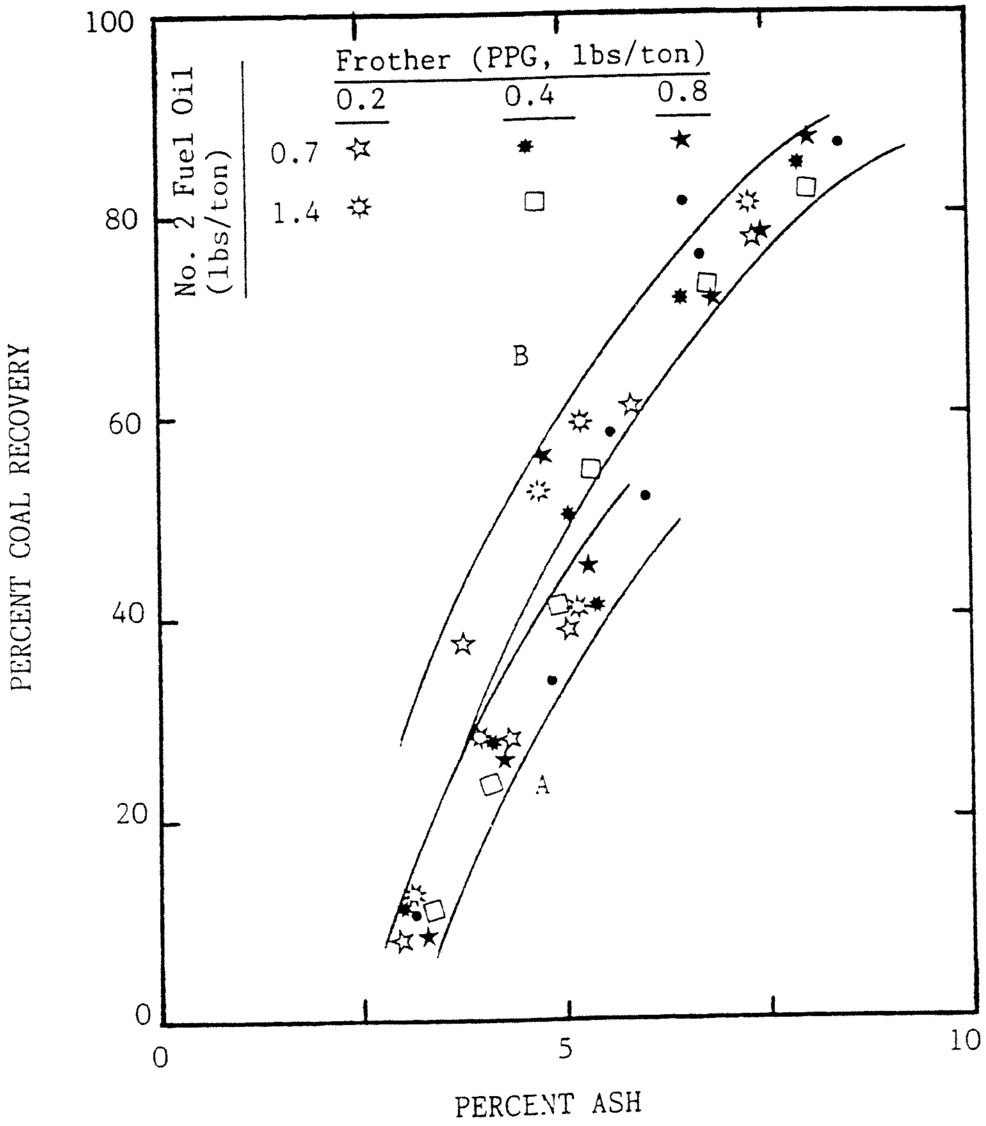


Figure 2.2. Grade – Recovery Performance of the Panther Valley Preparation Plant Flotation Circuit for 14 X 28 Mesh (A) and 48 X 65 Mesh (B) Size Fractions at Various Frother and No. 2 Fuel Oil Additional Levels.

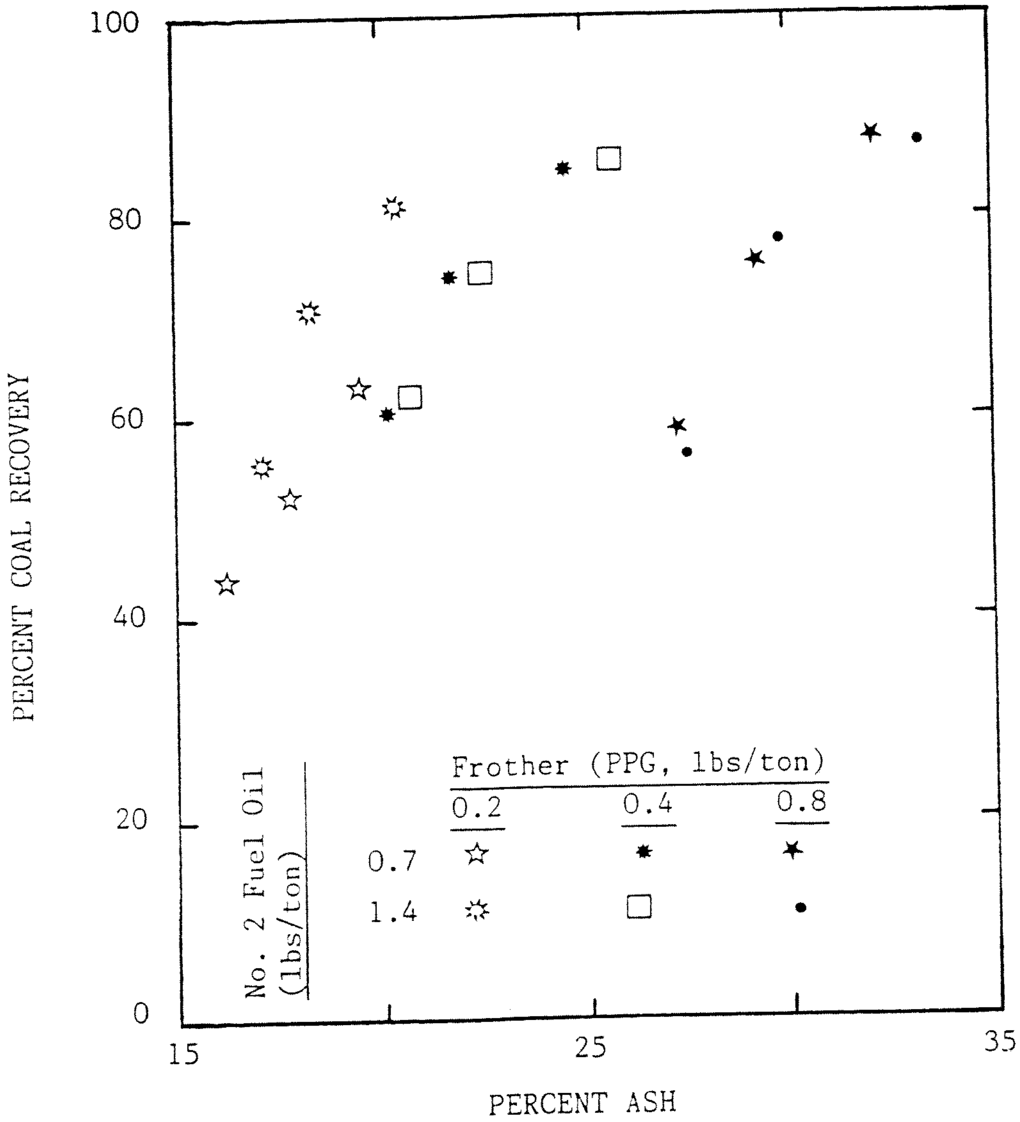


Figure 2.3. **Grade – Recovery Performance of the Panther Valley Preparation Plant Flotation Circuit for – 200 Mesh Size Fraction at Various Frother and No. 2 Fuel Oil Additional Levels.**

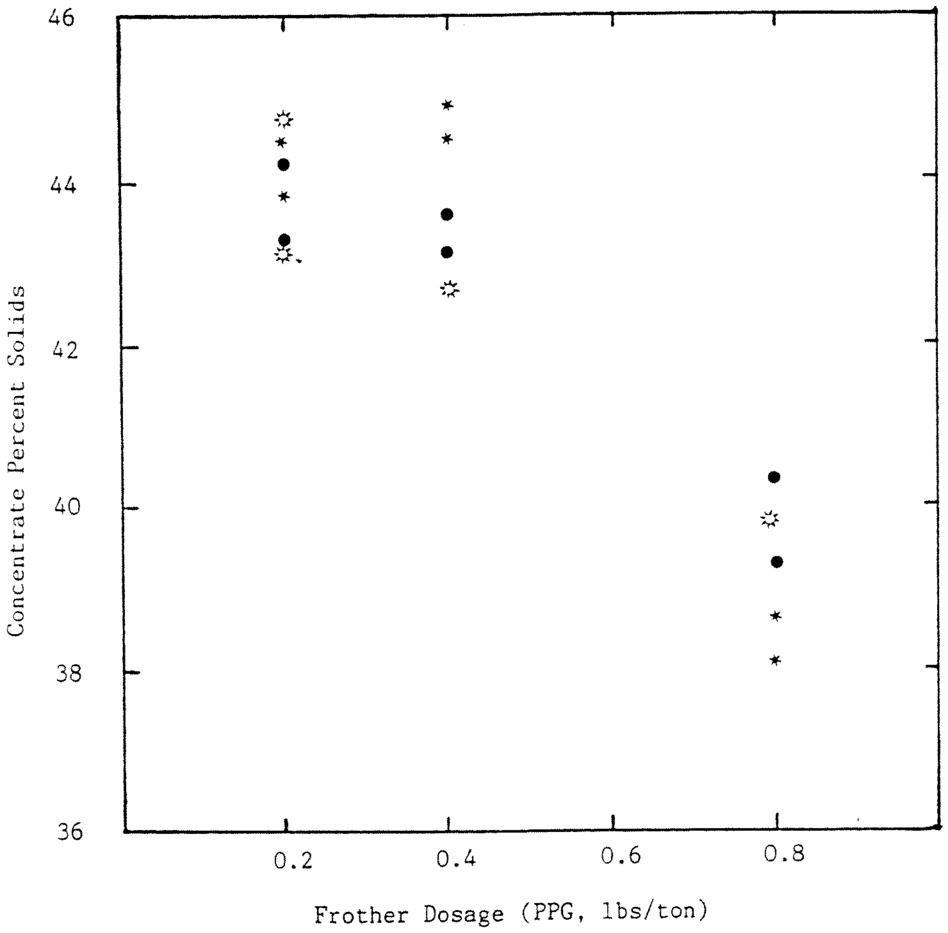


Figure 2.4. The Effect of Frother and Fuel Oil Dosage on Concentrate Percent Solids for the Panther Valley Preparation Plant Flotation Circuit.

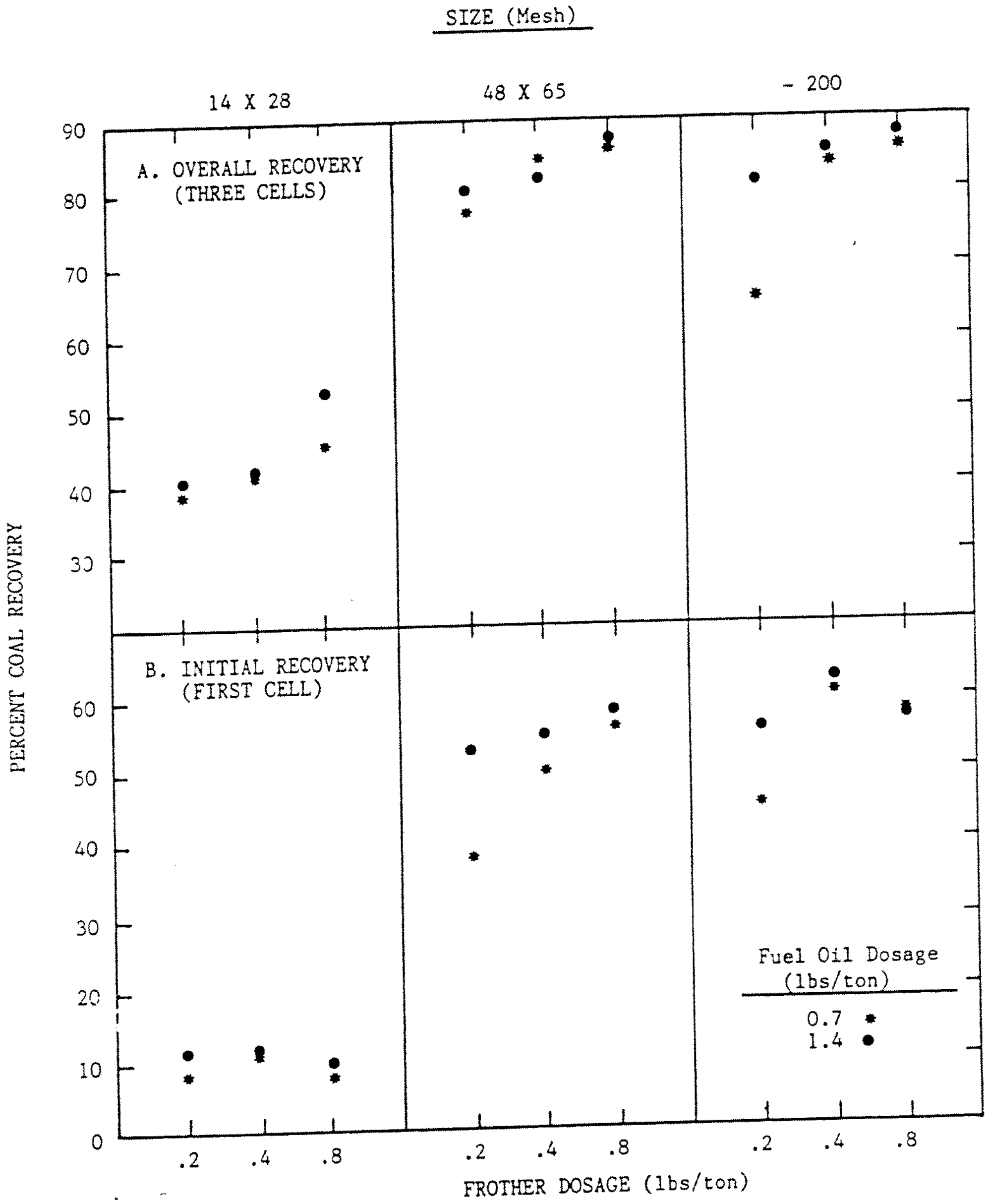


Figure 2.5. Coal Recovery – Reagent Dosage Response for Mammoth Seam Coal in the Panther Valley Preparation Plant Tests. Frother = PPG-200 and Collector = No. 2 Fuel Oil. A. Overall Recovery from Three Cells in the Bank and B. Initial Recovery from First Cell in the Bank.

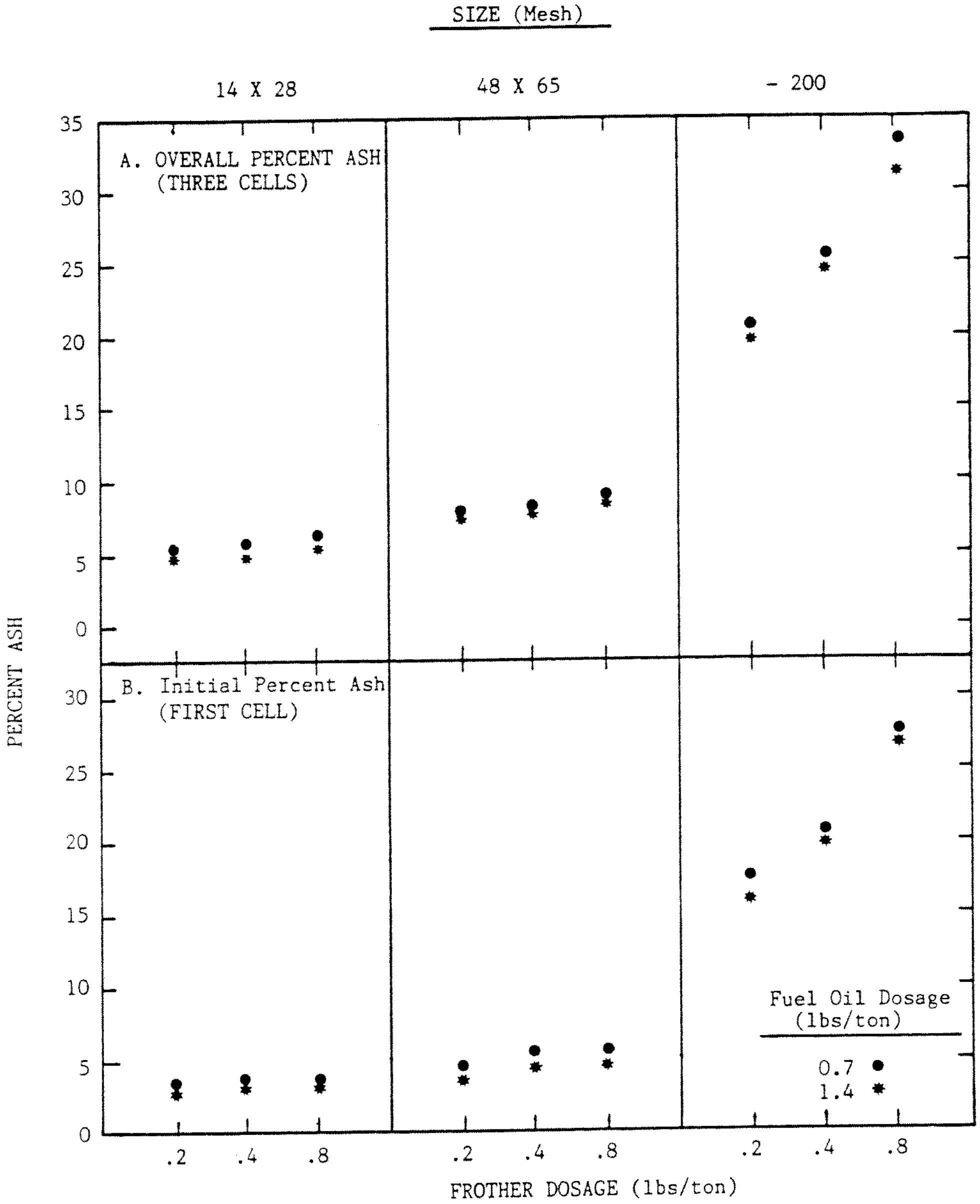


Figure 2.6. Percent Ash - Reagent Dosage Response for Mammoth Seam Coal in the Panther Valley Preparation Plant Tests. Frother = PPG-200 and Collector = No. 2 Fuel Oil. A. Overall Percent Ash from Three Cells in the Bank and B. Initial Percent Ash from First Cell in the Bank.

4. Figure 2.4: Increasing the frother dosage from 0.2 to 0.4 lb./ton had no effect on the froth percent solids. Further increasing the frother dosage from 0.4 to 0.8 lb./ton resulted in a drop in the froth percent solids. The fuel oil dosage had no effect on froth percent solids. This effect on water recovery is reflected in Figure 2.3, where the concentrate percent ash increased to a large extent with increasing frother addition, but only to a very limited extent with increasing fuel oil dosage.
5. It is not necessary to directly calculate R and K for comparative purposes in flotation process analysis, since useful relationships can be qualitatively inferred from the grade-recovery data measured at long and short flotation times. This is based on the first order response of particles as represented by Equations (2-1) and (2-2).

A. Figure 2.5: Coal recovery in the first cell was primarily controlled by the rate of recovery of coal species. Accordingly, the following observations were inferred from cell 1 recovery observations for the three coal species:

- The rate of recovery for 14 X 28 Mesh coal was unaffected by the reagent regime.
- The rate of recovery for 48 X 65 Mesh coal increased as the frother dosage went from low to moderate. Increasing the fuel oil dosage at low or moderate frother dosage also increased the rate of recovery. Further increase in the frother dosage, or changing the fuel oil dosage at the high frother setting had little effect. This response revealed the existence of optimal conditions under this reagent regime.

- The rate of recovery for - 200 Mesh coal increased as the frother dosage went from low to moderate (like the 48 X 65 Mesh coal); however, there was a drop-off at the high frother dosage. Altering the fuel oil dosage had no effect.

B. The combined coal recovery from all three cells ($r^{max.\ obs.}$) was a function of K, R, and t as shown by Equation (2-1). However, R was likely the controlling factor at this point near the end of flotation. Accordingly, the following observations were inferred from the overall recovery observations for the three coal species (i.e., size classes):

- $r^{max.\ obs.}$ for the 14 X 28 Mesh coal increased with increasing frother dosage. The fuel oil dosage was unimportant at the low and moderate frother dosage. At the high frother dosage, increasing the fuel oil dosage increased $r^{max.\ obs.}$.
- $r^{max.\ obs.}$ for the 48 X 65 Mesh coal increased with increasing frother dosage. Fuel oil dosage had no effect on $r^{max.\ obs.}$.
- $r^{max.\ obs.}$ for the - 200 Mesh coal increased with frother dosage. The fuel oil dosage had a large effect on $r^{max.\ obs.}$ at the low frother dosage. However, fuel oil dosage had no effect at the moderate and high frother dosages.

6. Figure 2.6:

A. Ash content in the cell 1 concentrate was primarily controlled by changes in the rate of recovery of ash species in comparison with coal species. This can be expressed as a kinetic selectivity ratio, (coal) / (ash), for each of the size ranges. Accordingly, the following observations were inferred from cell 1 percent ash observations:

- The kinetic selectivity ratio (coal) / (ash) for 14 X 28 Mesh species was unaffected by the reagent regime.
- The kinetic selectivity ratio (coal) / (ash) for 48 X 65 Mesh species decreased slightly with increasing frother dosage.
- The kinetic selectivity ratio (coal) / (ash) for -200 Mesh species decreased as frother dosage increases.
- These results revealed a trend towards greater recovery of ash bearing particles at finer sizes as the frother dosage was increased.
- Kinetic selectivity ratio (coal) / (ash) [all size fractions] was always slightly higher at the lower fuel oil dosage. This suggests that fuel oil increased the recovery of composite particles, as it was observed for all size fractions and not just the finest.

B. Ash recovery of the overall three cell product was also a function of K, R, and t as shown by Equation (2-1). However, R was likely the controlling factor at this point. The combined ash content is determined by the steady state selectivity ratio [$r^{max. obs.}$(ash)/$r^{max. obs.}$(coal)]. At extended times, this quantity is primarily a function of the maximum recovery selectivity ratio, i.e., R(coal)/R(ash), for each of the three size fractions. Accordingly, the following observations were inferred from the overall % ash observations:

- The steady state recovery selectivity ratio (coal)/(ash) [14 X 28 Mesh] decreased slightly with increasing frother dosage.
- The steady state recovery selectivity ratio (coal)/(ash) [48 X 65 Mesh] decreased slightly with increasing frother dosage from 0.2 to 0.4 lb./ton, then reached a plateau.

- The steady state recovery selectivity ratio (coal)/(ash) [-200 Mesh] decreased with increasing frother dosages. This reflected increased entrainment with decreasing size and increasing frother dosage.
- The steady state recovery selectivity ratio (coal) / (ash) was always very slightly higher at the lower fuel oil dosage. This reflected increased recovery of composite particles with increasing fuel oil dosage.

7. Plant recovery for each size fraction was always less than observed in lab tests, where it was above 95 % for the overall product.

2.1.2 Bituminous Coal

These tests were run at the Kitt No. 1 Mine, Clarksburgh, WV by Waters (1980) in the course of his MS-level research work. Waters collected a tremendous amount of raw data at that time, however, it was only partially analyzed as part of his MS-level research. As a full collaborator with him in a research group I assisted in the experimental design and initial analysis of raw data as reported in his thesis. Subsequently, that data was least-squares smoothed using an algorithm and associated program developed by Suardini (1982) and myself based on the work of Hodouin and Everall (1980). Results derived from that additional analysis are presented for the first time in this dissertation. Full details of experimental work are given in his thesis and only a summary is presented here.

This underground mine recovered coal from the Lower Kittanning seam. Nominally minus 28 Mesh (600 um) coal was the feed to flotation. The typical by-size ash and weight distribution for the flotation feed is given in Table 2.2. A large fraction of the feed was minus 44 microns. The coal in this seam typically contains a large fraction of ultrafine clay. The flotation circuit consisted of two banks of four 300 cubic feet Wemco cells. Each bank treated approximately 75 TPH of raw coal.

Table 2.2. Typical Flotation Circuit Feed Analysis at the Kitt Mine.

Size		Weight %	% Ash
Mesh	**Microns**		
28 X 48	600 X 300	13.97	10.76
48 X 100	300 X 150	20.42	11.00
100 X 140	150 X 106	16.15	14.48
140 X 200	106 X 74	10.09	17.99
200 X 270	74 X 53	10.09	20.78
270 X 325	53 X 44	6.06	21.02
- 325	- 44	23.22	37.34
Overall		100.00	19.94

Reagents used in the circuit were No. 2 fuel oil as a collector, MIBC as a frother, and a cationic flocculant to depress the clay slimes. The fuel oil and MIBC were both added to the feed box of each circuit and the flocculant was added directly to each cell. Only the effects of variations in fuel oil and frother dosages were investigated. The flocculant addition rate was held constant because:

1. there was a large fraction of ultrafine clay in the circuit feed that required depression and
2. potential problems associated with filtering a concentrate containing ultrafine clay caused the plant operators to avoid such variations.

This decision had a noticeable effect on test results which is discussed in more detail below.

A series of tests were run at frother and collector addition levels above and below the standard plant operating conditions. Two frother levels and four collector levels were used. All combinations were tested as follows:

No. 2 Fuel Oil Dosage (lb. / ton)	**Frother Dosage (lb. / ton)**	
	0.04	0.06
0.14	X	X
0.21	X	X
0.35	X	X
0.42	X	X

At the start of each test the reagent feeders were set at the appropriate rate and a suitable time was allowed for the circuit to reach steady state. Then the following samples were collected:

1. flotation feed,
2. froth from each cell, and
3. pulp from each cell.

Each sample was analyzed for the following:

1. percent solids,
2. size distribution, and
3. ash content for the entire sample and the +48, 48 x 100, and -100 Mesh size fractions.

This procedure was repeated for each test.

2.1.2.1 Results

The raw data from Waters (1980) was least-squares smoothed using an algorithm and associated program developed by Suardini (1982) and myself based on the work of Hodouin and Everall (1980). The result was an estimate of the volumetric flow rates for each of the solid species (+48, 48 x 100, and -100 Mesh coal and ash) and water in the flotation circuit under each of the eight test conditions (different frother and fuel oil dosage levels). The balanced data for each of the eight tests is given in Appendix II. Analysis of the recovery-time profiles resulting from each set of reagent regimes was performed using Equation (2-1).

The most interesting results are shown in Figures 2.1 and 2.7 to 2.13. A preliminary review of observations pertaining to each figure is presented below and a detailed discussion based on results from all of the plant and lab test work is given in Chapter 3:

1. Figure 2.1: Coal recovery increased with decreasing size from 425 to 212 um, then reached an apparent plateau from 212 to 74 um. Ash recovery was at a maximum for the intermediate size fraction.

2. Figures 2.7 a, b: The change in reagent regime had no effect on the grade-recovery response for the + 48 and 48 X 100 Mesh fractions. The grade-recovery response for the - 100 Mesh fraction was extremely noisy, with ash contents varying in a complex, possibly even random, fashion from 9 - 12 %. There was some indication that higher

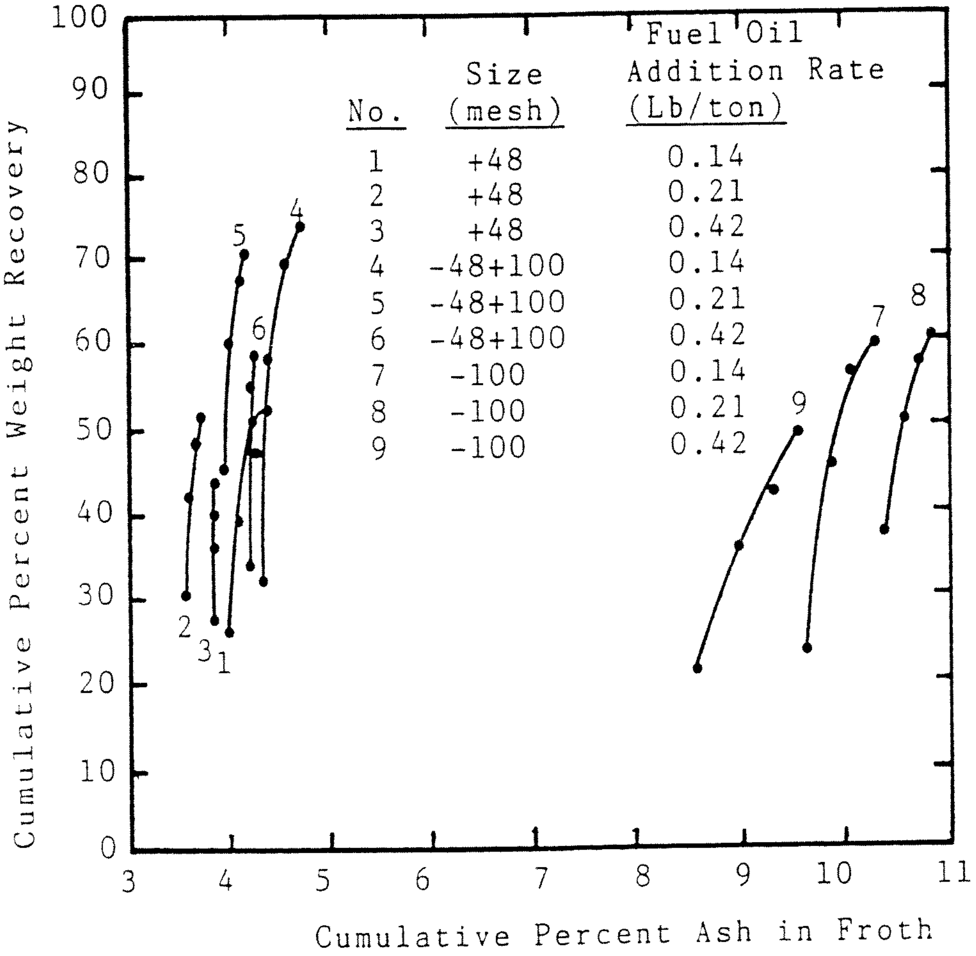


Figure 2.7a. Grade – Recovery Performance of the Kitt Mine Preparation Plant Flotation Circuit for Individual Size Fractions at a MIBC Addition Rate of 0.04 lb./ton and Fuel Oil Addition Rates of 100, 150, and 300 ml/min. (0.14, 0.21, and 0.42 lb./ton, respectively).

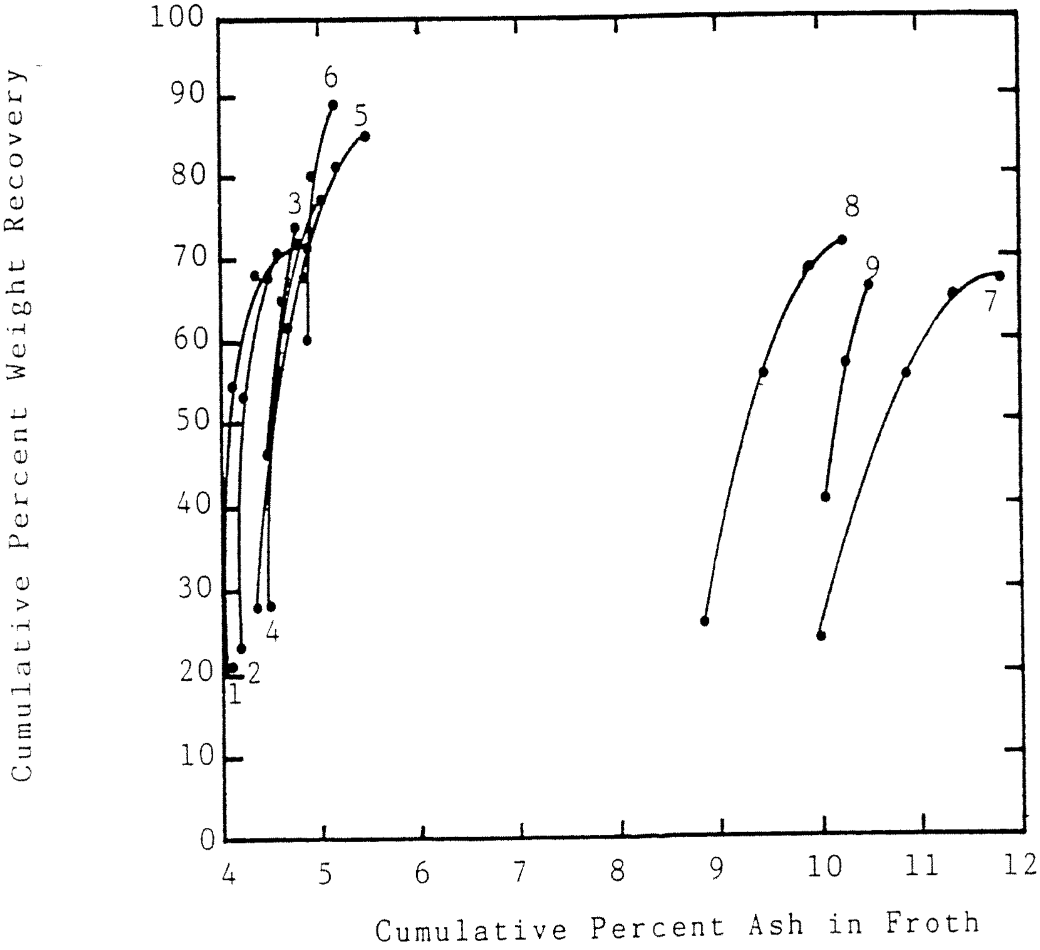


Figure 2.7b. Grade – Recovery Performance of the Kitt Mine Preparation Plant Flotation Circuit for Individual Size Fractions at a MIBC Addition Rate of 0.06 lb./ton and Fuel Oil Addition Rates of 100, 150, and 300 ml/min. (0.14, 0.21, and 0.42 lb./ton, respectively).

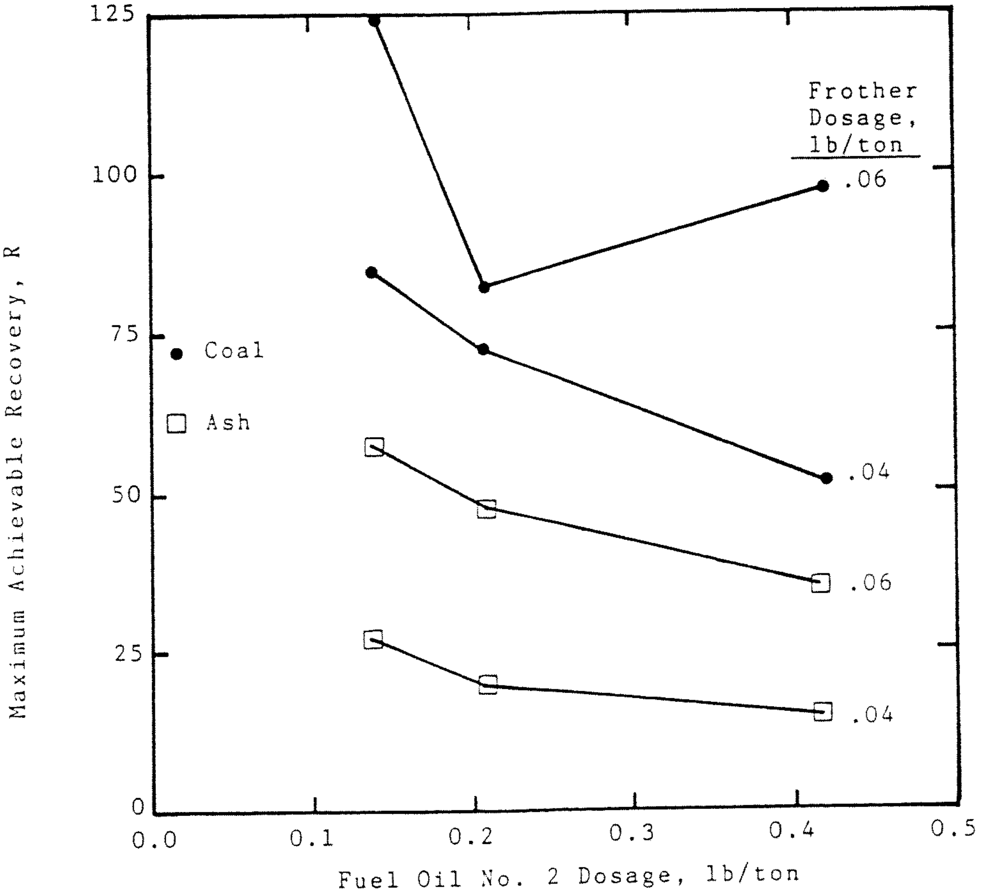


Figure 2.8a. The Effect of Frother and Collector Dosage on the Maximum Achievable Recovery of the Individual Size Fractions of a Lower Kittanning Seam Coal. A. + 48 Mesh Fraction.

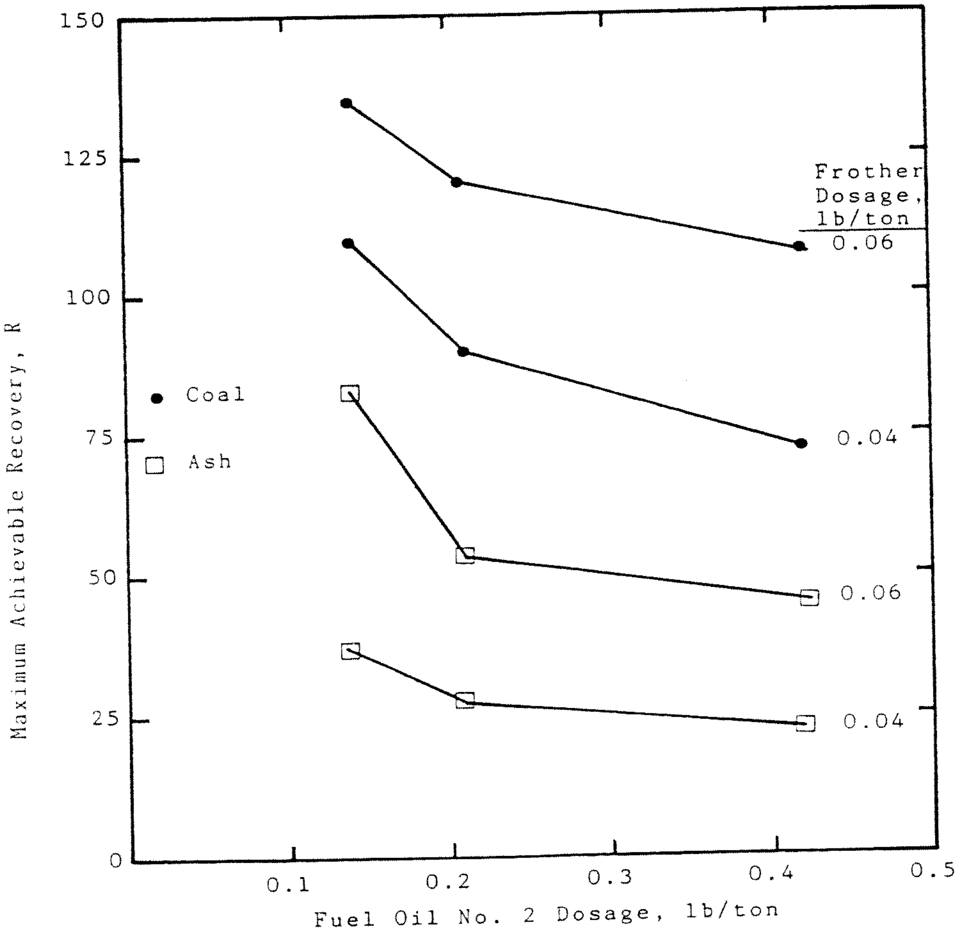


Figure 2.8b. The Effect of Frother and Collector Dosage on the Maximum Achievable Recovery of the Individual Size Fractions of a Lower Kittanning Seam Coal. A. 48 X 100 Mesh Fraction.

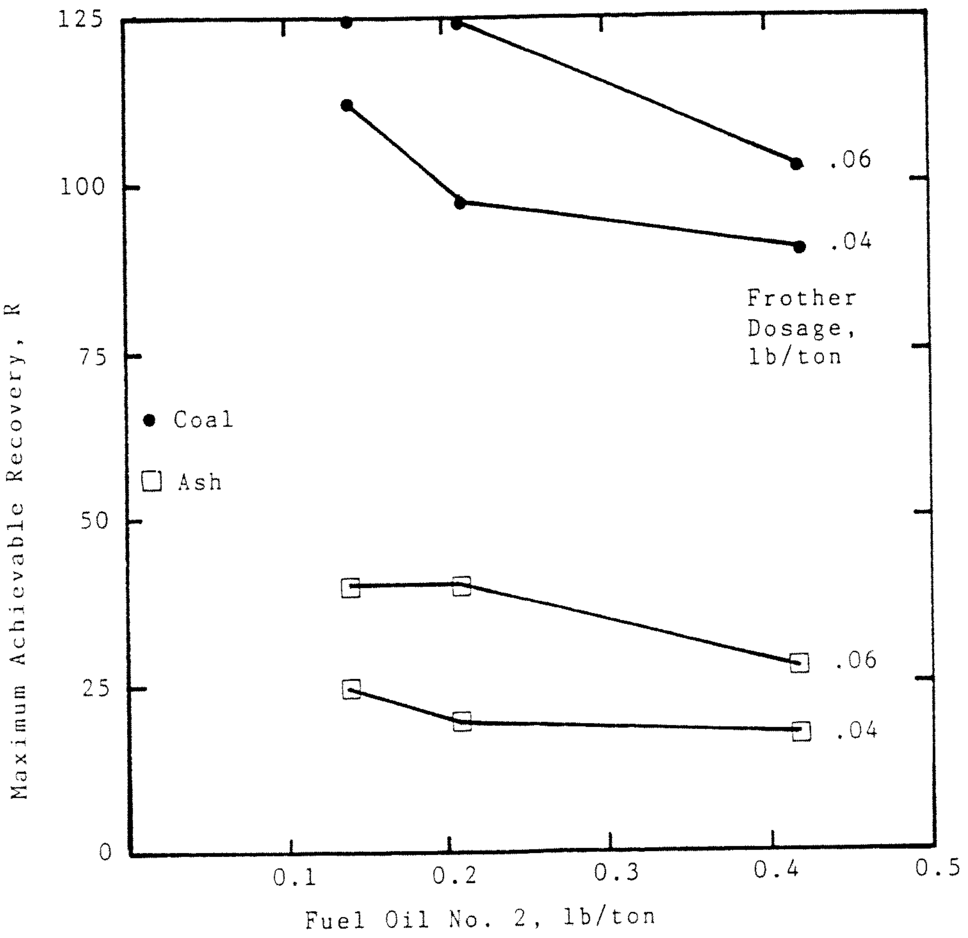


Figure 2.8c. The Effect of Frother and Collector Dosage on the Maximum Achievable Recovery of the Individual Size Fractions of a Lower Kittanning Seam Coal. A. - 100 Mesh Fraction.

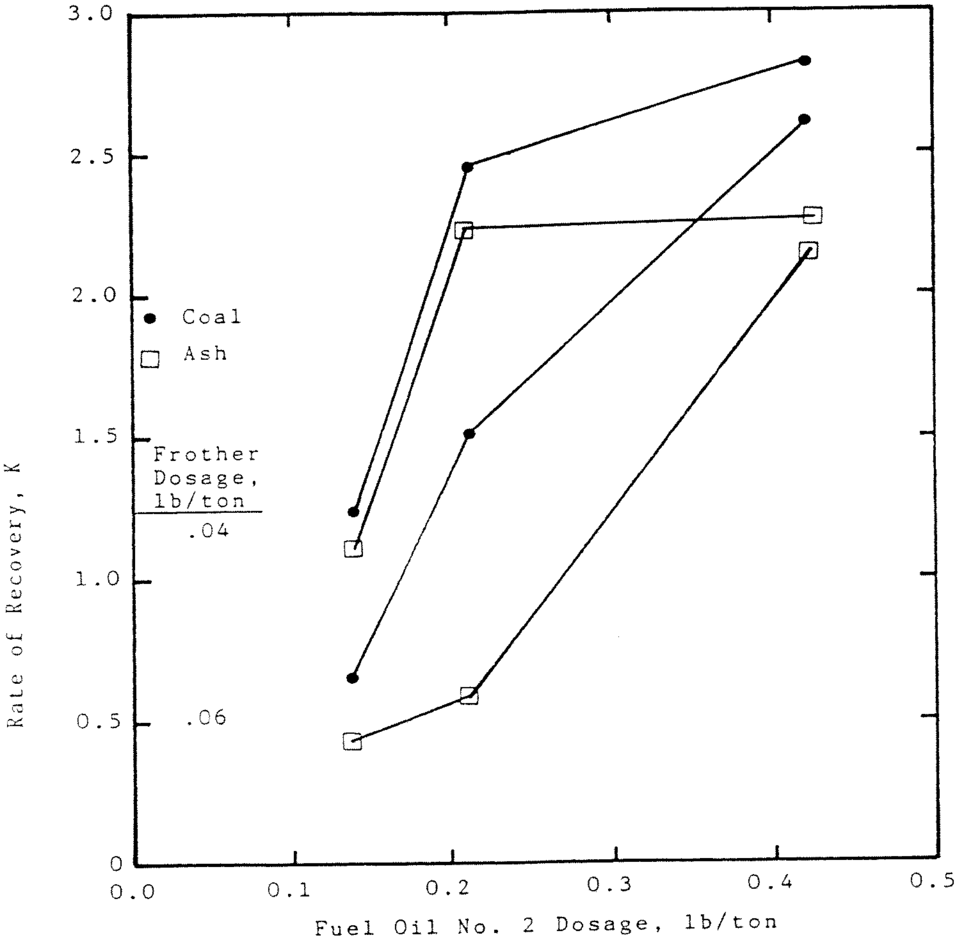


Figure 2.9a. The Effect of Frother and Collector Dosage on the Rate of Recovery of the Individual Size Fractions of a Lower Kittanning Seam Coal. A. + 48 Mesh Fraction.

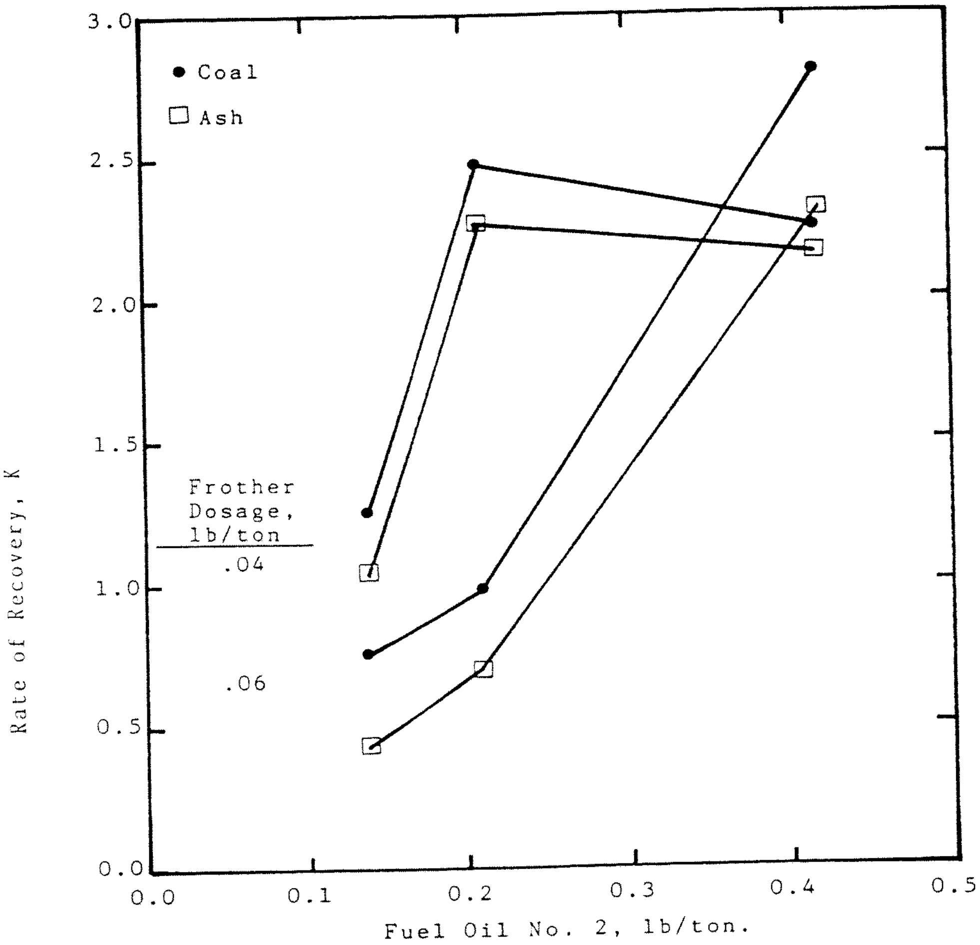


Figure 2.9b. **The Effect of Frother and Collector Dosage on the Rate of Recovery of the Individual Size Fractions of a Lower Kittanning Seam Coal. A. 48 X 100 Mesh Fraction.**

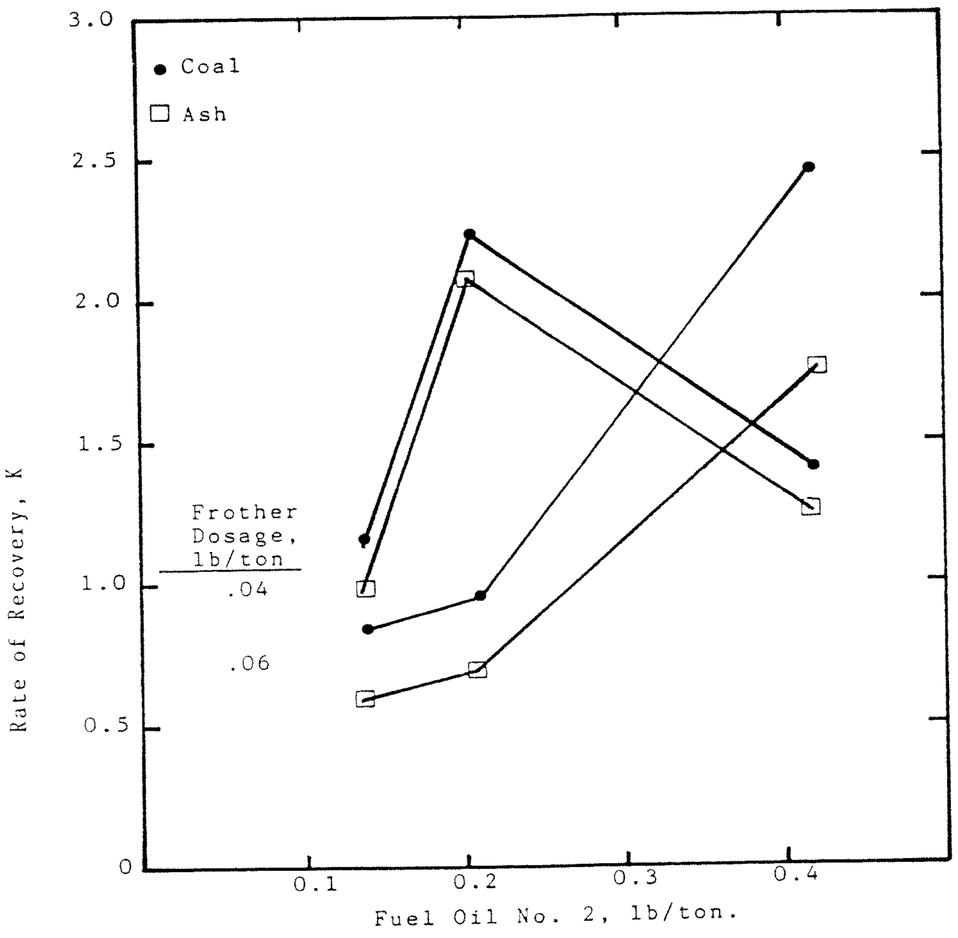


Figure 2.9c. The Effect of Frother and Collector Dosage on the Rate of Recovery of the Individual Size Fractions of a Lower Kittanning Seam Coal. A. - 100 Mesh Fraction.

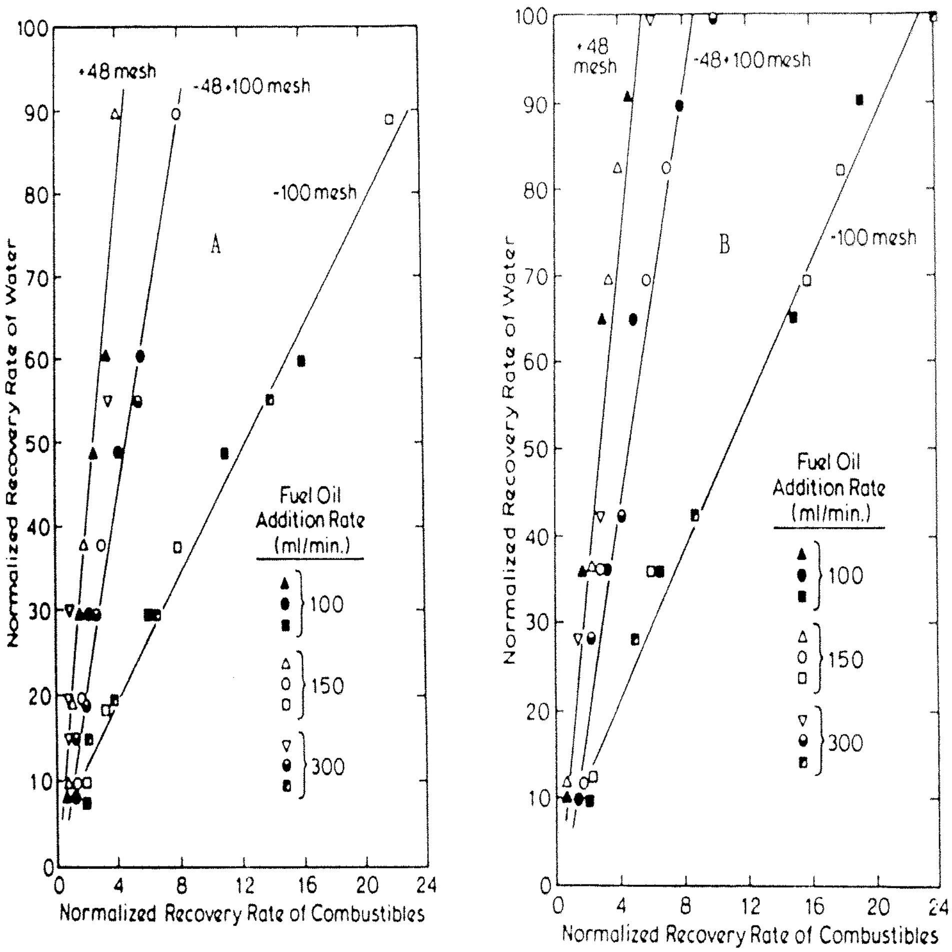


Figure 2.10. Relationship Between Water Recovery and Combustibles Recovery for Individual Size Fractions at MIBC Dosages of A. 0.04 and B. 0.06 lb./ton. All Test Data was Normalized to a Solids Feed Rate of 100. Fuel Oil Dosages of 0.14, 0.21, and 0.42 lb./ton (100, 150, and 300 ml/min., respectively).

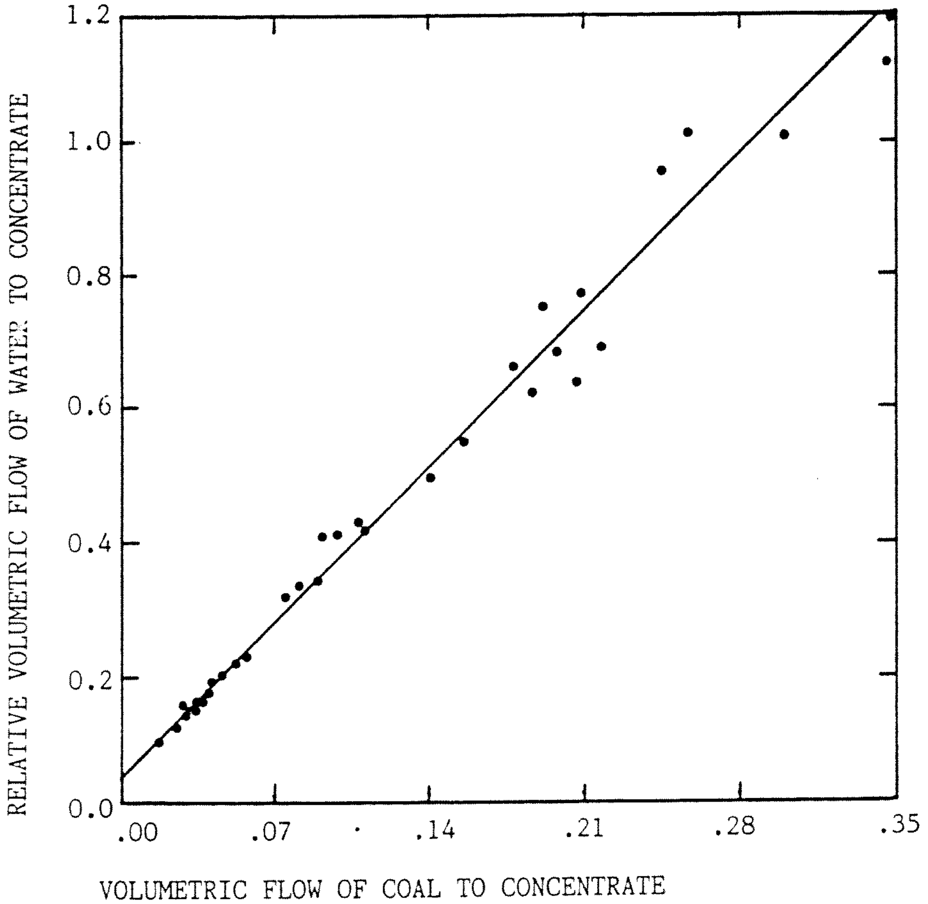


Figure 2.11. Relationship Between Water Recovery and Coal Recovery at the Kitt Mine. Data Points for all MIBC (0.04 and 0.06 lb./ton) and Fuel Oil (0.14, 0.21, 0.35, and 0.42 lb./ton) Reagent Combinations.

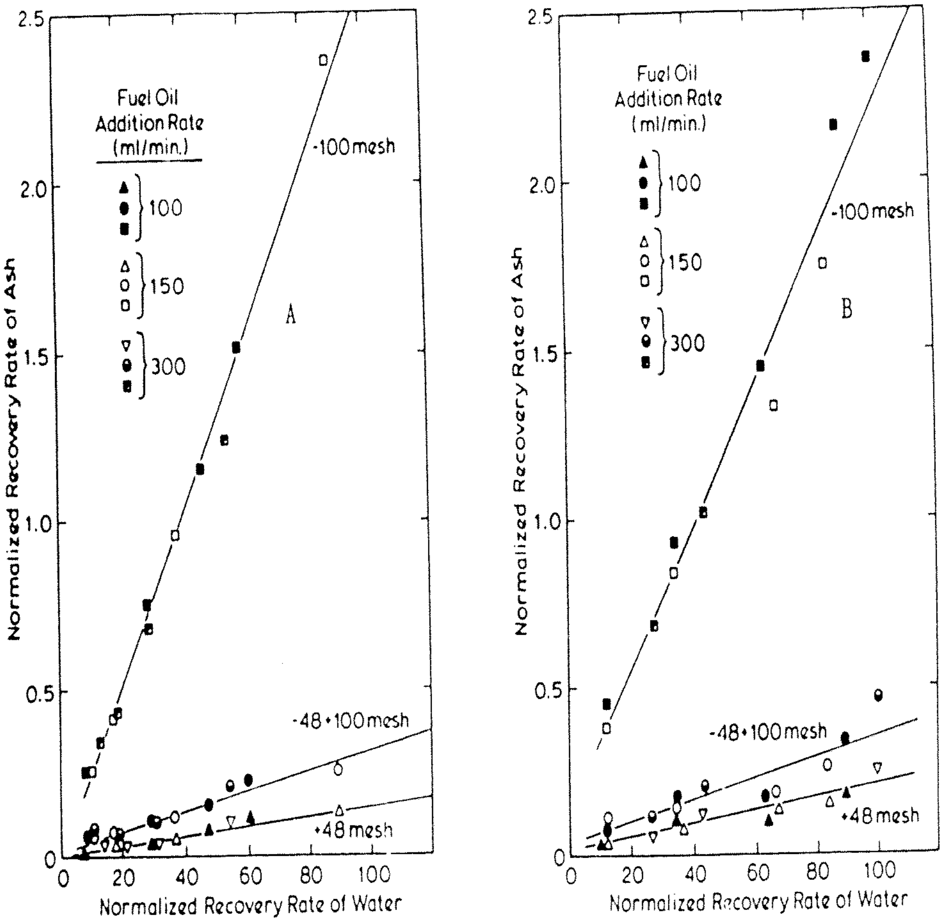


Figure 2.12. Relationship Between Ash Recovery and Water Recovery for Individual Size Fractions at MIBC Dosages of A. 0.04 and B. 0.06 lb./ton. All Test Data was Normalized to a Solids Feed Rate of 100. Fuel Oil Dosages of 0.14, 0.21, and 0.42 lb./ton (100, 150, and 300 ml/min., respectively).

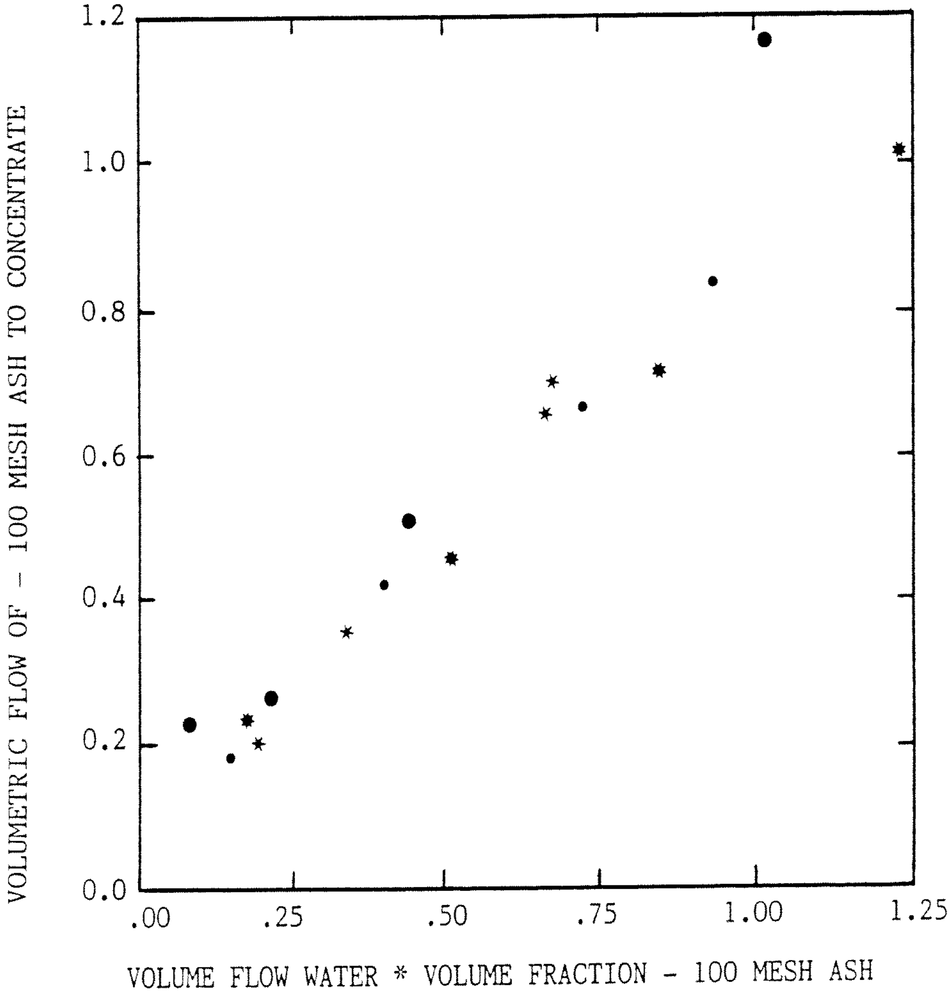


Figure 2.13a. Relationship Between Volumetric Flow of – 100 Mesh Ash into the Concentrate and Volumetric Flow of Water * Volume Fraction of – 100 Mesh Ash in the Pulp. A. MIBC Dosage of 0.04 lb./ton and Fuel Oil Dosages of 0.14, 0.21, 0.35, and 0.42 lb./ton.

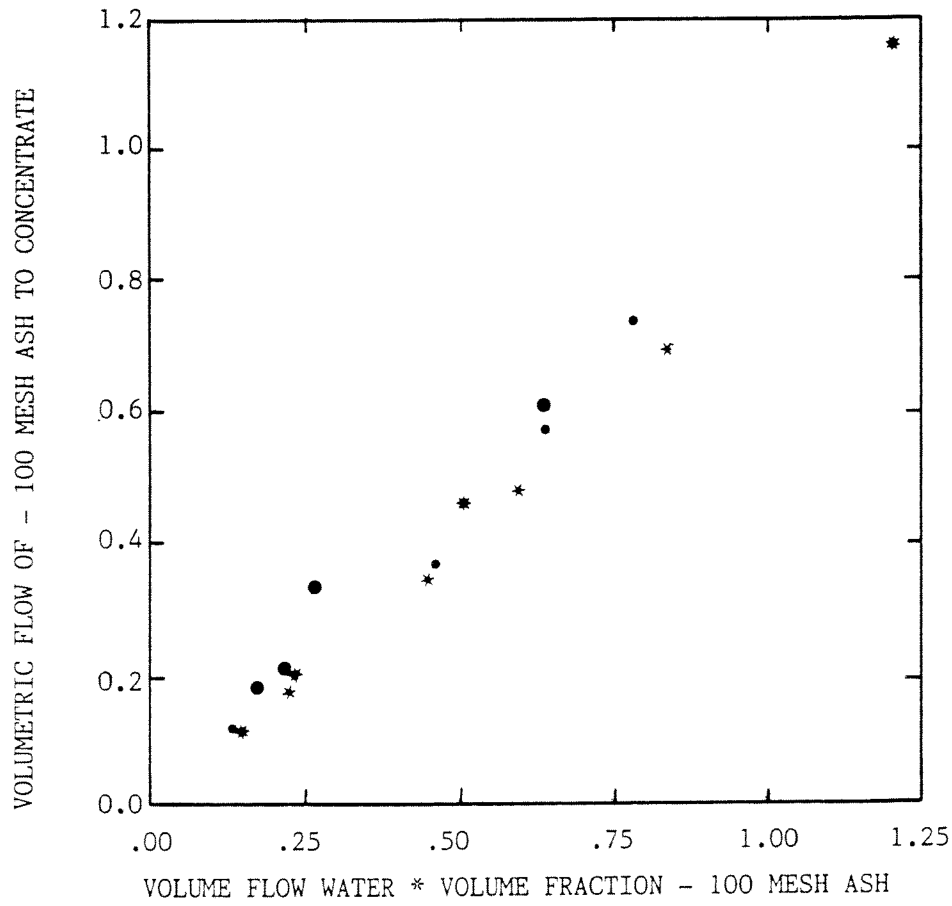


Figure 2.13b. **Relationship Between Volumetric Flow of – 100 Mesh Ash into the Concentrate and Volumetric Flow of Water * Volume Fraction of – 100 Mesh Ash in the Pulp. B. MIBC Dosage of 0.06 lb./ton and Fuel Oil Dosages of 0.14, 0.21, 0.35, and 0.42 lb./ton.**

3. fuel oil dosages reduced the concentrate ash content, possibly due to modified froth drainage.

   The small correlation between reagent regime and ash content for the - 100 Mesh fraction may reflect the use of a flocculant in this circuit. Flocculated fine ash particles would tend to behave as larger particles, perhaps even as intermediate size particles, and exhibit less entrainment. The flocculant dosage (lb./ton) may have varied, depending on the actual circuit feedrate, leading to the noisy response for the - 100 Mesh fraction.

   Higher frother dosages lead to increased recovery at all fuel oil dosage levels.

4. Figures 2.8 a, b, c: R for all species increased with increased frother dosage and decreased with increased fuel oil dosage.

4. Figures 2.9 a, b, c:

A. At the high frother dosage, K(all coal and ash species) increased with increasing fuel oil dosage. However, at the low frother dosage:

- K(+ 48 and 48 X 100 Mesh fractions of coal and ash) increased with increasing fuel oil dosage from the low to medium dosage and were relatively constant from the medium to high dosage.
- K(- 100 Mesh fraction of coal and ash) reached a maximum value at the intermediate dosage then decreased.

B. The effect of changes in frother dosage were:

- K(+ 48 Mesh fractions of coal and ash) decreased with increasing frother dosage at all fuel oil dosages.
- K(48 X 100 and - 100 Mesh fractions of coal and ash) decreased with increasing frother dosage at the low and medium fuel oil dosages.
- K(48 X 100 and - 100 Mesh fractions of coal and ash) increased with increasing frother dosage at the high fuel oil dosage.

C. As particle size decreased from + 48 to - 100 Mesh, K at the high fuel oil dosages changed from being equal at the low and high frother dosages to being less at the low frother dosages. This reflects reduced froth fluidity at low frother dosages and an increased probability of drainage for fine particles.

D. There were interactions between the increasing R and decreasing K parameters because some of the additional floated material consisted of composite particles with a lower rate of recovery. This conclusion was supported by lab results for Kitt Mine coal presented in Section 2.2.1.3.

E. The impact of increases in R coupled with decreases in K has been labeled as rate crossovers by Klimpel (1980). Their importance in flotation process analysis lies in the fact that, depending on the amount of retention time available in a plant system in comparison to the time required to nearly reach the equilibrium recovery, a plant system may be controlled by either K or R. Therefore, in some systems, improving R at the expense of reducing K, or vice versa, may actually reduce process efficiency; i.e., the opposite of the desired effect.

5. Figures 2.10 and 2.11:

A. A linear relationship existed between the recovery rates of all coal species and water under all reagent regimes.

B. The linear relationship for each coal specie was invariant under conditions of varying frother and fuel oil dosages.

C. The slopes of the curves in Figure 2.10 were directly related to the flotation circuits feed size distribution as given in Table 2.2 (i.e., +48 Mesh = 13.97 %, 48 X 100 Mesh = 20.42 %, and - 100 Mesh = 65.61 %). From a mechanistic point of view it appears that bubble-particle aggregates were carrying water into the concentrate (Kawatra and Seitz, 1984). Adding up the volumetric flows of all coal species into the concentrate and plotting them against the volumetric flow of water to the concentrate gave the linear relationship shown in Figure 2.11. This figure includes data points for all tested frother and fuel oil dosage combinations.

6. Figure 2.12:

A. A linear relationship existed between the recovery rates of all ash species and water under all reagent regimes.

B. The linear relationship for each ash specie was invariant under conditions of varying frother and fuel oil dosages.

C. The slopes for the + 48 and 48 X 100 Mesh size species and their recovery in comparison with the corresponding coal specie was directly related to the feed size distribution and the ash content of free and locked coal particles (this data is presented in Section 2.2.1.3). The slope for - 100 Mesh ash particles was much greater than expected from such analysis. This suggests fine ash was preferentially recovered into the concentrate.

7. Figures 2.13 a, b:

A. Indicated that the volumetric fraction of - 100 Mesh ash in the pulp in each cell did not affect the observed linear relationship between particle and water recovery in any fashion other than altering the axis.

B. Frother and fuel oil dosages influenced entrainment behavior by decreasing water recovery, not by altering the relationship between water and particle recovery.

8. Data given in Appendix II suggest that a maximum transport capacity of solids through the froth into the concentrate exists, regardless of the volume of coal in the cell or the reagent regime, for a particular system.

2.2 Laboratory Tests

2.2.1 Bituminous Coal Samples

Laboratory flotation tests were conducted with coal obtained from the Kitt Mine flotation circuit feed. A bulk sample was collected incrementally over a period of several days, air dried, mixed, and split by riffling into approximately 200 gram samples for tests. Table 2.2 gives the typical by-size ash and weight distribution for the flotation feed.

2.2.1.1 Equipment and Procedures

These tests were performed using a Denver D-12 laboratory flotation machine, with a 2.2 liter glass flotation cell.

General operating conditions were:

1. Houghton, MI city tap water, with a natural pH in the range of 6 to 8 was used.
2. Impeller speed equal to 1200 rpm.
3. The slurry percent solids was 9.6 percent.
4. The natural pulp pH was used and no pH adjustment was made.
5. Natural (self-induced) aeration was used.

The following procedure was established for this series of tests through preliminary experiments and past experience:

1. Each coal sample was conditioned in the cell for two minutes prior to reagent addition.
2. The collector (fuel oil) was added first and conditioned with the pulp for one minute. Then the frother was added and conditioned with the pulp for thirty additional seconds.
3. After conditioning, the air valve was opened.
4. Froth was scraped from the pulp until it was barren of coal. This usually took approximately three minutes.
5. A constant pulp level was maintained during the froth collection period by manually adding water as required.
6. The concentrate and tailings were filtered, dried, and weighed.

7. Separate riffled portions of these fractions were analyzed and screened at 48 and 100 Mesh.
8. The individual size fractions (+48, 48 X 100, and -100 Mesh) were weighed and analyzed for ash content.
9. Data for all of these tests is given in Appendix III.

2.2.1.2 Flotation Test Conditions

All possible combinations of three MIBC frother levels and eight No. 2 fuel oil levels were used for a total of twenty-four tests. Table 2.3 gives the reagent schedule for the test program. Tests were run in a random order to minimize errors.

Table 2.3. Reagent Schedule for Lab Test Series A on Lower Kittanning Seam Coal.

No. 2 Fuel Oil Dosage (lb. / ton)	Frother Dosage (lb. / ton)		
	0.108	0.216	0.324
0.084	1	9	17
0.168	2	10	18
0.252	3	11	19
0.336	4	12	20
0.420	5	13	21
0.504	6	14	22
0.588	7	15	23
0.672	8	16	24

An additional series of tests was performed to further explore the response of this coal to flotation. The procedure described above was used with these reagent levels:

Test No.	No. 2 Fuel Oil Dosage (lb. / ton)	Frother Dosage (lb. / ton)
26	0.084	0.167
27	0.672	0.167
28	1.340	0.167

These levels were selected to give a range of grade-recovery response. Each test was replicated, for a total of six tests, which were run in a random order. The concentrate and tailings were filtered, dried, and weighed. Separate riffled portions of these fractions were analyzed and screened at 48 and 100 Mesh. The individual size fractions (+48, 48 X 100, and -100 Mesh) were weighed, then separated according to density (specific gravity equal to 1.3 and 1.9). These specific gravity fractions, i.e., + 1.3, 1.3 X 1.9, and -1.9, are labeled as 1.25, 1.6, and 2.0, respectively. The individual size and gravity fractions were weighed and analyzed for ash content. Results for duplicate tests were averaged and are given in Appendix III.

2.2.1.3 Results

The detailed by-size and overall test results are given in Appendix III. The most interesting results are shown in Figures 2.14 to 2.21. A preliminary review of observations pertaining to each figure is presented below and a detailed discussion based on results from all of the plant and lab test work is given in Chapter 3:

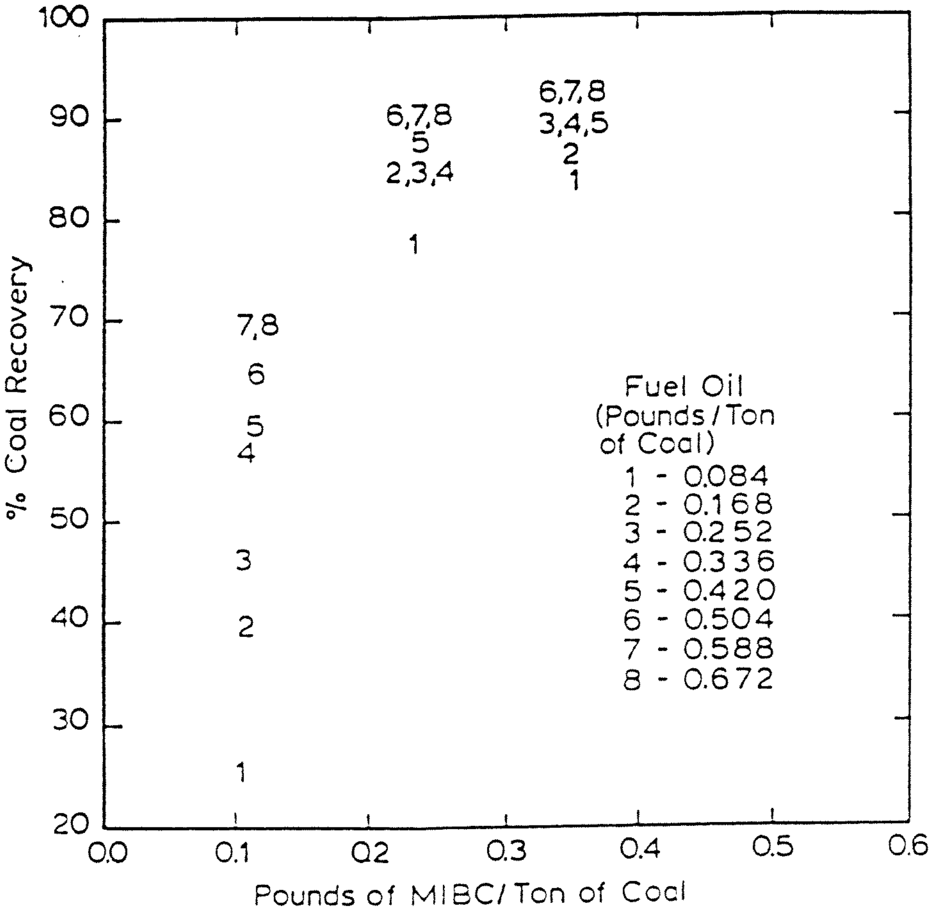


Figure 2.14. The Effect of MIBC Addition Level on the Percent Coal Recovery at Different Fuel Oil Addition Levels (lab tests on samples from the Kitt Mine Preparation Plant) (Kawatra and Seitz, 1984).

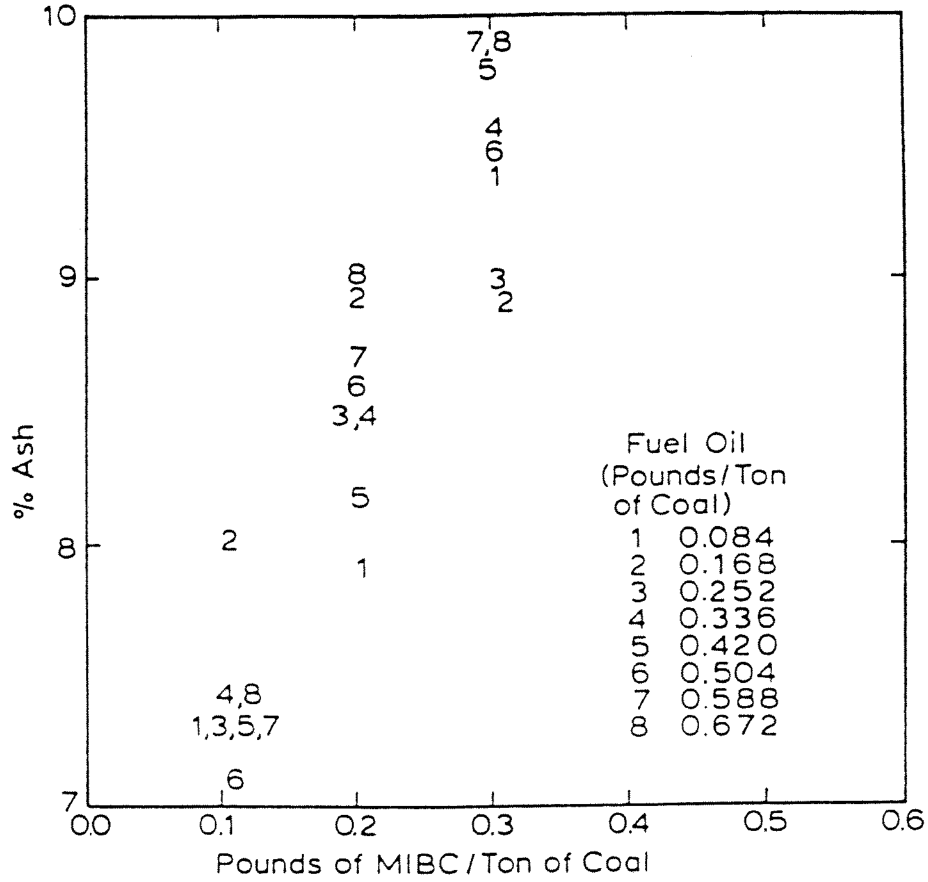


Figure 2.14. The Effect of MIBC Addition Level on the Concentrate **Percent** Ash **Recovery at Different Fuel Oil Addition** Levels (lab tests on samples from the Kitt Mine Preparation Plant) (Kawatra and Seitz, 1984).

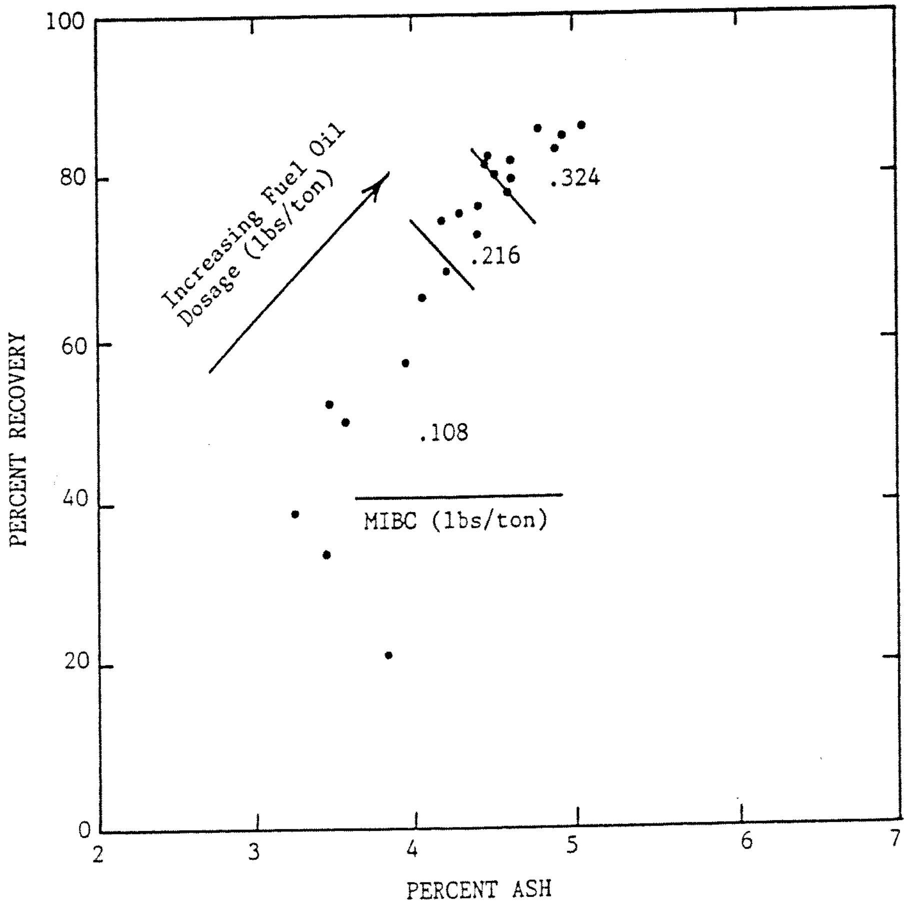


Figure 2.16a. Grade – Recovery Response for + 48 Mesh Fraction of Lower Kittanning Seam Coal in Laboratory Tests. Fuel Oil Dosage (lb./ton) was Increased from 0,.084 to 0.672 in Equal Increments for Each MIBC Dosage Level.

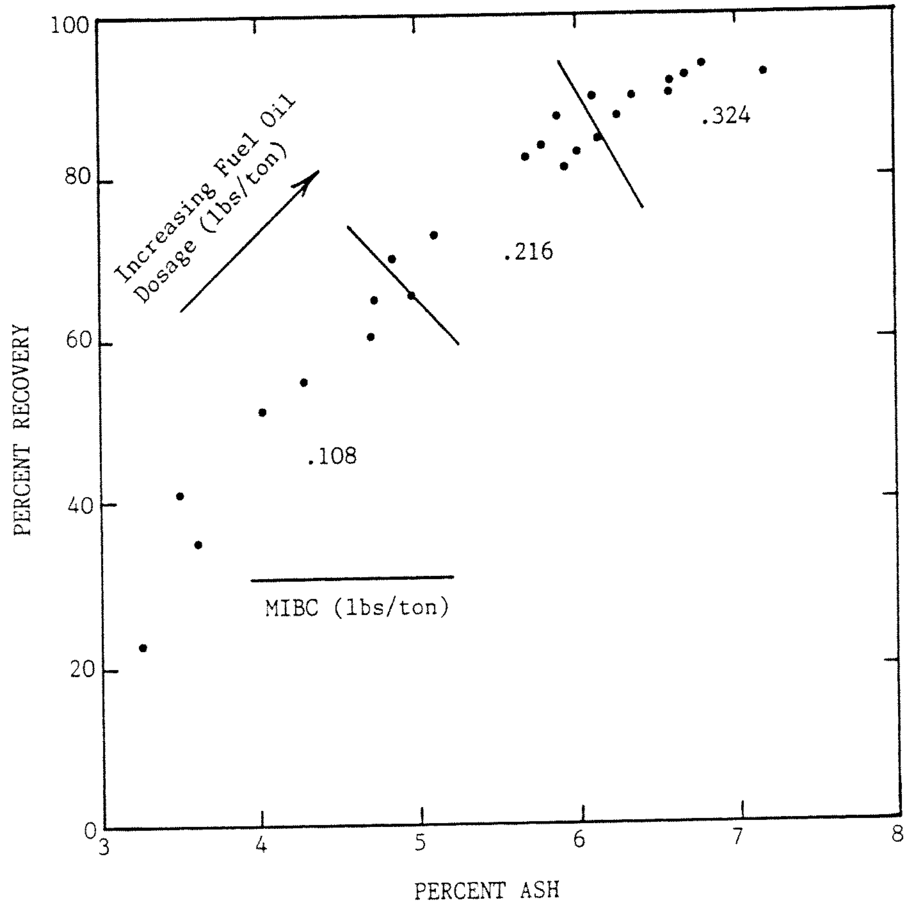


Figure 2.16b. Grade – Recovery Response for 48 X 100 Mesh Fraction of Lower Kittanning Seam Coal in Laboratory Tests. Fuel Oil Dosage (lb./ton) was Increased from 0,.084 to 0.672 in Equal Increments for Each MIBC Dosage Level.

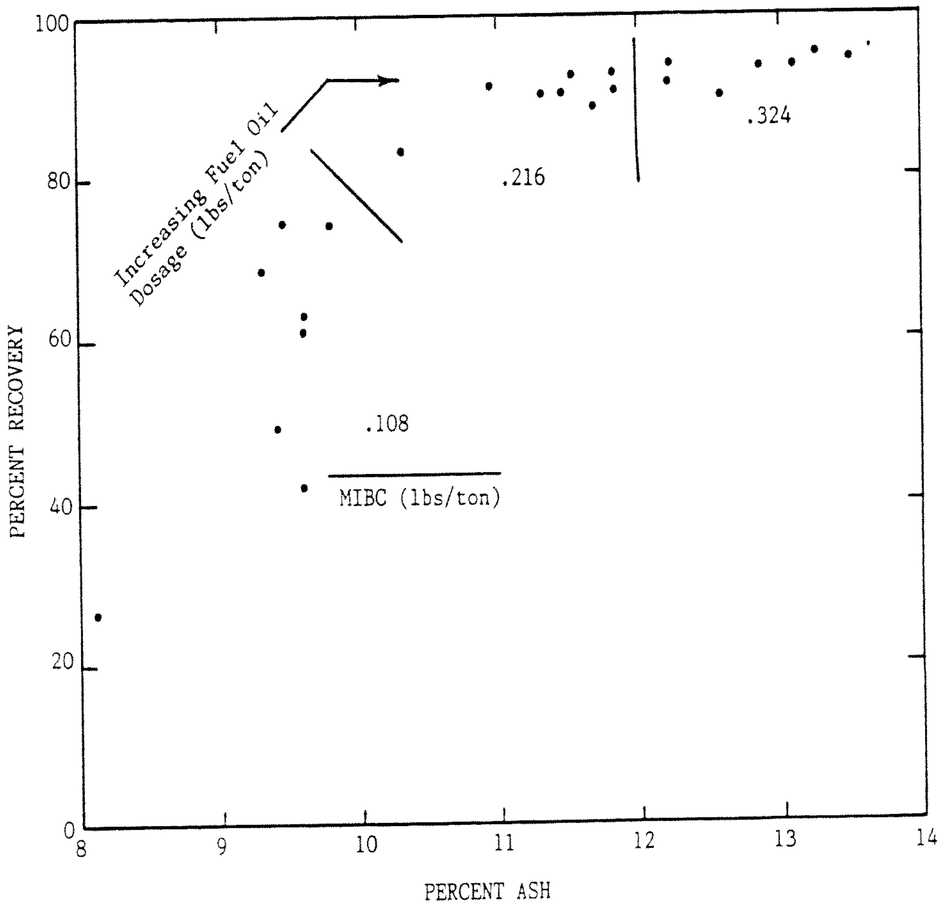


Figure 2.16c. Grade – Recovery Response for - 100 Mesh Fraction of Lower Kittanning Seam Coal in Laboratory Tests. Fuel Oil Dosage (lb./ton) was Increased from 0,.084 to 0.672 in Equal Increments for Each MIBC Dosage Level.

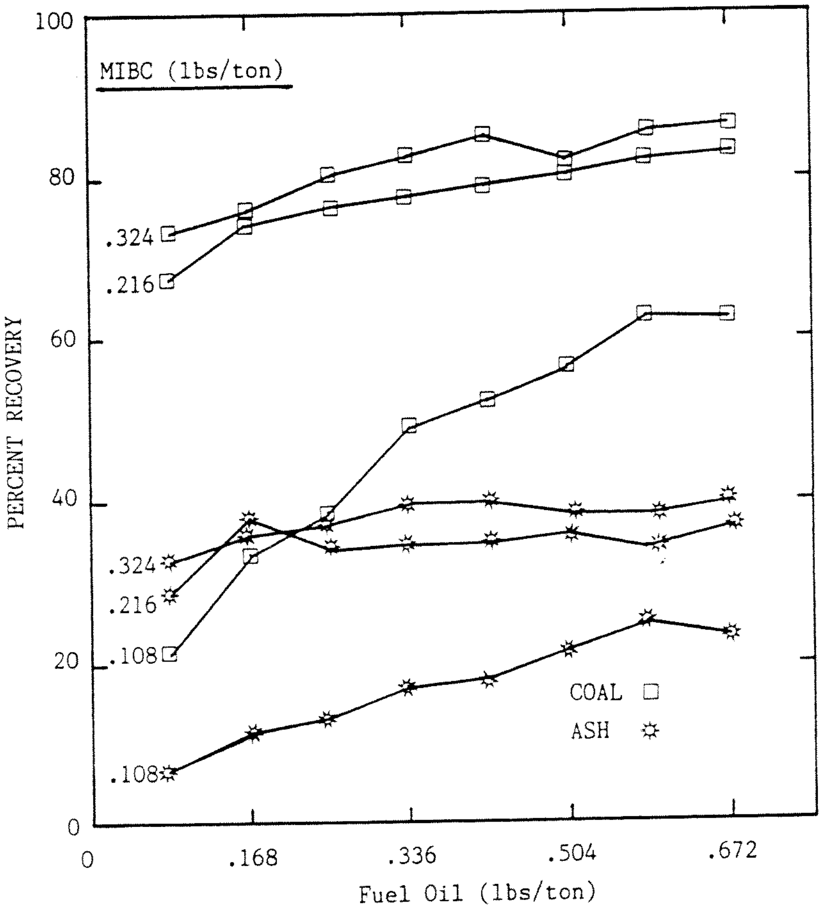


Figure 2.17a. Recovery – Dosage Response for + 48 Mesh Fraction of Lower Kittanning Seam Coal in Laboratory Tests.

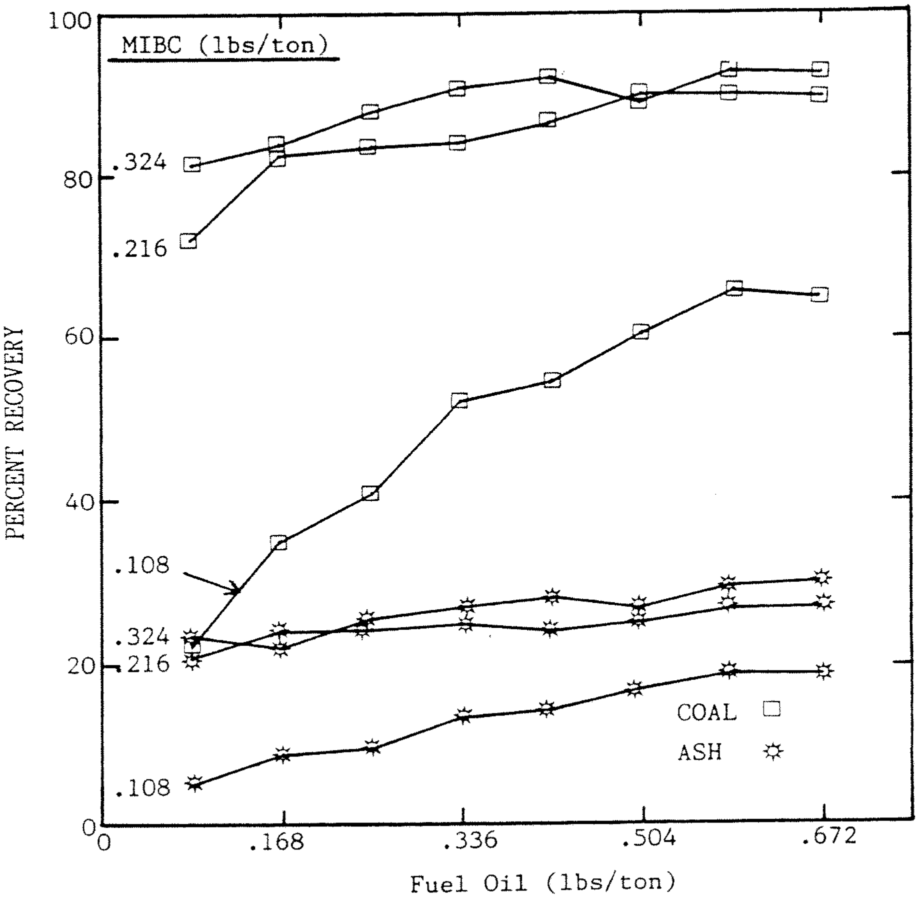


Figure 2.17b. Recovery – Dosage Response for 48 X 100 Mesh Fraction of Lower Kittanning Seam Coal in Laboratory Tests.

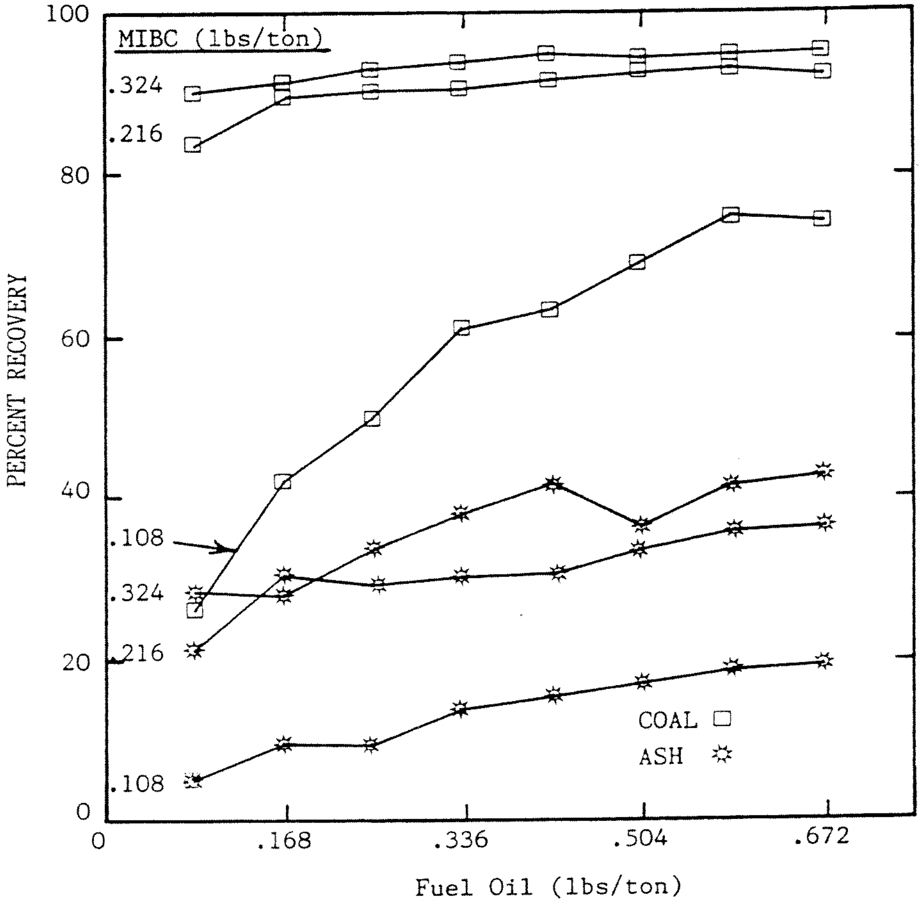


Figure 2.17c. Recovery – Dosage Response for - 100 Mesh Fraction of Lower Kittanning Seam Coal in Laboratory Tests.

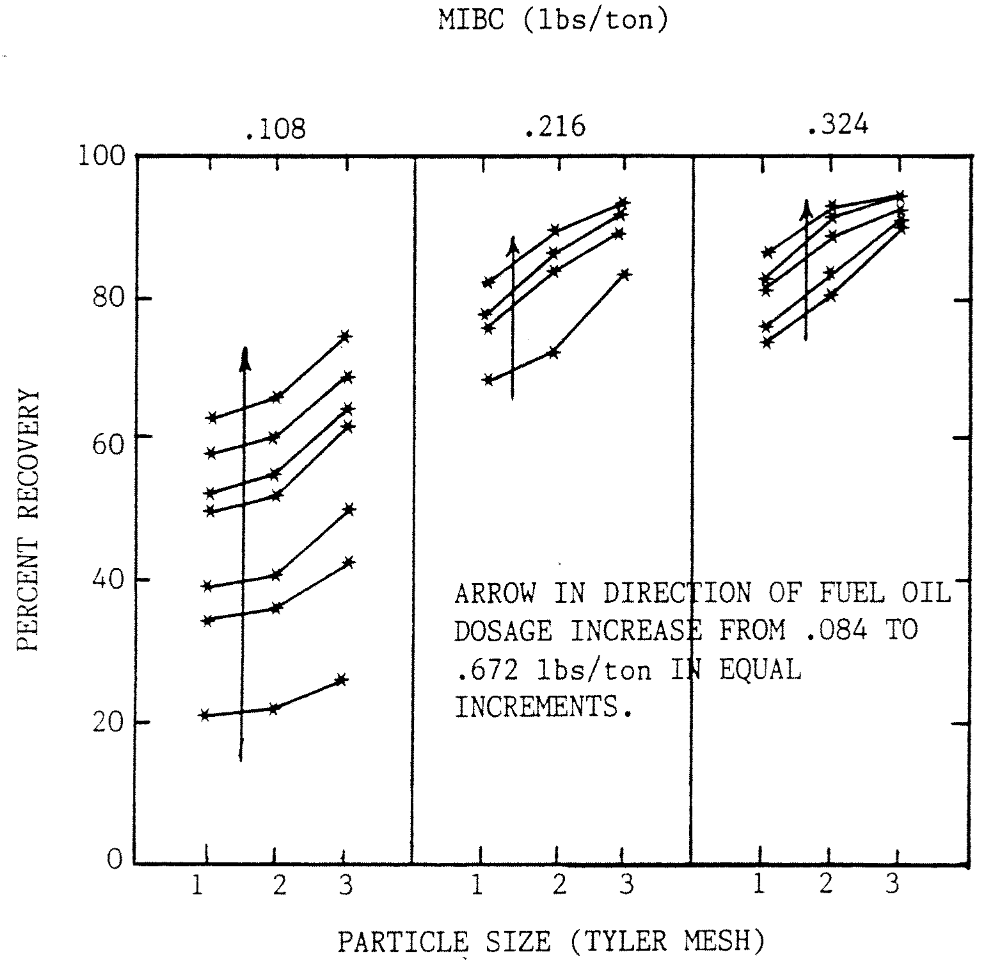


Figure 2.18. Recovery – Size Response for Lower Kittanning Seam Coal as a Function of Frother (MIBC) and Collector (No. 2 Fuel Oil) Dosages in Laboratory Tests. 1. + 48, 2. 48 X 100, and 3. – 100 Mesh.

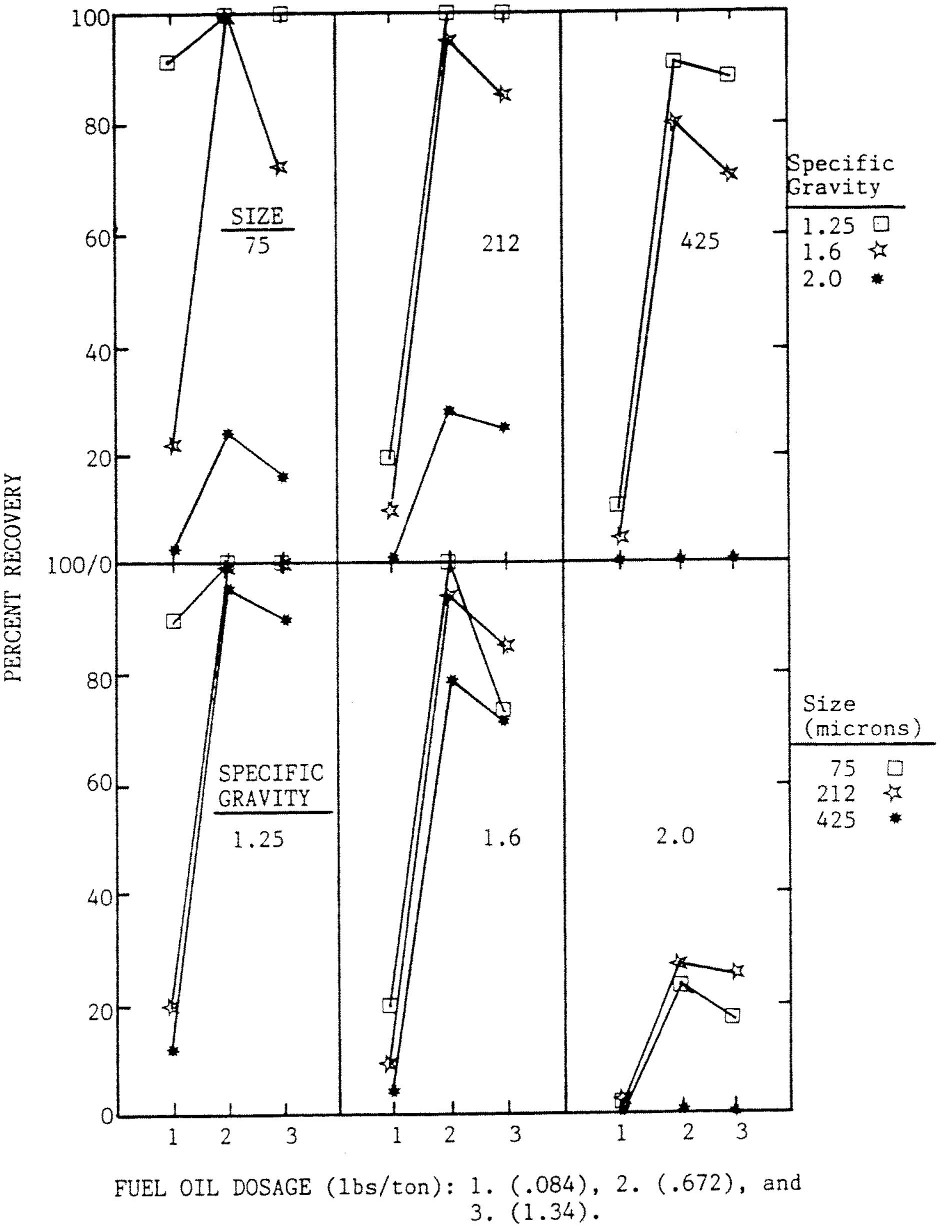


Figure 2.19. Recovery – Fuel Oil Dosage Response for Lower Kittanning Seam Coal in Laboratory Tests as a Function of Specific Gravity and Size.

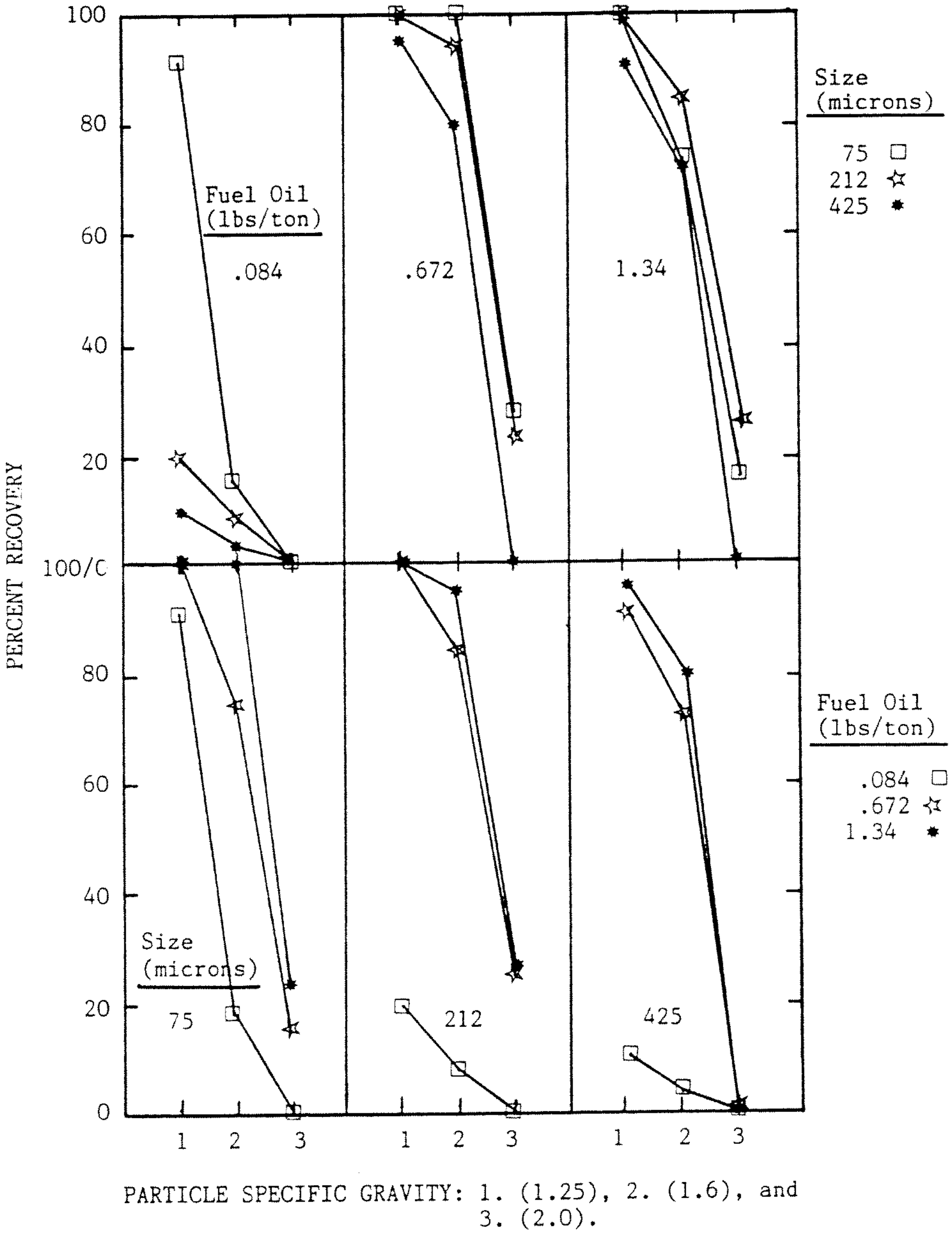


Figure 2.20. Recovery – Specific Gravity Response for Lower Kittanning Seam Coal in Laboratory Tests as a Function of Fuel Oil Dosage and Particle Size.

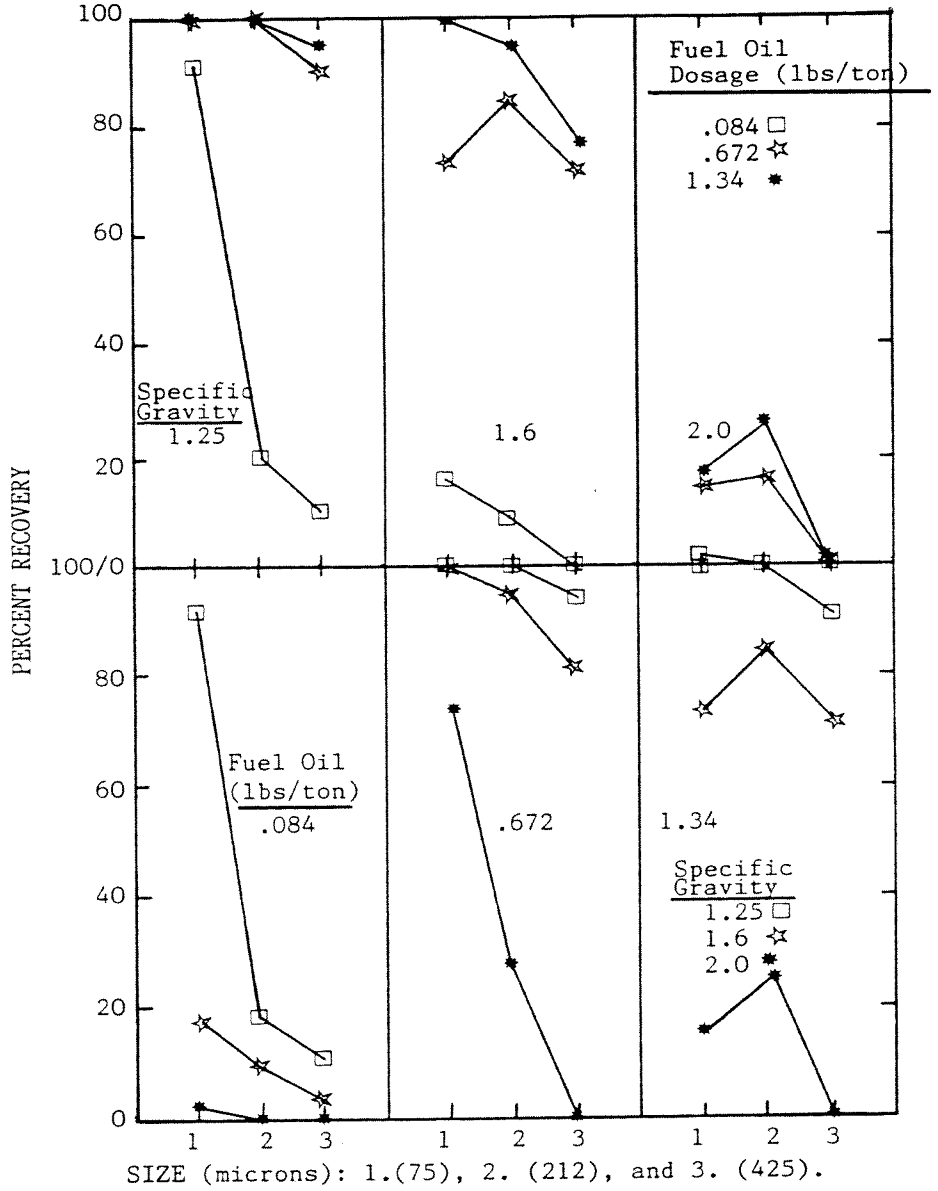


Figure 2.21. Recovery – Size Response for Lower Kittanning Seam Coal in Laboratory Tests as a Function of Fuel Oil Dosage and Specific Gravity.

1. Figures 2.14 and 2.15:

A. Coal recovery increased with frother or fuel oil dosage. The slope of the increase was initially high, but decreased with increasing reagent dosage.

B. Overall percent ash increased from 7.5 to 9.5 % with frother dosage and by 1.0 % with fuel oil dosage.

C. The same recovery was achieved with a wide range of frother and fuel oil reagent regimes, however, the higher frother dosage conditions invariably lead to higher ash concentrates.

2. Figure 2.16a:

A. A narrow grade-recovery curve was observed for the + 48 Mesh particles. Coal recovery and ash content increased with frother or fuel oil dosages to a maximum level, then the latter became a noisy response variable.

B. There was a small change in ash content (from 4.75 to 5.25 %) at the maximum recovery level, $r^{max.\ obs.}$.

C. The value for $r^{max.\ obs.}$ was 82 %. This value was similar to the maximum recovery (R) which could be calculated for the system under test conditions.

3. Figure 2.16b:

A. A narrow grade-recovery curve was observed for the 48 X 100 Mesh particles. Coal recovery and ash content increased with frother or fuel oil dosages to a maximum level, then the ash content became a noisy response variable.

B. There was a moderate change in ash content (from 6.5 to 7.5 %) at $r^{max.\ obs.}$. This was larger than observed for the + 48 mesh fraction.

C. The value for $r^{max.\ obs.}$ was 93 %. This value was similar to the maximum recovery (R) which could be calculated for the system under test conditions.

4. Figure 2.16c:

A. A comparatively wide grade-recovery curve was observed for the - 100 Mesh particles. Coal recovery and ash content increased with frother or fuel oil dosage to a maximum level, then the latter continued to increase in a continuous, non-random fashion. This resulted from increased entrainment of fine ash with increased frother dosages.

B. There was a much larger change in ash content (from 11.0 to 13.5 %) at $r^{max.\ obs.}$ than observed for the coarser sizes.

C. The value for $r^{max.\ obs.}$ was 92 %. This value was similar to the maximum recovery (R) which could be calculated for the system under test conditions.

5. Figures 2.16 a, b, c - The value of $r^{max.\ obs.}$ for all sizes was higher in the lab than in the plant. This reflected more aggressive flotation conditions in the former, e.g., perhaps a lower particle retention time for drainage in the lab froth phase.

6. Figures 2.17 a, b, c:

A. The recovery - dosage response was similar for all species in these tests.

B. The fuel oil dosage had a large effect on percent recovery of all species (coal and ash particles of all sizes) at low frother dosage. The fuel oil dosage had much less of an effect at the moderate and high frother dosage.

C. At all fuel oil dosages, the increase from low to moderate frother dosage greatly increased coal and ash recovery and the increase from moderate to high frother dosage had much less of an effect.

7. Figure 2.18: Particle recovery increased with decreasing size under all reagent regimes.

8. Figure 2.19:

A. Increasing the fuel oil dosage increased the recovery of all species (size and specific gravity fractions).

B. 1.25 S.G. Fraction: The - 100 Mesh fraction exhibited high recoveries under all test conditions and both +100 Mesh fractions required moderate fuel oil dosages to achieve high recoveries.

C. 1.6 S.G. Fraction: All size fractions required moderate fuel oil dosage to achieve higher recovery, the highest fuel oil dosage reduced recovery in comparison with the moderate dosage.

D. 2.0 S.G. Fraction: The recovery of all size fractions was low even at high fuel oil dosages. None of the + 48 mesh particles were recovered.

E. Coal recovery was a function of size, specific gravity, and fuel oil dosage. Coarser and higher specific gravity particles required more fuel oil to achieve the necessary hydrophobicity for a given degree of flotability.

F. From Appendix III, the average ash content of the various specific gravity fractions in the concentrates from these tests (there was essentially no variation in ash content across all the size fractions) was:

1.25 S.G. = 2.6 % ash

1.6 S.G. = 18.5 % ash, and

2.0 S.G. = 65.7 % ash.

In comparison with the flotation data for this Lower Kittanning seam coal this meant that:

i. For the + 48 Mesh fraction, moderate amounts of composite particles float until higher fuel oil or frother dosages were added.

ii. For the 48 X 100 Mesh fraction, composite particle recovery required higher fuel oil or frother dosages, but less than for the + 48 mesh.

iii. For the - 100 Mesh fraction, many composites or fine ash particles were recovered at all fuel oil and frother dosages.

Comparing the by-size ash content for the laboratory and plant test data revealed that the former produced somewhat higher ash contents:

Size (Mesh)	% Ash Plant Tests	 Lab Tests
+ 48	4.5	4.5 - 5.0
48 X 100	5.5	6.0 - 7.0
- 100	9.5 - 12.0	11.5 - 14.0

The difference in ash content increased with decreasing size. This probably resulted from differences in the thickness of the froth phase, i.e., < 1 inch in the lab vs. > 3 inches in the plant. Since the particle residence time in the froth was directly proportional to froth thickness, the drainage of water and entrained particles increased and the ash content decreased as the residence time increased. The effect was more noticeable for the -100 Mesh fraction because more entrained particles were present in that fraction. The overall effect of this difference was the observed difficulty in comparing lab and plant grade-recovery results, particularly in regard to behavior of the fines. These differences illustrate a need for developing lab procedures that more closely emulate plant froth phase behavior. They may also have resulted in the problems experienced with the Panther Valley lab frother comparisons.

G. For all sizes, many combinations of frother and collector dosages gave similar recoveries, but the higher frother dosage combinations invariably gave higher ash concentrates. This resulted from greater carryover of water into the concentrates with higher frother dosages, and consequently increased entrainment.

H. Over the range of tested reagent regimes, there was great selectivity for 1.25 S.G. coal particles vs. 2.0 S.G. particles which were primarily ash. The recovery of 1.6 S.G. particles, which are composites of coal and ash, was controllable over a wide range through variation of fuel oil dosage.

2.2.2 Anthracite Coal Samples

Laboratory flotation tests were conducted with coal obtained from the Panther Valley Mine flotation circuit feed. A bulk sample was collected incrementally over a period of several days, air dried, mixed, and split by rotary splitter into approximately 400 gram samples for tests. Table 2.1 gives the typical by-size ash and weight distribution for the flotation feed.

2.2.2.1 Equipment and Procedures

Tests were performed using a Wemco Fagergren laboratory batch flotation machine, together with a modified flotation cell with mechanical froth scraping paddles and constant level control. This cell was constructed by the author based on US DOE plans (Miller, personal communication, 1979). A schematic outline of the system is shown in Figure 2.22.

General operating conditions were:

1. Bethlehem, PA city tap water, with a natural pH in the range of 7 to 8 was used.
2. Impeller speed equal to 1800 rpm.
3. The slurry percent solids was 10 percent.
4. The natural pulp pH was used and no pH adjustment was made.

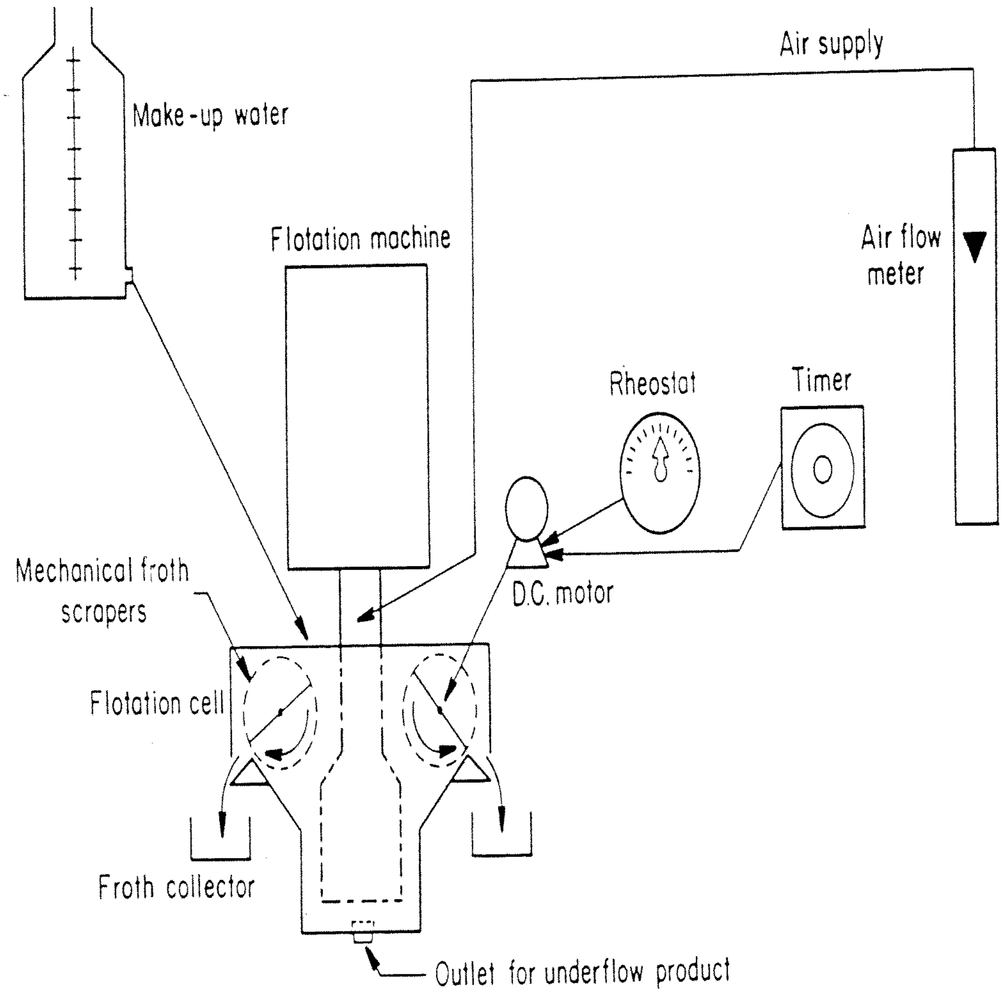


Figure 2.22. Laboratory Batch Flotation Unit with Mechanical Froth Scrapers.

5. Aeration was held constant, by a flowmeter, at the level which would naturally occur under the set conditions of pulp percent solids, pulp depth, and impeller rpm's. This was done to minimize the potential for variation during tests.

The following procedure was established for this series of tests through preliminary experiments and past experience:

1. Each coal sample was conditioned in the cell for two minutes prior to reagent additions.

2. The collector was added first and conditioned with the pulp for one minute. Then the frother was added and conditioned with the pulp for 30 seconds.
3. After conditioning, the air valve was opened.
4. Four froth increments were collected during each test: from 0 - 15, 15 - 45, 45 - 90, and 90 seconds - to the end of flotation (i.e., froth scraping intervals of 15, 30, 45, and variable seconds). Samples were collected in this manner to permit subsequent analysis of the recovery-time profiles resulting from each set of reagent addition conditions using Equation (2-1).
5. A constant pulp level was automatically maintained during the froth collection period.
6. The incremental concentrate fractions and tailings were filtered, dried, weighed, and analyzed.
7. Data for all of these tests is given in Appendix IV.

2.2.2.2 Flotation Test Conditions

Tests were performed using a variety of different frothers:

MIBC, PPG-200, DF1012, DF400, and DF1263

to yield a wide range of froth characteristics from weak to strong, respectively. Number 2 fuel oil was used as the collector. The composition of these frothers and collectors was:

Reagent	**Approximate Composition**	**Molecular Weight**
MIBC	Methyl isobutyl carbinol	
PPG200	CH_3 - (O - $C_3H_6)_3$- OH	200
DF1012	CH_3 - (O - $C_3H_6)_{5.5}$ - OH	400
DF400	H - (O - $C_3H_6)_7$ - OH	400
DF1263	Reaction product of DF250 and butylene oxide: CH_3 - (O - $C_3H_6)_4$ - BO	400

No. 2 Fuel Oil: C& to C18 Paraffins and iso-paraffins, with aromatics, naphthalenes, and related hydrocarbon derivatives of S, N, and O, that were not removed by refining. These molecules are recovered over a given boiling range by fractional distillation.

A set of preliminary screening tests was performed with each frother to roughly identify the dosage levels giving similar grade-recovery response. With this as a basis, a simple two level factorial design with frother and No. 2 fuel oil dosage levels as factors was run for each frother type. The test reagent schedule is given in Table 2.4. Tests were run in a random order to minimize errors.

Table 2.4. Performance Characteristics of Some Frothers Used in the Flotation of Mammoth Seam Coal.

Frother Type	Frother Dosage (lb./ton)	Fuel Oil Dosage (lb./ton)	K -Coal	K-Ash	R-Coal	R-Ash	K-Coal / K-Ash	R-Coal / R-Ash
MIBC	1.0	0.70	3.1	2.4	115	39	1.29	2.97
	1.0	0.35	2.5	1.8	106	36	1.22	3.40
	0.5	0.70	3.3	2.7	99	29	1.39	2.98
	0.5	0.35	1.9	1.4	117	36	1.26	3.30
PPG200	1.4	0.70	1.9	1.3	107	36	1.46	2.98
	1.4	0.35	2.9	1.8	102	36	1.52	3.16
	0.7	0.70	4.4	2.9	95	30	1.61	2.82
	0.7	0.35	2.5	1.6	108	37	1.56	2.88
DF1012	1.4	0.70	2.6	1.6	105	36	1.63	2.89
	1.4	0.35	2.6	1.5	108	40	1.53	3.01
	0.7	0.70	2.6	1.7	104	34	1.73	2.67
	0.7	0.35	2.1	1.3	110	38	1.62	2.87
DF400	2.0	0.70	3.2	1.9	111	42	1.68	2.62
	2.0	0.35	3.3	1.9	108	41	1.94	2.58
	1.0	0.70	3.1	1.6	109	42	1.74	2.59
	1.0	0.35	2.8	1.7	119	46	1.65	2.67
DF1263	1.4	0.70	2.2	1.1	113	47	2.00	2.37
	1.4	0.35	1.9	0.8	122	64	1.67	2.63
	0.7	0.70	1.5	0.9	129	49	2.38	1.91
	0.7	0.35	3.1	2.0	114	41	1.55	2.80

2.2.2.3 Results

The recovery of coal and ash in each time increment was calculated. This raw data is given in Appendix IV. The most interesting results are shown in Figures 2.23 to 2.28 and Table 2.4. A preliminary review of observations pertaining to each figure and the table is presented below and a detailed discussion based on results from all of the plant and lab test work is given in Chapter 3:

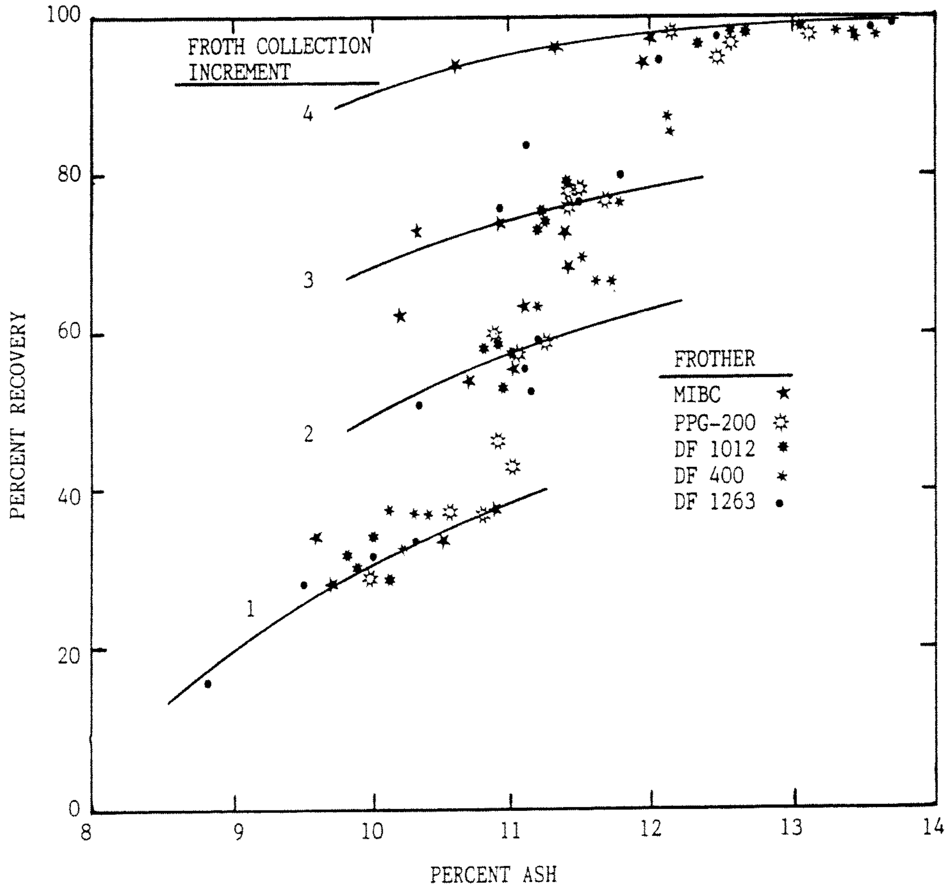


Figure 2.23. Grade – Recovery Response for Mammoth Seam Coal in Laboratory Tests where Frother Type and Dosage were Varied.

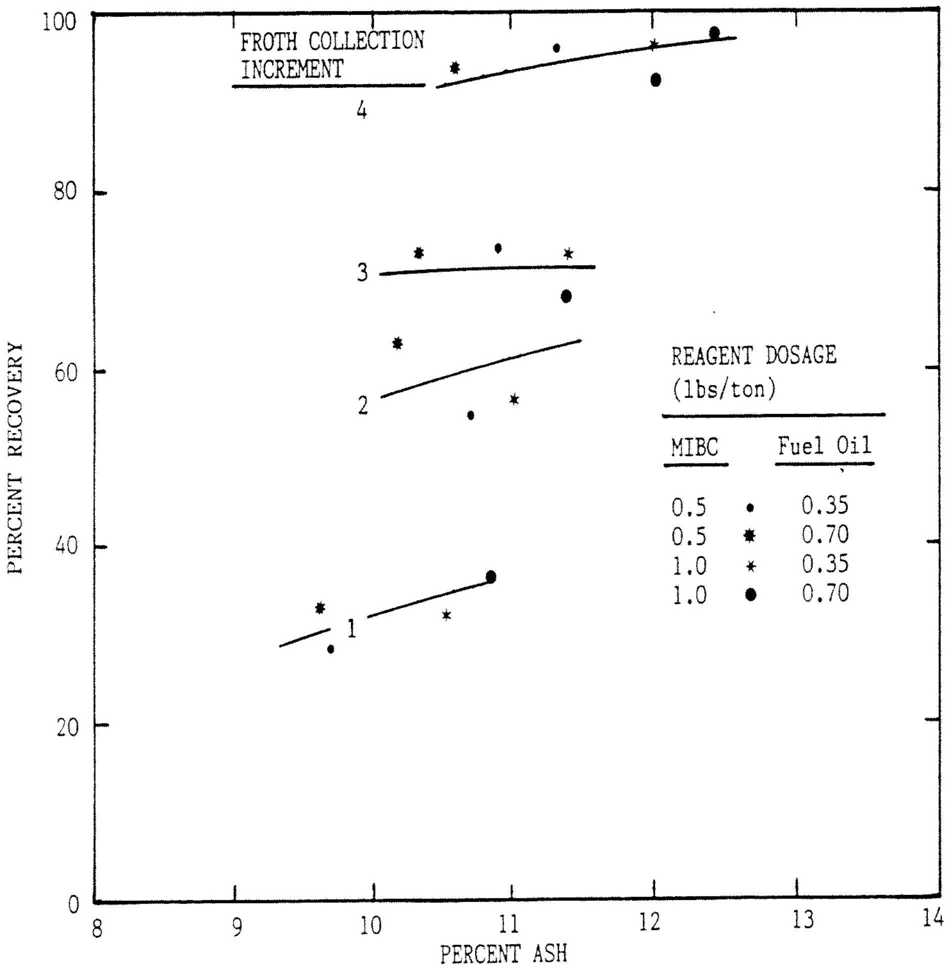


Figure 2.24. Grade – Recovery Response for Mammoth Seam Coal in Laboratory Tests Using MIBC: Frother and Collector Dosage Varying.

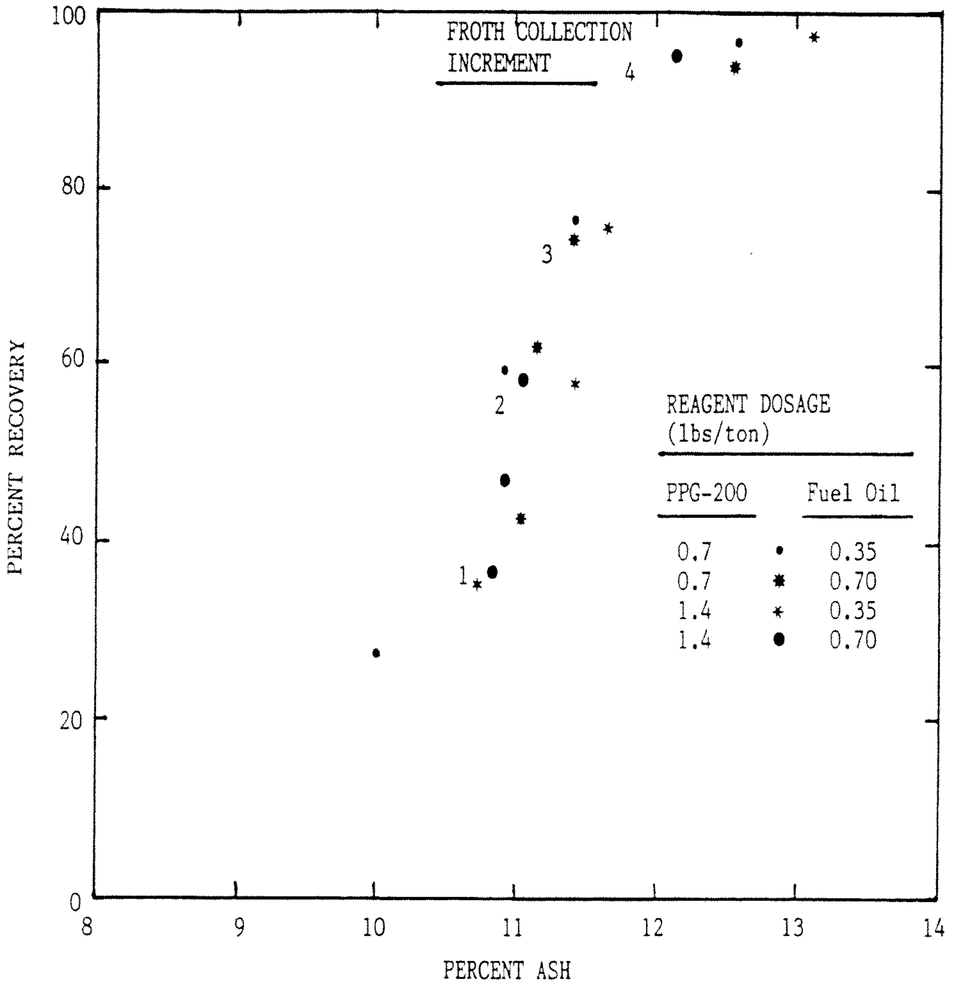


Figure 2.25. Grade – Recovery Response for Mammoth Seam Coal in Laboratory Tests Using PPG-200: Frother and Collector Dosage Varying.

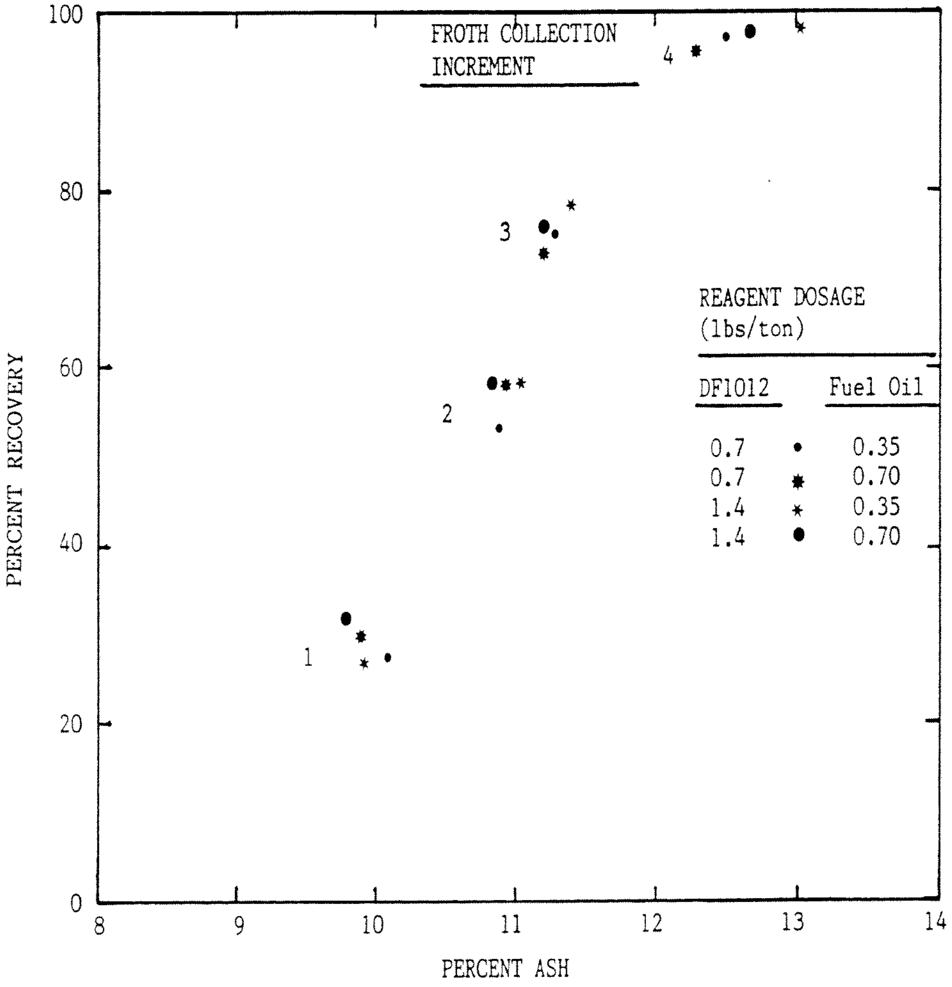


Figure 2.26. Grade – Recovery Response for Mammoth Seam Coal in Laboratory Tests Using DF1012: Frother and Collector Dosage Varying.

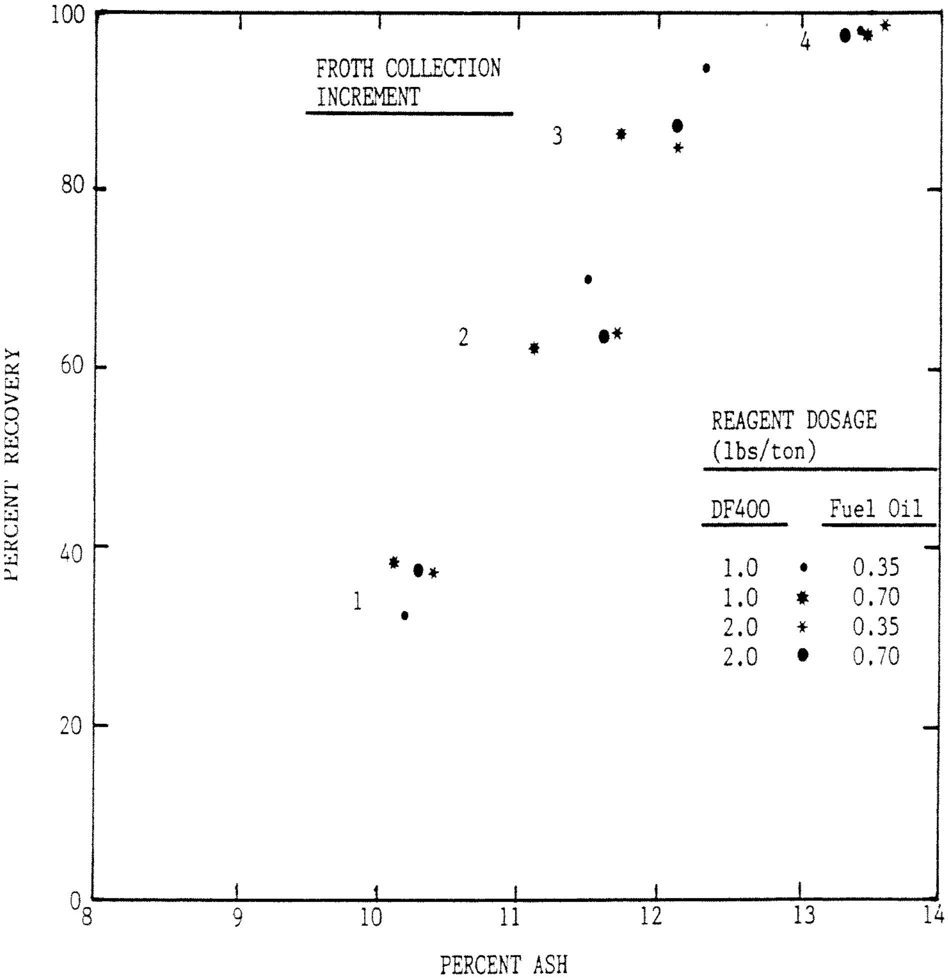


Figure 2.27. Grade – Recovery Response for Mammoth Seam Coal in Laboratory Tests Using DF400: Frother and Collector Dosage Varying.

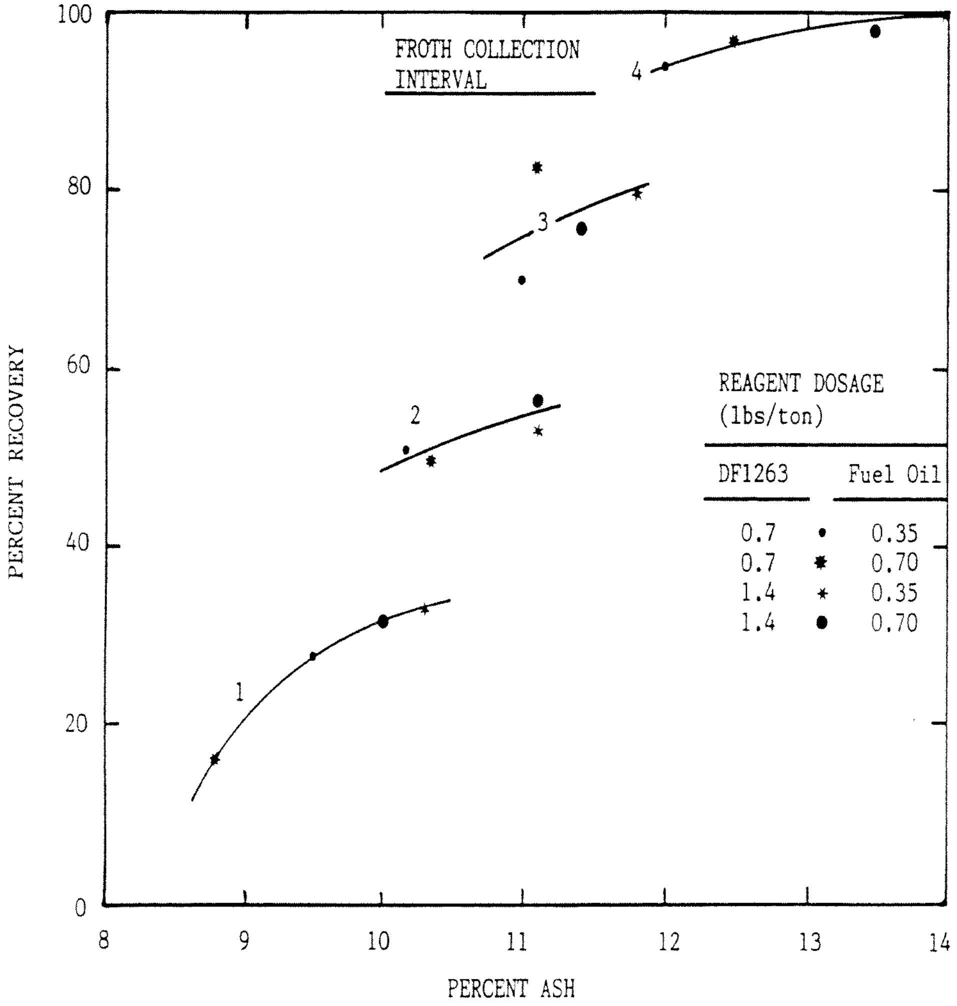


Figure 2.28. Grade – Recovery Response for Mammoth Seam Coal in Laboratory Tests Using DF1263: Frother and Collector Dosage Varying.

1. Figure 2.23 - The overall grade-recovery curve for each time increment of all tests clearly indicates that frother dosage and type had an effect on the particular response along a fairly general curve. Frothers conventionally thought of as producing a stronger froth gave a less selective separation, i.e., results towards the right hand side of the curve.

From the observed ash content at $r^{max. obs.}$, the "order of strength" for the five tested frothers was:

MIBC < PPG-200 < DF1012 < DF400 < DF1263.

On the basis of results after time period 1, the "order of strength" was:

PPG-200 > MIBC > DF400 > DF1263 > DF1012.

Some of the rankings presented below based on aspects of R and K analysis using Equation (2-1) were similar, showing that the model fit problems discussed above and observed for this data set did not affect data interpretation.

Differences in the dosages used for the different frothers and the lack of overlap on a lb./ton basis resulted in the possibility of a direct per dosage comparison only between MIBC and DF1263. In addition, results from lab and plant tests on the Kitt Mine material suggest that differences existed between the froth phases present in each type of test. Since much of the probable difference in froth behavior relates to drainage behavior, it seems likely that the reduced opportunity for drainage in the lab confounded efforts directed at determining the effects on water recovery and fines entrainment that might be observed in plant tests.

2. Figure 2.24 (MIBC):

A. There was a large variation in grade-recovery response with changes in the reagent regime.
B. All of the tested combinations of frother and fuel oil dosages gave similar recoveries, but the low frother dosage conditions gave lower concentrate ash.
C. The combination of observations A and B suggests that low frother / high fuel oil reagent regimes give better ash rejection.

3. Figure 2.25 (PPG-200):

A. There was a moderate variation in the grade-recovery response with changes in the reagent regime.
B. Higher fuel oil dosages gave rise to slightly better ash rejection.
C. The combination of observations A and B suggests that low frother / high fuel oil reagent regimes give better ash rejection.

4. Figure 2.26 (DF1012):

A. There was a slight variation in the grade-recovery curve with changes in the reagent regime.
B. Increasing the frother dosage increased the concentrate ash content.
C. Increasing the fuel oil dosage decreased the concentrate ash content. The combination of observations B and C suggests that low frother / high fuel oil reagent regimes give better ash rejection.

5. Figure 2.27 (DF400): There was slight variation in the grade-recovery curve with changes in the reagent regime.

6. Figure 2.28 (DF1263):

A. There was a large variation in the grade-recovery curve with changes in the reagent regime.

B. Higher frother dosages resulted in higher ash concentrates. This observation suggests that low frother / high fuel oil reagent regimes yield better ash rejection.

Most of the data for these frothers indicated a potential for increased entrainment of fine ash into the coal concentrate when high frother / low collector dosage regimes were used in contrast to low frother / high collector dosage regimes.

7. Table 2.4:

A. The "order of strength" from looking at K results was the same as observed from short-term grade-recovery information, i.e.:

PPG-200 > MIBC > DF400 > DF1263 > DF1012.

B. The "order of strength" from looking at R results was:

DF1263 > DF400 > MIBC > DF1012 > PPG-200.

These results were similar to those observed from analysis of time period 4 cumulative data, except the recovery predicted for MIBC was much higher than observed.

C. The K selectivity ratio, K(coal)/K(ash), increased in the order:

MIBC < PPG-200 < DF1012 < DF400 < DF1263.

This indicated a potential for better grade-recovery response under kinetically controlled conditions, using reagents to the right-side of the order.

D. The R selectivity ratio, R(coal)/R(ash), decreased in the order:

MIBC > PPG-200 > DF1012 > DF400 > DF1263.

This indicated a potential for better grade-recovery response under equilibrium recovery controlled conditions, using reagents to the left hand side of the order.

E. For MIBC:

i. K(coal) increased with increased fuel oil dosage.
ii. K(ash) increased with increased frother dosage at the low fuel oil dosage and decreased with increased frother dosage at the high fuel oil dosage.
iii. R(coal and ash) was only slightly affected by the reagent regime.
iv. K(coal)/K(ash) slightly increased with increased fuel oil dosage and slightly decreased with increased frother dosage.
v. R(coal)/R(ash) decreased with increased fuel oil dosage and was unaffected by increased frother dosage.

F. For PPG-200:

i. K(coal and ash) increased with increased frother or fuel oil dosage from low to high, but decreased when both were high.

ii. R(coal and ash) was lowest at low frother / high fuel oil dosages, all other reagent regimes gave nearly the same response.
iii. K(coal)/K(ash) decreased with increased frother dosage, decreased with increased fuel oil dosage at high frother dosage, and increased with increased fuel oil dosage at low frother dosage.
iv. R(coal)/R(ash) increased with increased frother dosage and decreased with increased fuel oil dosage.

G. For DF1012:

i. K(coal and ash) increased with increased frother or fuel oil dosage.
ii. R(coal and ash) was unaffected by the reagent regime.
iii. K(coal)/K(ash) decreased with increased frother dosage, increased with increased fuel oil dosage, and was at a maximum at low frother / high fuel oil dosages.
iv. R(coal)/R(ash) increased with increased frother dosage, decreased with increased fuel oil dosage, and was at a minimum at low frother / high fuel oil dosages.

H. For DF400:

i. K(coal) increased with increased frother or fuel oil dosage.
ii. K(ash) increased with increased frother dosage, but was unaffected by the fuel oil dosage.
iii. R(coal and ash) was unaffected by the reagent regime.

iv. K(coal)/K(ash) increased with increased frother or fuel oil dosage from low to high levels, but decreased when both were high.

v. R(coal)/R(ash) was unaffected by the reagent regime.

I. For DF1263:

i. K(coal and ash) decreased with increased frother or fuel oil dosage from low to high levels, but it somewhat recovered when both were high

ii. R(coal) increased with increased frother or fuel oil dosage and decreased when both were high.

iii. R(ash) increased with increased frother dosage at low fuel oil dosage and was unaffected by frother dosage at high fuel oil dosage. It increased with increased fuel oil dosage at low frother dosage and decreased with increased fuel oil dosage at high frother dosage.

iv. K(coal)/K(ash) increased with increased fuel oil dosage. It increased with increased frother dosage at low fuel oil dosage and decreased with increased frother dosage at high fuel oil dosage.

v. R(coal)/R(ash) decreased with increased fuel oil dosage. It decreased with increased frother dosage at low fuel oil dosage and increased with increased frother dosage at high fuel oil dosage.

8. K/R kinetic analysis and grade-recovery analysis provided similar results with regard to evaluating various reagent regimes. The former separates phenomena into their kinetic and equilibrium portion, permitting generalizations and suggesting alternative operating conditions. However, it is also one step further removed from the data and extremely dependent on the accuracy of the model fit. Accordingly, while the K/R approach is very useful for screening tests and general analysis, grade-recovery analysis is still necessary and extremely useful in the fine-tuning stages of process analysis.

CHAPTER 3. DISCUSSION

Flotation is an extremely complex process depending on the interacting influence of many independent variables on physicochemical processes. Considerable thought and effort have gone into developing an explanation for the flotation behavior of coal. However, although the general fundamental principles have been described (e.g., Leja, 1982), a comprehensive theory including the physical mechanisms of flotation has not been developed. Thus, even with the considerable available knowledge that exists as background it is still difficult to apply, optimize, and control the flotation process. A fundamental, mechanistic based understanding is required because coals are highly variable in composition and consequently in their response to flotation.

One objective of this research was to analyze the influences of reagent regime and particle size and composition on process performance and its optimization. Another objective was to use results from experimental test work in conjunction with an analysis of the technical literature in order to formulate a general theory explaining particle behavior. The theory was developed and tested using experimental results from examining the influence of reagents on process grade-recovery and kinetic response. A technique for optimizing reagent conditions to match feedstock characteristics was incidentally developed as an outgrowth from this work.

3.1 Recovery of Particles

The effect of independent variables listed in Table 1.1 on the maximum recovery or rate of recovery of particle species follows one of two general types of functional relationship between response and variable. These curves (e.g., see Figure 3.1) are

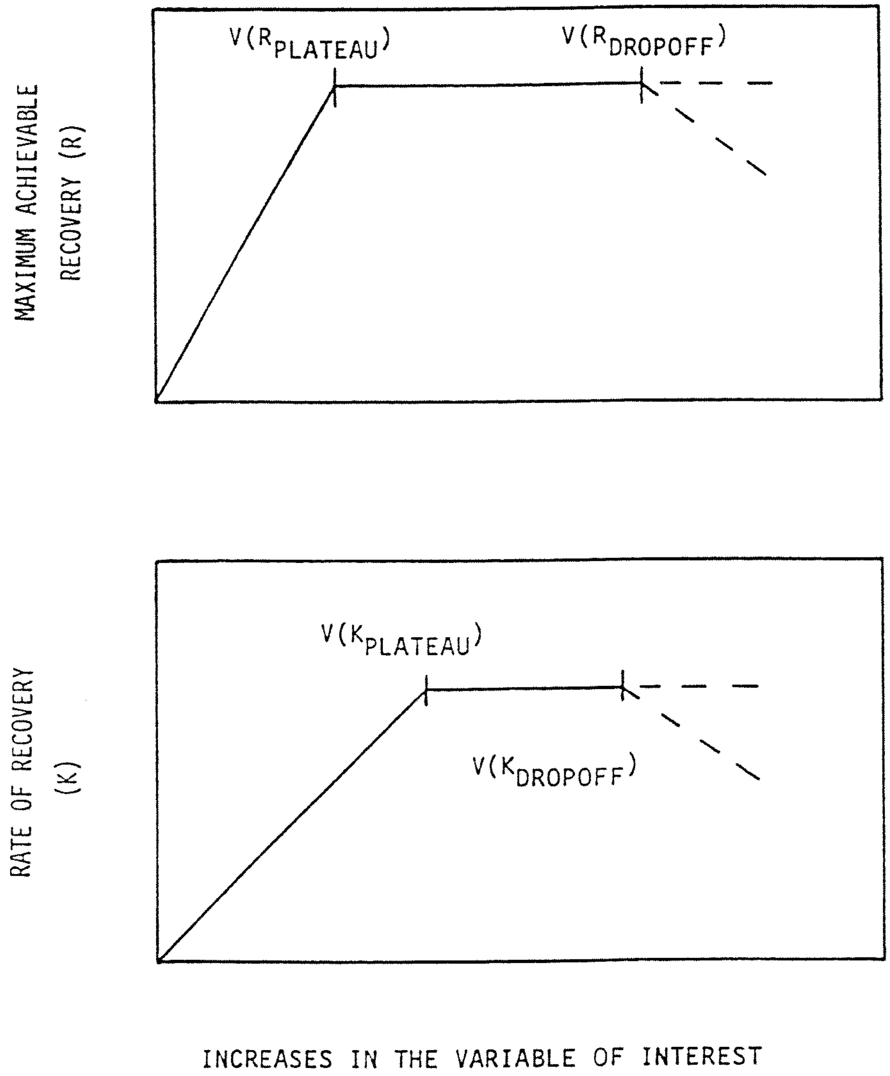


Figure 3.1. **The Typical Effect of Increases in Independent Variables on the Rate of Recovery, K, and the Equilibrium Recovery, R; Where V (R-plateau or K-plateau) Refers to the Value of the Variable Required to Reach the Plateau and V (R-drop-off or K-drop-off) Refers to the Value of the Variable at Which the Plateau Ends (Seitz and Kawatra, 1985).**

characterized by an increase in the response of interest as the variable increases until a plateau is reached; followed by:

- an eventual decrease in some cases or
- no decrease in other cases.

This type of behavior is exhibited by liberated coal particles, liberated ash particles, and composite particles in each of the three size ranges as shown in Figures 2.19 to 2.21. The exact relationships differ for each species of particles, e.g., Figures 2.8 and 2.9 show the response for coal and ash species versus frother and collector dosage. Hence, the mass distribution of particles into species must be considered when using this type of analysis as a basis for optimizing flotation circuit performance. Table 3.1 summarizes the effect of changes, over a reasonable range, in particle size and reagent regime on the rate of recovery or maximum recovery.

3.1.1 Fine Size Fraction

An important aspect of recovery-size analysis of coal flotation is evaluation of results in the sub-sieve size range, i.e., minus approximately 74 microns. Some of the main problems in flotation are associated with this size range (see Section 1.3):

- entrainment;
- inadvertent flotation of carbonaceous material and sulfide gangue minerals possessing some degree of hydrophobicity; and
- inadvertent flotation of fine gangue minerals of all types through partial coating with collector, especially when collector dosage is increased in an attempt to promote better flotation of coarse particles.

The nature of coal flotation pulps makes it difficult, but not impossible, to use recovery-size analysis to estimate the magnitude of these problems and to evaluate any attempts at corrective action.

Table 3.1. Brief Summary of Some R and K Parameter Trends in Laboratory and Plant Tests with Changing Variable Settings Over Reasonable Ranges (after Klimpel, 1984; Seitz and Kawatra, 1985a). *

Variable	**Change in Variable**	**Change in K**	**Change in R**
Liberated Coarse++ Particle Size	Increase	Decrease	Decrease
Liberated Intermediate++ Particle Size	Increase	None	None
Liberated Fine++ Particle Size	Increase	Increase	Increase
Collector or Frother Dosage (@ Starvation Dosage)	Increase	Increase	Increase
Collector or Frother Dosage (@ Moderate Dosage)	Increase	Moderate Decrease	Increase
Collector or Frother Dosage (@ Heavy Dosage	Increase	Decrease	Moderate Increase
Froth Mobility or Removal	Increase	Increase	Decrease

* It is important to note that exceptions to the trends of this table have been identified, but this information is a useful operator oriented guide.

++ The actual particle size range for these phenomena varies widely, dependent upon coal type and liberation characteristics.

The tendency of components, such as shale, to disintegrate in water increases the difficulty of analyzing the behavior of fine particles; as it calls into question the use of wet sizing processes as a reliable method for sizing the fine particles, and dry sizing, with its attendant problems, cannot suffice. Additionally, there are no means of allowing for shale disintegration during flotation. Therefore, caution must be taken in analyzing results for flotation of fine coal. However, a tremendous amount of data is available for mineral systems (e.g., Trahar, 1981) and similarities in the results from those studies and the results presented in Chapter 2 provide a good basis for believing that together they provide a meaningful picture of the response of fine particles during coal flotation.

Figure 2.19 is useful for illustrating the general nature of the problem of having to compromise between coarse particle recovery and fine ash particle rejection. This data shows that addition of a nonpolar oil collector improved both coarse and fine particle recovery, but at the expense of increased ash recovery in the concentrate from particles of all sizes, especially the fines. It is also useful to plot ash recovery versus size (e.g., see Figure 2.21), to clarify the increased recovery of fine high ash material (e.g., carbonaceous shale) following the addition of a nonpolar oil collector.

The relationship between fine ash particle and water recovery observed in Figures 2.13 a and b (results discussed in Section 2.2.1.3), i.e., showing an increase in ash content with decreasing size even though the coal is of lower inherent ash content, and the higher ash content obtained in lab tests due to less drainage of fine ash particles, indicate that many fine ash particles are transferred to the concentrate by entrainment rather than by bubble attachment. Entrainment of gangue particles into the concentrate is an important aspect of all flotation operations, and in some cases it may be the main limitation to achieving high concentrate grades (e.g., coal and cassiterite flotation).

The Kitt Mine tests revealed an invariant relationship between water recovery and fine ash particle recovery for a wide range of reagent regimes. This means water recovery must be reduced to decrease the concentrate ash content or other means for altering the relationship must be identified. It indicates that alternative processing techniques or reagent regimes were necessary in order to decrease contamination by entrainment. Results from tests at Panther Valley indicated that the relationship between coal recovery and fine ash recovery could be controlled by altering the reagent regime. The experimental results of Brookes and Bethel (1979) indicated that amine type reagents used correctly and in small quantities could markedly improve flotation results for low rank coals. They appear to be effective in supplementing the action of more conventional reagents by improving the selectivity of fine particle flotation and improving froth fluidity. This latter effect is similar to that mentioned in Chapter 2 and discussed by Lynch et al. (1981) and Kawatra and Seitz (1984); i.e., an increase in frother dosage is useful in overloaded froth conditions, tending to increase froth mobility and drainage, which counteracts the overoiling effects of excess collector. Additionally, the results presented in Chapter 2 indicate that, with normal froth conditions, the use of reagent regimes with either high frother/low collector or low frother/high collector dosages yields similar recoveries, but the latter conditions may result in better concentrate quality (i.e., lower ash content) due to decreased entrainment of fines.

Froth spraying has been used to improve concentrate grade, with significant beneficial results usually being realized (e.g., Klassen and Mokrousov, 1963, pp. 378-

380). Results from some studies suggest that the main benefit may arise from rejection of larger intermediate size composite particles rather than the extreme fines (Miller, 1969). The selective flocculation of fine shale also offers some possibilities (Halvorsen, 1979), and has been implemented in some plants, such as the Kitt Mine (e.g., Kawatra and Seitz, 1984). However, techniques based on the modification of froth properties may offer more potential (Jowett, 1983; Kawatra and Seitz, 1984).

A further problem involving very fine particles is the phenomenon of slime coating. This is difficult to diagnose, as there is nothing in recovery-size curves which reveals slime coatings, but it may be common in coal flotation slurries which contain considerable amounts of material which can disintegrate into clay slimes. In addition, although the flocculation of particles due to the presence of oil is common (e.g., Seitz, 1979), it is difficult to ascertain its effect on flotation.

3.1.2 Intermediate Size Particles

The principal mechanism responsible for the recovery of intermediate size particles is bubble attachment with a contribution from entrainment which becomes substantial towards the lower end of this size region. Intermediate particles are frequently liberated and float so fast that recovery is close to 100% over a considerable size range for typical residence times. These particles pose no problem in flotation. The range of the intermediate size region varies with the coal and reagent system. Although there is a scarcity of data on different coal systems, available data indicates that this region can extend up to very coarse sizes with favorable circumstances.

It should be noted that the sizes defining the limits of intermediate particle type behavior and the mass ratio of intermediate size particles to other size particles for each significant component, e.g., coal, ash, pyrite, and composite particles of all sorts, are important parameters to establish when assessing the response of a coal sample to flotation, as they are indicative of the degree of difficulty to be expected in effecting a separation for the whole.

3.1.3 Coarse Size Particles

In general, the recovery of coarse particles is by bubble attachment with a negligible contribution from entrainment. Referring to Figures 1.2 and 2.1, coarse particle recovery is usually lower than that of the intermediate size, but this is not always true. Coarse particle recovery is highly variable and extremely sensitive to the physical and chemical environment when compared with intermediate size particles, for which the response is moderately sensitive, and with fines, where it is only slightly sensitive (Trahar, 1981). Thus, as seen in Figure 2.21, the first sign of a deficiency of collector (or promoter), of an excess of depressant, of an unfavorable pH or chemical environment, indeed of any variable which could reduce the hydrophobicity of coal, is shown by a decrease in coarse particle recovery. This information also indicates that pulling coarse particles into the concentrate will result in the collection of intermediate and fine particles, even those of a composite nature.

Excluding for the moment effects due to froth conditions or those relating to slime coatings, the behavior of coarse particles is probably due to the fact that the degree of hydrophobicity required to promote a high degree of flotability increases with increases in particle size (Gaudin, 1927). Recovery data, given in Figures 2.19 to 2.21 and discussed in Section 2.2.1.3, for various species (size and specific gravity fractions) as a function of collector dosage provides a visual representation of the form of this relationship. Thus, with a range of particle sizes no single collector addition will be appropriate for all sizes and the most efficient compromise will depend on the size distribution of the important minerals. Kakovsky et al. (1961) showed that the principal benefit of thiol collectors with long chains was in the recovery of coarse particles; such collectors produced no change in the flotation rate of fine or intermediate size particles. Robinson (1959-60) concluded that there was a critical degree of hydrophobicity for the attainment of maximum flotability, which can be distinguished from some threshold at which flotation just becomes perceptible. This data provides strong confirmation for hypothesizing that the difference between threshold and critical levels increases rapidly with particle size.

A proposed form for the relationship between flotability and hydrophobicity based on this hypothesis is presented in Figure 3.2 [after Trahar (1981); based on detailed data for the sphalerite-copper sulfate system (Anthony et al., 1975)]. It is similar to the behavior of the coal system shown in Figures 2.19 to 2.21. There is no reason for attempting to distinguish between minerals which become flotable by the addition of collector or those which become flotable by partial oxidation of surfaces, such as chalcopyrite, pyrrhotite, and galena, or naturally hydrophobic materials, such as coals. The dominating requirement is the total degree of hydrophobicity obtained from all possible sources, i.e., collectors, frothers, mineral oxidation products, etc.

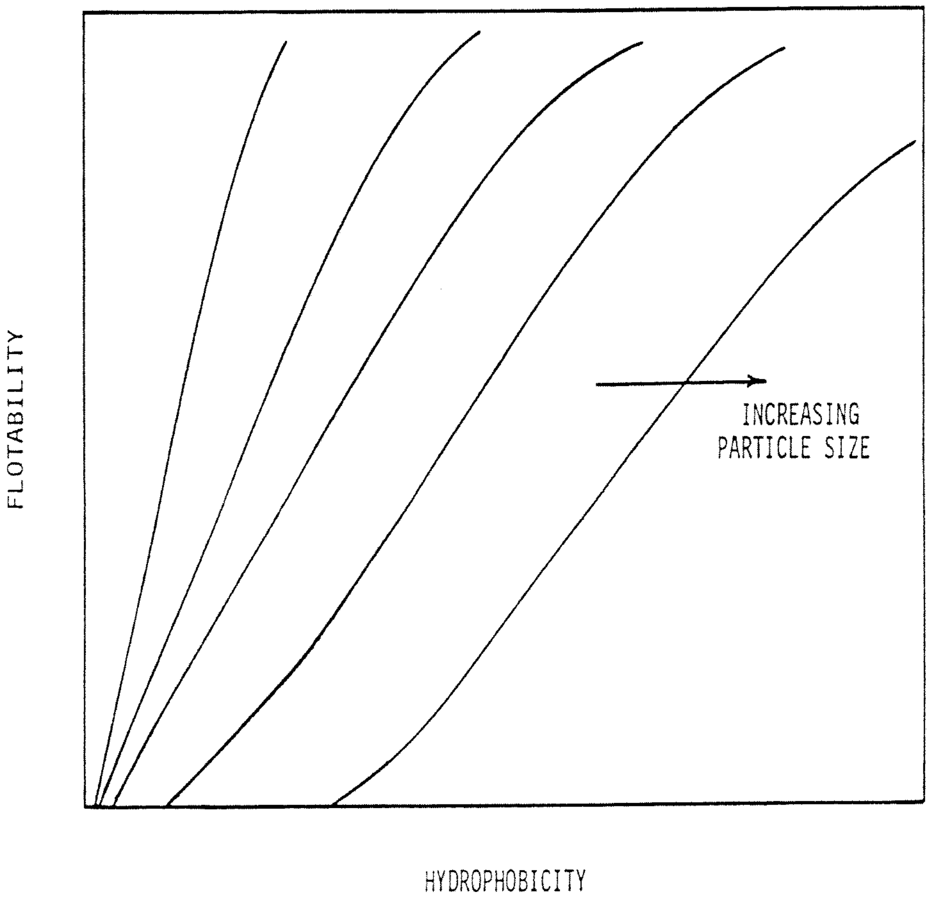


Figure 3.2. A Qualitative Representation of the Influence of Particle Size on the Relationship Between Flotability and Hydrophobicity (after Trahar, 1981; Seitz and Kawatra, 1985).

3.1.4 Composite Particles

Raw coals are generally treated "as is" and are not ground to achieve liberation. Thus, many of the particles in the feed to flotation are composites, containing varying fractions of different carbonaceous materials, minerals, and pyrite. Therefore, the behavior of composite particles in coal flotation is very important and the effect of particle composition on recovery and rate of recovery must be determined. Figure 2.20 shows that composite particles float less readily than liberated particles and that a correlation exists between surface composition and flotability. The behavior of composite particles has been studied in some detail in recent years (e.g., Olson, 1979; Bennett et al., 1983; Bustamante and Warren, 1983, 1984; Sarker et al., 1984; Seitz and Kawatra, 1985).

Figure 2.20 also illustrates that relatively lower levels of hydrophobicity are necessary to float fine and intermediate size fraction particles. Thus, provided that the fraction of hydrophobic material exceeds some low threshold value, the flotation properties of composite particles in these size regions will not differ significantly from those of liberated particles. The hydrophobicity required for flotation of coarse particles is more difficult to achieve, and in this size fraction the flotability is more sensitive to the decreasing fraction of hydrophobic material in composite particles. Consequently, composite particles exhibit coarse particle behavior at a smaller particle size, that is determined by the contributions to particle wettability of the other minerals present.

3.2 The Effect of Reagents

The relationships between reagent regime, particle size and type, and maximum recovery (R) and rate of recovery (K) are discussed in the following section. The typical recovery-time response for coarse, intermediate, and fine particles of coal and minerals is shown in Figure 3.3, which is based on the kinetic data presented in Chapter 2. For coal; the intermediate particles are recovered first, followed by the coarse and fine particles. For gangue; the fine particles are recovered first, followed by intermediate particles, and then possibly even some coarse particles. By measuring this recovery-time response for particles at various control variable levels, it is possible, as discussed in Chapter 2, to

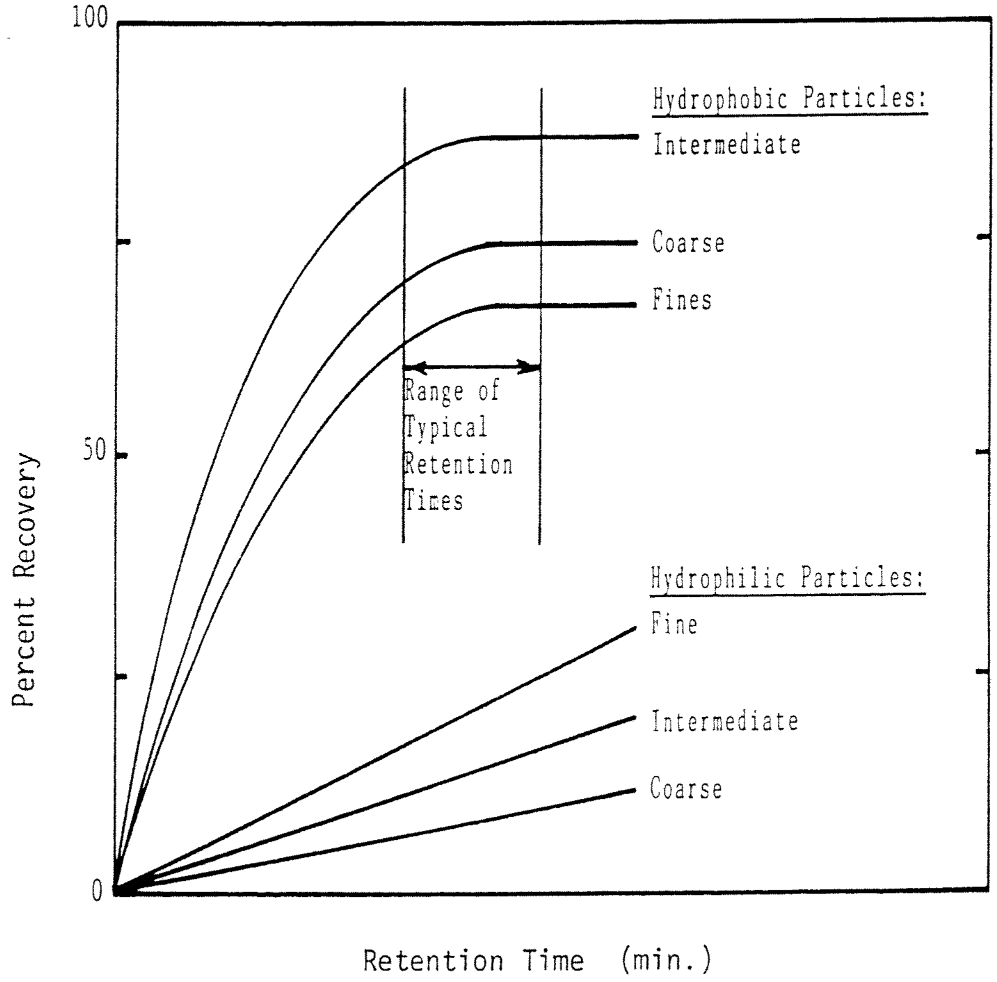


Figure 3.3. Typical Recovery – Time Profile of the Behavior of Fine, Intermediate, and Coarse Size Ranges of Hydrophobic (Coal) and Hydrophilic (Gangue) Particles in Flotation.

determine the relationship between R or K, residence time, and control variable level for the fine, intermediate and coarse size fractions of coal and mineral particles.

The retention time for a typical flotation circuit lies within the range indicated in Figure 3.3. Depending on the recovery-time response for a given species, either the rate of recovery or maximum recovery will play the major role in controlling the grade-recovery response of each species for a given retention time. At long retention times, the maximum recovery is the controlling factor; while for shorter retention times, the rate of recovery is the controlling factor.

The particular significance of laboratory data concerning changes in rate of recovery or maximum recovery with regard to industrial behavior for a given flotation circuit, depends on the "time equivalency" of the laboratory recovery-time profile to the plant flotation circuit. That is, whether the retention time for the plant's circuit is such that performance is controlled by maximum recovery or rate of recovery. Frequently, the maximum recovery is critical for intermediate size particles and the rate of recovery is critical for coarse and fine particles.

In the majority of fines processing circuits in coal preparation plants, optimization of the rate of recovery becomes important due to short retention times and considerable variation in the feed rate and size distribution of the circuit feed. For example, comparing the differences between lab and plant recoveries for both the Panther Valley and Kitt Mines suggests that the latter were somewhat limited by the lack of available retention time. The rate of recovery plays a primary role in determining the optimum levels of variables under conditions of limited retention time.

This data also revealed that ash recovery was higher in the lab than in the plant. The increasing difference in concentrate percent ash for individual size fractions with decreasing size suggests that this resulted from greater entrainment of fines in the lab tests. Such differences in the effect of the froth phase must be considered in comparing test results and in understanding process performance.

3.2.1 Performance Characteristics of Reagents

The separation of coal particles from gangue particles in a flotation circuit may be controlled and optimized by selectively altering the mechanisms responsible for particle recovery as follows:

1. The bubble attachment mechanism, by altering the hydrophobicity of various particle species and the kinetics of bubble-particle interaction.
2. The entrainment mechanism, by controlling the volume of entrained pulp per bubble-particle aggregate.
3. The loss of both bubble attached and entrained, coal and gangue particles, back into the pulp; by controlling the breakdown and drainage of the froth phase.

Selective control of these mechanisms can be achieved with varying degrees of success by using chemical and/or physical methods (Jameson et al., 1977). However, regardless of the method or methods selected, control of the flotation process is complicated by the fact that both chemical and physical methods simultaneously affect more than one of these mechanisms (see Figure 1.3). Consequently, the development of successful control and optimization strategies requires an understanding of the effect of a particular strategy on each mechanism.

Reagents have the following effects on process mechanisms:

1. Frothers:

- the kinetics of bubble-particle interaction, by their effects on the last stages of bubble-particle interaction;
- water and particle entrainment, by altering bubble size and number; and
- froth characteristics, by altering froth stability and drainage.

2. Collectors:

- bubble attachment, by altering hydrophobicity and bubble-particle interaction kinetics;
- entrainment, by altering the number of bubble-particle aggregates; and
- froth characteristics, by controlling froth stability and the flow of particles into the froth.

3. Depressants:

- bubble attachment, by altering hydrophobicity and bubble-particle interaction;
- entrainment, by increasing the size of gangue particles through flocculation; and
- froth characteristics, by controlling froth stability and the flow of ultrafine particles into the froth.

Although it is well known that the surface chemistry of minerals and the nature of reagent absorption, e.g., of collectors, influences the maximum recovery (R) and the rate of recovery (K) of particles, the role of frothers and other reagents besides collectors in optimizing flotation kinetics is frequently ignored. Following the program of plant and lab tests reported in Chapter 2 and a review and analysis of the literature, it has been possible to identify general patterns of behavior resulting from changes in reagent types and addition levels.

3.2.1.1 Frothers

Economical industrial scale identification and use of frothers requires direct experimental comparisons in laboratory flotation cells and plant scale operations. The discussion in Sections 2.2.1.3 and 2.2.2.3 covers some of these problems. In addition, the use of two phase columns can be extremely useful in characterizing froth phase behavior. Because of the lack of reliable data on the effects of frother dosage and of different types of frothers for a wide variety of coal flotation systems, characterization programs were undertaken at several research laboratories, i.e., Dow Chemical Company (Klimpel, 1980, 1984), American Cyanamid Co. (Strydom et al., 1983; Groppo, 1984), and Michigan Technological University, (Seitz and Kawatra, 1985, 1987). These studies involved the analysis of grade-recovery and recovery-time profiles from both lab and plant studies and, in some cases, froth column data. Sufficient data were obtained to permit some correlation between factors. Such comparisons assisted in identifying the general characteristics of frother behavior discussed below. However, the by-size differences in concentrate ash content for lab and plant tests, as discussed in Section 2.2.1.3., indicate a potential problem from reliance on data from the former to predict performance of the latter. This problem can only be overcome by altering lab test procedures to better emulate plant conditions.

Analysis of the plant and laboratory data presented in Chapter 2 and the literature indicates that the results shown in Figures 2.2 and 2.3 are typical of the effect of frother dosage on the grade-recovery performance of a coal flotation circuit. For each of the three size ranges, increases in frother dosage result in increased coal recovery and sometimes lower grade concentrates. However, the reduction in grade is only significant for the fine size fraction.

Analysis of the recovery-time profiles underlying these grade-recovery curves revealed that this behavior resulted from the maximum recovery and rate of recovery versus frother dosage behavior of hydrophobic coal species and hydrophilic ash species (see Figures 2.8 and 2.9), and the retention time available in the flotation circuit. The general nature of both grade-recovery and K / R curves in turn indicates that there are different relationships between rate of recovery or maximum recovery and frother dosage for the coarse, intermediate, and fine size fractions of coal and ash. This behavior results from the relationships between particle hydrophobicity, size, water recovery, and entrainment, as illustrated in Figures 2.19, 2.11, and 2.12, respectively. However, the general nature of the relationship is illustrated in Figure 3.4.

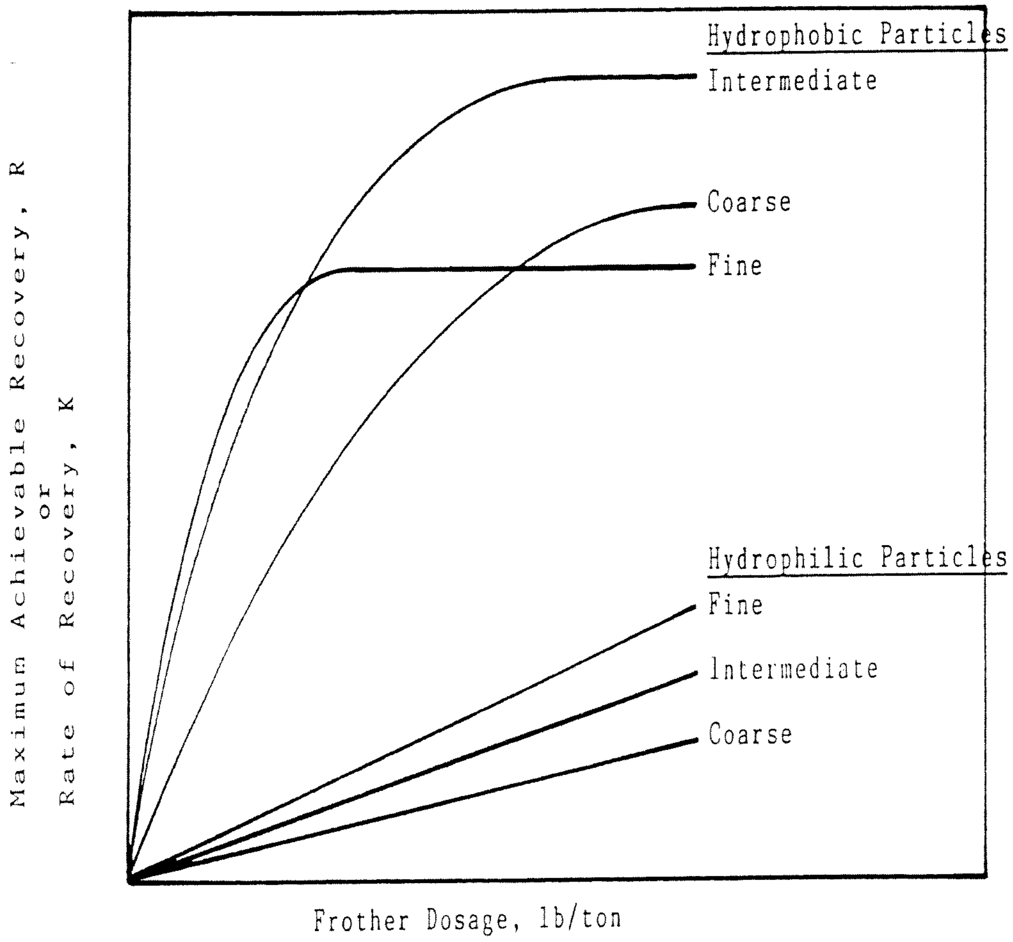


Figure 3.4. The Typical Relationship Between Frother Dosage and Maximum Achievable Recovery, R, or Rate of Recovery, K; for Fine, Intermediate, and Coarse Hydrophobic and Hydrophilic Particles in Flotation.

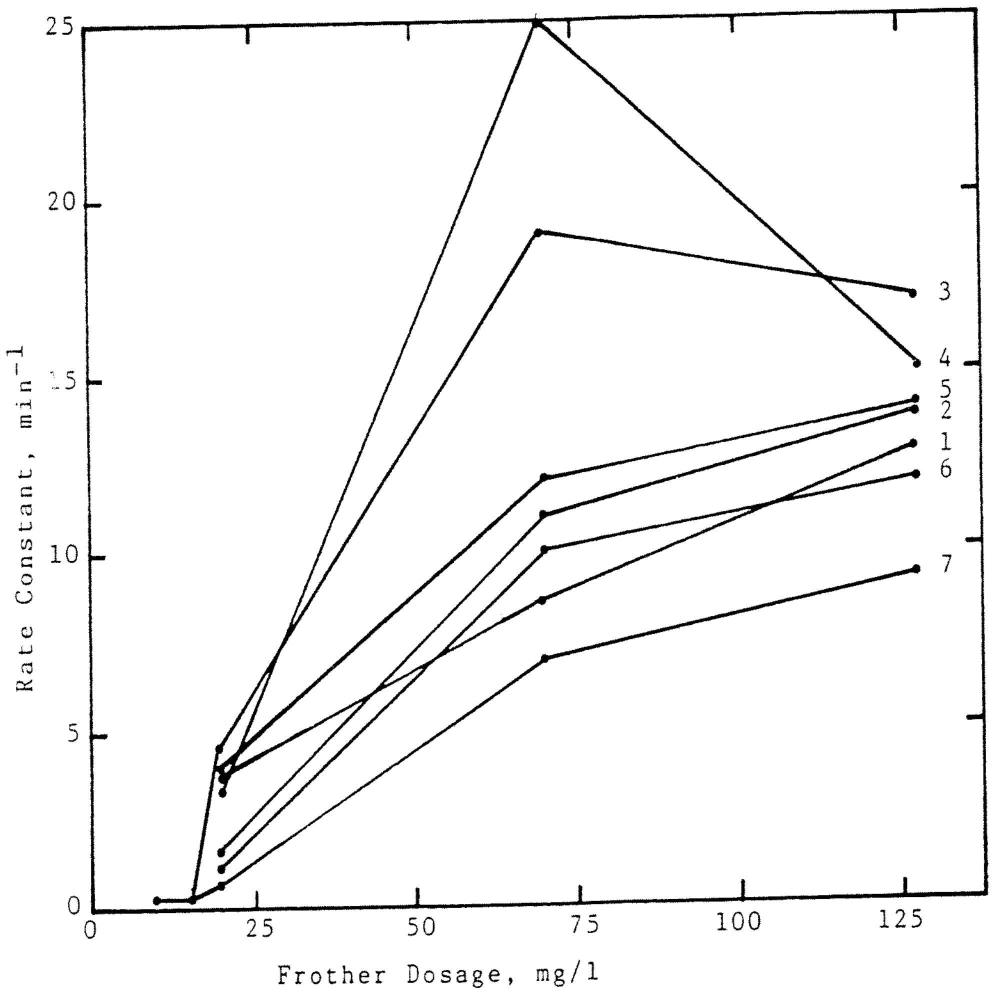


Figure 3.5. The Effect of Frother Dosage on the Rate of Recovery of Different Size Fractions of a 92.5 % Carbon Coal, Using m-Cresol as a Frother (after Safvi, 1959). 1. 33, 2. 76, 3. 105, 4. 153, 5. 211, 6. 300, and 7. 420 microns.

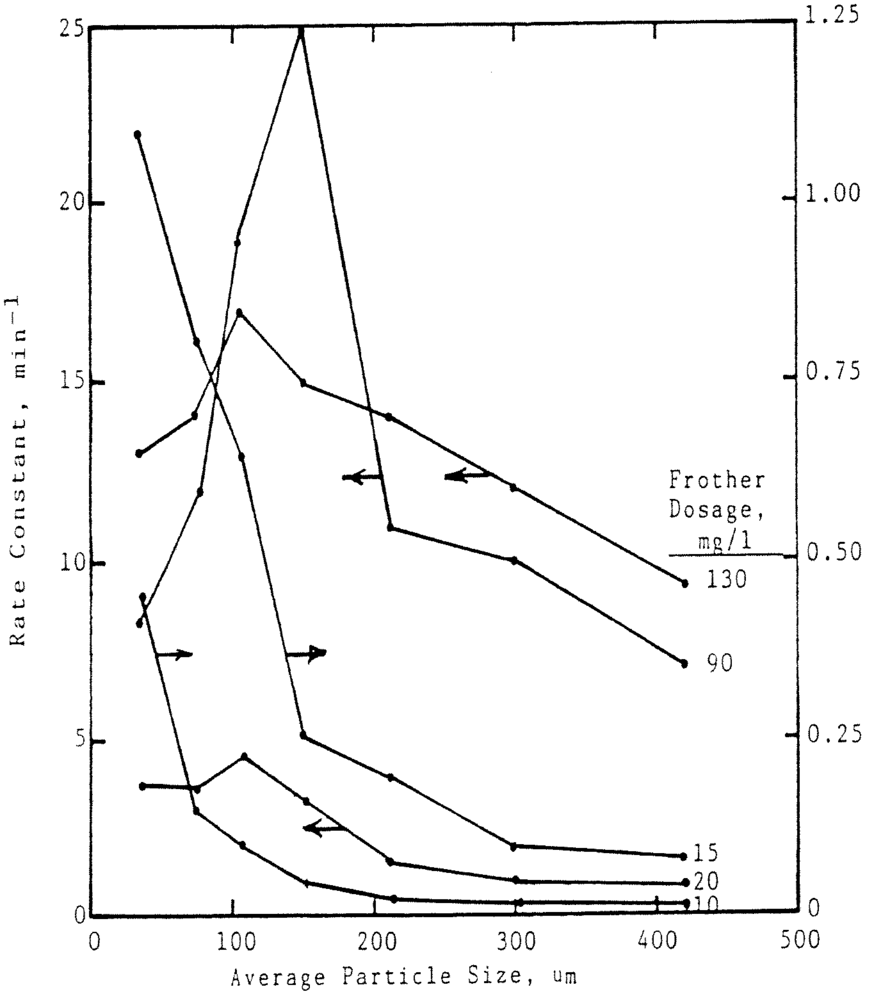


Figure 3.6. The Effect of Frother Dosage on the Rate of Recovery – Size Behavior of a 92.5 % Carbon Coal Using m-Cresol as a Frother (after Safvi, 1959).

Further elucidation of this behavior is provided by Figures 3.5 and 3.6. These results show variations in the rate of recovery greater than two orders of magnitude, caused by changes in frother dosage, with the maximum rate moving from the extreme fines to intermediate sizes (100 to 150 um) as frother dosage increased. In addition, the rate of recovery of 100 X 200 um particles reached a maximum and then decreased while the rate of recovery of the other size fractions never reached a plateau in the range of frother dosages tested.

It is commonly observed that different frothers give better maximum recovery or rate of recovery performance for a given coal or for different size fractions (e.g., Banerjee et al., 1962; Klimpel and Hansen, 1984; Seitz and Kawatra, 1985, 1987). Furthermore, blends of various types of frothers will often improve circuit grade-recovery performance by improving the recovery of all size fractions (e.g., Klimpel, 1984). This latter behavior is responsible for the increasing use of frother blends in the treatment of hard-to-float coals.

Table 2.4 shows the effect of frother and collector dosage on the recovery and rate of recovery of coal and gangue, and various ratios related to selectivity for a series of five frothers. The grade-recovery results after each period of froth collection are given in Figure 2.23. These frothers were selected to give a range of behaviors from weak (MIBC) to strong (DF1263). However, the observed process behavior for the frothers did not differ as much as expected. This reflects the fact that either:

- the structural differences which control particle transport through the froth phase were insufficiently altered in the lab tests for some of the frothers or
- the drain time in the lab froth was too short for the structural differences to have any effect.

The selectivity ratios in Table 2.4 show that in going from MIBC to DF1263, the kinetics of coal recovery increased faster than for ash recovery; while the final selectivity decreased in the same order. This means that the initial product is of higher quality but the final product will be worse. As discussed above, kinetic factors are of primary importance in frother selection since the cell residence time is usually limited in industrial operations. Consequently, DF1263 would likely be chosen over MIBC for the Panther Valley Plant. Table 3.2 summarizes the results presented in Section 2.2.2.3 and literature results and presents qualitative guidelines for frother selection, with the indicated performance of particular reagents being the optimum achievable with that chemical by adjusting dosage.

Table 3.2. Average Relative Performance characteristics of Frothers (after Klimpel and Hansen, 1984; Seitz and Kawatra, 1987a).

Frother	Maximum Recovery, R	Rate of Recovery, K	R_{coal} / R_{ash}
Pine Oil	Poor	Poor	Poor
MIBC	Medium	Low	High
2-Ethylhexanol	Medium	Low	Medium
Low Boiling Cresylic Acid	Poor	Poor	Poor
High Boiling Cresylic Acid	Poor	Poor	Poor
1,1,3 Triethoxybutane	Low	Low	Medium
DF200	Low	Low	Medium
DF250	Low	Low	Medium
DF1012	High	High	Medium
DF400	High	High	Medium

Note: Poor < Low < Medium < High

The performance characteristics given in Table 3.2 are "averages", and it is possible to identify exceptions for any given plant (with given cell types, aeration, particle size, etc.). The "art" of flotation is the process of identifying frothers which show unusual or unexpected performance. This can only be done by direct flotation cell experimentation using this information as a starting point. Table 3.3 lists some of the pure components of frothers listed in Table 3.2. Note that commercial frothers available from different sources vary widely in both the amount of the stated active ingredient(s) and purity of product form (Klimpel, 1984).

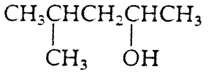
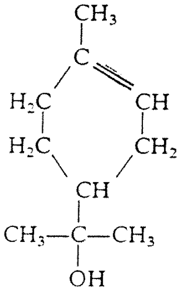
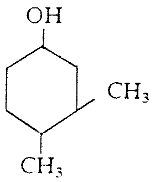
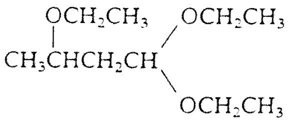
Type	Formula	Water solubility
Aliphatic Alcohols R = Alkyl with 5 to 8 carbon atoms	R—OH	Slight
MIBC	 $CH_3\underset{CH_3}{\underset{\vert}{C}}HCH_2\underset{OH}{\underset{\vert}{C}}HCH_3$	
Pine oils Terpineols		Slight
Cresylic acid		Slight
Alkoxyparaffins 1,1,3-triethoxybutane		Slight
Polyglycolethers Dowfroth Aerofroth	$R(OR')_xOH$	Miscible at low *x* to partial solubility at higher *x*

Table 3.3. Typical Compounds Used as Frothers in Flotation.

A direct linear correlation between the recovery rates of water and gangue minerals is commonly observed in data from laboratory tests and plant flotation circuits (e.g., Figures 2.12 and 2.13) (also Lynch et al., 1981; Kawatra and Seitz, 1984; Seitz and Kawatra, 1985b). The slope of these curves increases in the order:

coarse < intermediate < fine particles.

Results discussed in Chapter 2 indicate that increased frother dosage or use of a stronger frother reduces bubble breakage and increases mobility, thereby increasing the water recovery rate in the concentrate and the entrainment of fine ash particles as shown in Figure 2.3. Although frother addition rate is a particularly useful variable for use in overcoming froth overloading problems, it can drastically increase the recovery of fine high ash particles as shown in Figure 2.3. Thus, it should only be used to eliminate froth overloading.

Optimum frother selection is also influenced by the presence of clay slimes, due to differences in the froth structure that is produced by the various frothers and in turn controls water drainage and particle entrainment. The primary effect of froth structure differences is to change the ratios of coal and gangue flotation rates (K_{coal}/K_{gangue}), and maximum recoveries (R_{coal}/R_{gangue}), as shown in Table 2.4. Stronger frothers, e.g., Dowfroth 1263, yield superior selectivity in this case due to such factors as finer bubble size and lower surface tension. However, in other cases, strong frothers reduce selectivity due to the larger quantity of water and entrained particles which they carry into the froth. For these reasons, low molecular weight frothers such as MIBC should be used when large amounts of fine clay are present, while high molecular weight frothers should be used for low-slime coals, where entrainment is not as important and good rate performance is needed.

The data in Table 3.2 do not give a complete picture of all the information involved in making an industrial frother evaluation. Other factors, such as cost, performance, safety and human health considerations, vendor reliability and technical service, etc., also play a role in the industrial use of frothers.

3.2.1.2 Nonpolar Oils

Analysis of the results from plant and laboratory studies presented in Chapter 2 and the literature indicates that the results shown in Figures 2.2 and 2.3 are typical of the effects of collector dosage on the grade-recovery performance of a coal flotation circuit. For each of the three size ranges, increases in collector dosage resulted in increased coal recovery and, sometimes, slightly lower grade concentrates.

Typical recovery-time profiles for coal and mineral species are shown in Figure 3.3. Analysis of these profiles for different collector dosage conditions that resulted in particular grade-recovery curves revealed the effect of collector dosage on the recovery and rate of recovery of individual coal and mineral species. Typical results from such analysis are similar to the results shown in Figures 2.8 and 2.9 for individual size fractions of the Lower Kittanning seam coal analyzed using Equation (2-1). The trade-off between maximum recovery and rate of recovery is particularly important. This phenomenon is frequently observed in flotation with variation in frother or collector dosage.

In general, an increase in the addition rate of a nonpolar oil collector can either increase or decrease the rate of coal recovery as well as the concentrate percent ash; depending on the nature of these curves and the dosage prior to change, as seen in Figure 2.19. Where initial nonpolar oil dosages are low, an increased dosage affects the hydrophobicity and flotability of the coal particles, resulting in increased recovery. However, if the initial dosages are high, increases have no further effect on particle hydrophobicity and the excess actually counteracts the effects of the frother and results in froth overloading, a condition which is discussed in Section 1.2.2. The loss in recovery due to froth overloading cannot be entirely regained when retention time is limited.

Analysis of batch flotation concentrates clearly shows that increased collector addition significantly increases the recovery of coarse particles and normally slow-floating composite particles in the early stages of flotation, e.g., see Figure 2.20. This indicates that increasing collector addition converts some slow-floating species to fast-floating species. It also shows that increasing the nonpolar oil dosage can increase the recovery of normally non-flotable, highly composite species in the later stages of flotation. Since composite and coarse particles response is most heavily influenced by high collector dosages, an increase in recovery due to overaddition of collector can result in increased concentrate percent ash.

The most important points to emphasize regarding the use of nonpolar oils as collectors in coal flotation are:

1. They can significantly increase maximum recovery (R) and rate of recovery (K) for coarser particles.
2. In the presence of composite particles of intermediate specific gravity their effect on selectivity must be carefully monitored and controlled.
3. Only the high ash particles will be rejected with their use at the required higher dosage levels, i.e., high coal recovery in the concentrate at lower grades.
4. They will act as collectors for some lower rank and oxidized coals.

The problem of achieving sufficient selectivity among various carbonaceous species, ranging in ash content up to 40%, is a persistent one which is difficult to solve using nonpolar oil collectors. Their chemical nature and consequent mechanism of attachment, i.e., spreading on surfaces, precludes the possibility of selective attachment which is common in the use of chemisorbing reagents or heteropolar reagents (either cationic or anionic compounds) as collectors. Consequently, significant improvements in the performance of coal flotation circuits treating refractory coals are only likely to result from use of the heteropolar promoter reagents which have been developed in recent years.

There is little justification for investigating more exotic and expensive collectors to use in coal flotation operations aimed at recovering a maximum of easily flotable coal of adequate ash content. However, in any situation where a more refined flotation operation is desirable (e.g., due to a refractory coal or where selective separation of petrographic constituents is required) or essential (e.g., coal-pyrite separation), there is justification for more careful selection of flotation reagents.

3.2.1.3 Frother/Nonpolar Oil Interaction

Analysis of the data from both plant and laboratory tests presented in Chapter 2 indicates that equal coal recovery can be achieved with a series of frother and collector combinations ranging from high frother / low collector to low frother / high collector, e.g., the coal recovery-ash content response is as shown in Figures 2.2, 2.3, 2.14, and 2.15. However, use of high frother dosages to improve recovery leads to high ash concentrates in some cases. Increased entrainment of fine high ash particles was responsible for this behavior.

The results from Panther Valley Plant tests (see Figures 2.2 and 2.3) clearly illustrate the different effects of frother dosage on fine and coarse particles. Reduced process performance is only expected when the fines are a significant fraction of the feed and the fines contain a considerable amount of fine high ash particles. As seen at the Kitt

Mine (see Figures 2.7 a and b), the use of a flocculant to depress fine ash particles can minimize this effect. These conclusions hold for all of the plant and laboratory test work that we have conducted (Chapter 2; Suardini and Kawatra, 1982; Kawatra and Seitz, 1984 a, b; Seitz and Kawatra, 1985 a, b, 1987a). Therefore, the frother: nonpolar oil ratio is primarily significant in controlling the grade-recovery response of fine size range particles. Interactions between the frother and collector were suggested by Soviet scientists (Goncharova et al., 1974; Gluschenko et al., 1975), but with little associated investigation.

The rate of recovery or maximum recovery versus reagent dosage response for any coal is controlled by the relationship between hydrophobicity, flotability, and particle size which is illustrated in Figure 3.2. Thus, required reagent dosage depends on coal surface characteristics and particle size distribution; and grade-recovery response depends on the liberation characteristics of feed particles and the contribution of entrainment to fine particle recovery.

The potential drop-off in recovery or rate of recovery with overdosing of collector or frother, shown in Figure 3.1 and 2.19 must be carefully monitored. As discussed in Section 1.2.2, the explanation of this phenomena lies in the multiple roles played by the froth, e.g.:

i. as the recovery of particles increases, the ability of the froth to transport particles from the pulp/froth interface to the launder is eventually exceeded (i.e., the froth is overloaded) and
ii. the apparent flotation rate decreases because the transport capacity of the froth is reduced once it overloads.

The interactive effects of frother and collector dosage levels on the froth have already been described. In particular, a change in the reagent dosage may increase or decrease froth percent solids, depending on the state of the system under existing conditions. The behavior depends on whether solids recovery or water recovery is more greatly affected by the change. Some of the difference in flotation performance observed when comparing plant and laboratory results reflects the thinner froth layer present in a laboratory flotation cell (1 to 1.5") versus a froth layer of 3 to 4" in a plant cell, e.g., see the comparison in Section 2.2.1.3.

3.3 Control of Coal Flotation Circuits

The control of coal flotation circuits involves two separate aspects:

1. Stabilizing control; to reduce the effects of process disturbances.
2. Optimizing control; to yield optimal circuit grade-recovery performance.

Thus, the general factors to be considered during control strategy development include:

1. Circuit design and operating practice.
2. Manipulation of control variables to achieve:

- grade control, e.g., by frother or collector dosage, aeration rate, or water sprinkling, and
- recovery control, e.g., by frother or collector dosage, aeration rate, impeller speed, retention time (pulp level).

3.3.1 Design and Operating Practice

Circuit design is an important factor contributing to the ease of developing a process control strategy. Good design can reduce the burden placed on the control strategy by presenting a relatively stable feed to the circuit. Consider Table 1.1, five of the seven disturbance variables listed are somewhat controllable by design (both of the entire preparation plant and of the circuit directly feeding the flotation circuit) and by operating practice.

A considerable degree of improvement in performance can be achieved by stabilizing these variables as much as possible by design and operation, e.g., as only a fraction of the raw feed is processed by flotation and because the feed is often reclaimed from size-segregated stockpiles, wide variations in feed percent solids, size distribution, ash content, etc. are often observed in plant operations. Some degree of circuit stabilization can be achieved by providing the best conditions for flotation as follows:

A. Devoid of particles that are either too coarse or too fine, and therefore are easier to beneficiate by processes other than flotation. Because of the critical importance of particle size, the removal of plus 600 microns (28 Mesh) particles prior to flotation is necessary; and the difficulty of rejecting ultrafine clay particles by flotation necessitates the use of desliming circuits prior to flotation when such particles are present in such an amount as to affect flotation results.

B. Water pH and hardness should be such that coal recovery is not depressed.

C. One final consideration is that automatic pulp level control in the flotation banks is necessary to achieve any degree of circuit stability.

By achieving some degree of stability and optimization using the factors discussed above, it is possible to considerably reduce the burden of stabilization on the control strategy. This in turn may permit a greater degree of optimization from the control strategy.

3.3.2 Control of Circuit Performance

The variables selected for control should be used, as much as possible, to reduce the effects of disturbances while at the same time yielding optimal circuit behavior. A control strategy cannot be developed that is universally applicable to all coal flotation circuits. Rather, site particular factors, such as coal characteristics, circuit design and operating practice, and selected control variables, must be considered during strategy development.

Particle size distribution and liberation characteristics play an important role in controlling the performance of coal flotation circuits since different size and liberation fractions exhibit varying responses to given variable levels, e.g., Figure 2.20 and Seitz and Kawatra (1985 a, b). When an attempt is made to recover the coarser or finer coal particles through altering control variables, an increased quantity of gangue particles may be recovered through bubble attachment and entrainment. Hence, a compromise between coal recovery and loss must be made in order to achieve an acceptable concentrate grade. The ideal is to achieve maximum recovery at a specified grade, i.e., operating on the optimal grade-recovery curve.

As a preliminary step in control strategy development it is convenient to determine and consider the process matrix (Shinsky, 1979) for the coal flotation system. The process matrix for Illinois No. 6 coal was obtained by simulating the systems reaction to step changes in potential manipulated variables, e.g., aeration rate, impeller speed, frother addition, and tailings pumping flowrate (Herbst and Bascur, 1984). The first three responses were obtained at constant pulp level to simulate practical operating conditions. The results for four manipulated variables are summarized in Table 3.4, where "+, 0, or -" refer to the direction of change in a controlled variable resulting from an increase in manipulated variable and "fast and slow" refer to the speed of the response.

This process matrix shows certain interactions between variables are inevitable; i.e., it is not possible to change just one manipulated variable and have it affect only one controlled variable. Such information is very valuable in pairing controlled and manipulated variables to form an overall control strategy. For example, it suggests that grade could be controlled by manipulation of aeration rate and/or frother addition rate, and recovery by acting on impeller speed, and/or pulp level. Only by proper decoupling of interactions can an effective multivariable control system be implemented.

Table 3.4 Process Matrix for Coal Flotation indicating the Response of Controlled Variable to Changes in Manipulated Variables (Herbst and Bascur, 1984).

Control Variables	**Dependent Variables**		
	Grade	**Recovery**	**Froth Depth**
Aeration Rate	- fast	+ fast	+ fast
Impeller Speed	0 - slow	+ - fast	+ slow
Pulp Level (tailings flowrate)	- slow	+ fast	- slow
Frother Addition Rate	- fast	+ fast	+ slow

Pulp percent solids and flowrate are the easiest of the circuit operating variables to monitor, and reagent addition levels are conceptually simple and relatively economical variables to use for control. These variables will certainly provide an adequate basis for circuit control and the following discussion is based on their use.

The important concerns are:

1. What should the steady stage frother and collector dosages be?
2. How should the frother and collector addition dosages be used to control circuit behavior?

The minimum frother level in any case must be high enough to prevent froth overloading. The frother addition level should be based on the volumetric flowrate of water into the circuit, so that the frother concentration in the pulp is constant and pulp aeration processes are relatively constant. The collector addition level should be based on the solids feed rate to the circuit.

The results shown in Figures 2.2, 2.3, and 2.16 are typical of the behavior of individual size fractions in coal flotation. Combining knowledge of individual circuit feed characteristics with the behavior illustrated in these figures suggests the possibility for development of circuit-specific operating and control strategies.

As discussed above, the grade-recovery performance of flotation circuits is controlled by the mass distribution of material into species according to size and composition. When attempts are made to improve the response of one specie vs. another, through altering operating practices, circuit layout, reagent regime, or control practices, the behavior of all other species present must also be considered. The goal is to operate at a point on the optimal grade-recovery curve where a reasonable compromise between coal recovery and loss is made in order to achieve an acceptable grade.

Attaining this objective in a rational, not chance fashion, requires first determining the primary recovery mechanism for each specie of interest, i.e., bubble attachment or entrainment, because different actions are required to alter entrainment, composite particle recovery, or true flotation. Then, the appropriate remedial action may be determined, e.g., decrease water recovery and ash entrainment, increase or decrease composite recovery, or increase true flotation of coarse coal. The overriding theme of this approach is to identify the cause of problems prior to investigating or suggesting corrective actions. The application of these concepts is reviewed below for the Panther Valley and Kitt Mine preparation plants.

The fines processing circuit in the Panther Valley preparation plant consisted of a single stage of rougher flotation. The typical circuit feed analysis is given in Table 2.1. The reagent regime consisted of No. 2 fuel oil as collector and a polypropylene glycol (PPG-200) as frother.

This flotation circuit was designed and installed because about 7 percent of the plant feed was 30 X 200 mesh (600 X 74 um) and 8 percent was minus 200 mesh (74 um). The heavy media circuits were unable to beneficiate this material and there was too much of it to discard. At the time the designers were unaware of any means to achieve acceptable performance of the combined flotation and dewatering circuits without removing the minus 200 mesh fraction by desliming. Hence, the fines circuit comprised sending the 30 X 200 mesh to flotation and the minus 200 mesh to waste.

As shown by comparing the feed ash content with the information in Figures 2.2 and 2.3, the ash reduction at high coal recoveries was good for the 14 X 30 and 50 X 70 Mesh fractions; 5.0 vs. 10.0 % ash and 8.0 vs. 18.4 % ash, for the product and feed in each size fraction, respectively, regardless of the reagent regime. However, the ash reduction for the minus 200 Mesh fraction was only acceptable when the low frother dosage reagent regimes were employed. The minus 200 Mesh product varied from 20 to 33 % ash, when the frother dosage was increased from 0.2 to 0.8 lb./ton.

Several alternatives were recommended for improving the overall performance of fines processing in this plant. The feed preparation screens should be modified to redirect the 14 X 30 Mesh material to the heavy media circuits. The recovery of this fraction by flotation is only 40 %, which could easily be increased to > 85 % in the heavy media circuit. This would yield an additional 1000 TPY of product for a small investment and provide additional capacity for treating the remaining material in a fashion more appropriate to its size. The collector and not the frother should be used to drive recovery of the remaining material from the circuit. This would minimize ash entrainment while yielding better product quality. Technology is currently available to process the minus 200 Mesh fraction currently discarded as slimes. A column flotation cell could process this 50 TPH of material and recover 40,000 TPY of coal. That action should have a fast payback.

The fines processing circuit in the Kitt Mine preparation plant also consisted of a single stage rougher flotation. The typical circuit feed analysis is given in Table 2.2. The reagent regime consisted of No. 2 fuel oil as a collector, MIBC as a frother, and a flocculant was used to depress clay.

This circuit was designed and installed because the other plant circuits could not beneficiate this material and there was too much to be discarded. The overall circuit performance was accepted, although an attempt was made to improve performance by using the flocculant to depress clay

As shown by comparing the feed ash analysis with Figures 2.8a and 2.8b, the ash reduction at high yields was very good for the 30 X 50 and 50 X 100 Mesh fractions; about 4.5 vs. 10.8 % ash and about 5.0 vs. 11.0 % ash, for the product and feed in each size fraction, respectively, regardless of the frother and collector dosages. However, the ash reduction for the minus 100 Mesh fraction was inadequate, about 10.0 vs. 24.7 % ash, probably due to the presence of clay. In these tests, both low frother and high collector and high frother and low collector reagent dosages had no discernibly different effect on process performance, which was much noisier than for the plus 100 Mesh material. This was probably due to the fine particle flocculation.

Results from the lab tests on this material, shown in Figures 2.16a to 2.16c, are more in line with the increase in product ash associated with increasing frother dosages observed at Panther Valley. A relatively simple explanation may account for this difference. Data in Figure 2.12 shows that the recovery of each size fraction of ash was directly proportional to water recovery, but only for the minus 100 Mesh fraction was the recovery greater than would be expected from recovery within composite particles. Thus, the recovery of fine ash was primarily due to entrainment. The difference in plant vs. lab response probably resulted from the following factors:

1. The relatively coarse cut size of 100 mesh used to separate fine and intermediate size particle behavior in these experiments means that the variability in behavior of ultrafine clay (minus 325 mesh) is confounded with the behavior of 100 X 325 mesh particles.
2. A cationic flocculant was used to depress clay in the plant, but not in the lab. Consequently, flotation conditions were actually different in the two sets of tests.
3. Reducing the frother dosage may have failed to reduce water recovery to the point where entrainment was significantly affected.
4. Differences in the thickness of the froth phase in the plant and lab tests as discussed above.

All of these factors combined to eliminate any apparent relationship in the data.

One additional set of conclusions were made from the Kitt Mine data. The recovery-size-specific gravity response for particles in lab flotation tests is shown in Figures 2.19 to 2.21. This data shows that one major effect of increasing the fuel oil dosage was to increase the recovery of both composite and coarse particles. This effect was acceptable at the Kitt Mine because essentially all of the liberated and composite particles were being recovered by design. However, recovery of a low ash product would require the use of a specific frother/collector dosage ratio reagent regime directed at recovery of low ash particles and some sacrifice of recovery in order to avoid the recovery of higher ash particles . These observations suggests that the optimum frother to collector ratio is a function of both the system and the process objective.

Two alternatives were recommended for improving the overall performance of fines processing in this plant. Their technical and economic feasibility should be compared to the existing system:

1. Desliming the feed at 325 Mesh and discarding the slimes.
2. Size classifying the feed at, e.g., 200 Mesh, and processing the plus 200 Mesh fraction in bank 1 of the circuit and the minus 200 Mesh material in bank 2.

The first alternative would eliminate 23 % of the feed in a stream containing 37 % ash and permit operating the circuit to improve recovery of the plus 100 Mesh fractions, e.g., recovery in the 30 X 50 Mesh fraction was only 70 %. Improving recovery of just the 30 X 50 Mesh material from 70 to 80 % would result in the recovery of an additional 4000 TPY of higher quality coal. This circuit would also eliminate a primary source of ash from the concentrate. The second alternative would permit optimizing the grade-recovery performance for each size fraction in a separate circuit.

Recovery in the current circuit could be driven with either frother or fuel oil, without harming product quality. Additional study is required to verify that flocculation may have been responsible for the failure of the fine fraction to respond to variations in the frother/collector ratio for this plant circuit, in direct contrast to others we have studied (Kawatra and Seitz, 1984).

CHAPTER 4. CONCLUSIONS

The research reported in this dissertation addresses the influence of reagent regime on flotation process performance. In addition, results from experimental test work and the technical literature were used to formulate a generally useful theory explaining particle behavior based on the following considerations:

1. Differential particle recovery occurring by either bubble attachment or entrainment as the basis for selectivity in separation.
2. Figure 1.2 represents the recovery-size response for different types of particles in flotation. The most critical factors in controlling response are size and hydrophobicity. This analysis indicates particle behavior rather neatly, and mechanistically, falls into general categories according to species; i.e., particle size and hydrophobicity classes as determined by a combination of surface composition and reagent regime. The correlation between mechanisms responsible for separation, species identity, and the effects of reagent regime provides a framework for understanding and predicting particle behavior.
3. Figure 1.3 outlines the general relationships between fundamental physicochemical phenomena, independent process variables, and grade-recovery response. As such it provides an excellent starting point for flotation process analysis. Understanding these mechanisms and means for their control provides a rational basis for optimizing circuit performance.

This theory is supported by experimental results from both lab and plant studies of the response of coal flotation to variations in the reagent regime. These experiments also revealed considerable information about process behavior and its analysis as follows:

1. Analysis of process performance requires considering the behavior of particle as species, since the mechanisms responsible for particle recovery are directly related to size and hydrophobicity. This concept is a powerful unifying technique for analyzing and understanding the flotation process.
2. The mass distribution of particles into species, the maximum recovery (R) and rate of recovery (K) for each species, and circuit retention time (t) for a raw coal feedstock should be considered as part of any experimental work addressing process response behavior. This provides a simpler route to identification of variable settings that result in operating on the optimal grade-recovery curve and eases the tasks of analysis, application, control, and optimization.
3. Frother dosage and, to some extent, type (molecular structure and weight) affect froth structure and consequently process response. The effects on process response resulting from changing froth characteristics are difficult to discern in the lab. This reflects a comparatively thin froth layer in lab flotation tests that gives shorter times for particle drainage. As a consequence of these shorter times, significant drainage of fine ash particles does not occur and greater concentrate ash values are observed. For example, increased frother dosage tends to increase coal recoveries and lower product quality at high dosages because of the strong froth and resultant high water recovery. Therefore, the reagent regime should be matched to feedstock characteristics in order to achieve optimal grade-recovery response. Examples of this include the following:

- Equivalent recoveries may be achieved using a wide range of frother / collector dosage combinations. Reductions in one component can be partially compensated for by increasing the other. However, a critical dosage level of each must be exceeded before this trade-off can be made. Mixtures involving high frother dosages result in high ash concentrates for some feedstocks. This behavior suggests a potential for selecting optimal frother and collector dosages, based on the specific characteristics of raw coal feedstocks and designed to maximize the differences in hydrophobicity between coal and mineral particles and minimize entrainment. The controlling factor is the mass distribution of particles into species.

- Use of high frother dosages to improve coarse particle recovery or rate of recovery is acceptable when the entrainment of fines is unimportant.

4. Fuel oil dosage affects both particle hydrophobicity and froth characteristics. Both the rate of recovery and maximum recovery increase as the fuel oil dosage is initially increased from starvation levels. With further increases, the maximum recovery keeps increasing, but the rate of recovery begins to drop-off. This response can sometimes be recognized at the plant level as a decrease in froth mobility. Such behavior causes the cross-over in recovery-time profiles that is sometimes observed for different reagent regimes. This is very important since the retention time in plant flotation circuits is often limited and the rate of recovery controls overall process response. This makes it essential to obtain kinetic data from lab and plant tests, along with the usual grade-recovery data.
5. Different reagent regimes (combinations of frother and fuel oil dosages) can also give crossing recovery-time profiles or grade-recovery curves as a function of time. These trade-offs reflect opposing effects of process variables on the maximum recovery and rate of recovery (Klimpel, 1980,1984). The optimum reagent regime may differ according to available circuit retention time as a result of this trade-off.

6. Flotation process analysis can be performed using either grade-recovery analysis, possibly as a function of time, kinetic / maximum recovery techniques (K / R), or some combination of the two methods. Although both approaches can yield similar conclusions, one technique may be more powerful than the other under different circumstances. The fitting of Equation (2-1) to recovery-time data provides maximum recovery (R) and rate of recovery (K) information that is an extremely useful supplement to grade-recovery analysis since it permits ascertaining whether changes reflect kinetic or steady state processes.
7. The response of fine ash particles is controlled by entrainment. Therefore, it is a function of overall water recovery. Ash in the intermediate and coarse fractions is primarily recovered via flotation of composite particles. Thus, it is controlled by their maximum recovery or rate of recovery, depending on the retention time available for flotation.
8. Changing the reagent regime to influence the behavior of one species will influence the response of others, perhaps negatively.
9. Process selectivity for separating low specific gravity (S.G.) versus medium and high S.G. species is controllable via the reagent regime. The response of medium S.G. particles is more difficult to control than that of the high S.G. particles.
10. Flotation response in plant and laboratory tests may differ. This reflects differing rate of recovery and maximum recovery behavior and retention time. A portion of these differences certainly reflects different froth phase behavior.

The behavior of particles in flotation becomes much more understandable using this theory correlating the mechanisms of separation with particle behavior as species. This also permits some important questions to be addressed:

1. What are the effects of process variables on the mechanisms responsible for particle behavior in flotation?
2. How can knowledge of these effects be used to apply, optimize, and control flotation circuits?

In particular, coupling knowledge of the major mechanisms responsible for particle recovery in flotation, i.e., bubble attachment and entrainment, with an understanding of the relationship between particle hydrophobicity, flotability, and size, or water recovery, entrainment and size, respectively, provides a qualitative mechanistic theory which explains the effects of process variables on coal flotation from a fundamental point of view.

The relationship between hydrophobicity, flotability, and size for hydrophobic particles is discernible from Figures 1.2 and 3.2 and the relationship for hydrophilic particles is likewise discernible from Figures 1.2, 2.10, and 2.20. It is also possible to proceed in the other direction to get a general idea of the probable behavior of any given coal in flotation or to identify means for improving the performance of coal flotation circuits.

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Appendix I. Panther Valley Plant Test Data.

Table I-1. Grade-Recovery Results for Panther Valley Plant Tests.

Reagent Dosage (lb./ton)			**Cumulative % Coal Recovery**			**Cumulative % Ash**		
No. 2 Fuel Oil	**PPG200**	**Size (Mesh)**	**Cell 1**	**Cell 2**	**Cell 3**	**Cell 1**	**Cell 2**	**Cell 3**
0.7	0.2	**14 X 28**	8.1	27.9	38.5	3.1	4.3	5.1
		48 X 65	37.5	60.9	77.5	3.8	5.8	7.4
		- 200	43.9	52.0	63.1	16.1	17.8	19.5
0.7	0.4	**14 X 28**	10.7	27.8	40.9	3.1	4.2	5.4
		48 X 65	50.0	71.6	84.7	5.1	6.5	7.9
		- 200	60.2	73.9	84.3	20.2	21.8	24.6
0.7	0.8	**14 X 28**	8.2	25.9	45.0	3.3	4.2	5.3
		48 X 65	55.9	71.5	87.1	4.8	6.8	8.1
		- 200	58.7	74.1	87.8	27.3	29.2	32.1
1.4	0.2	**14 X 28**	12.2	28.2	40.8	3.2	3.8	5.2
		48 X 65	52.7	58.9	80.7	4.7	5.3	7.4
		- 200	55.1	70.5	80.9	17.2	18.3	20.5
1.4	0.4	**14 X 28**	10.5	23.9	40.7	3.4	4.2	5.0
		48 X 65	54.5	73.0	81.9	5.3	6.7	8.1
		- 200	62.1	74.0	85.3	20.7	22.5	25.7
1.4	0.8	**14 X 28**	10.1	33.7	51.9	3.1	4.8	6.1
		48 X 65	57.9	75.5	86.7	5.6	6.6	8.5
		- 200	56.0	77.1	88.7	27.4	29.6	33.2

N.B. All data are averages for successful tests run under given conditions (N = 2 or 3).

Table I-2. Froth Percent Solids for Panther Valley Plant Tests.

Reagent Dosage (lb./ton)		
No. 2 Fuel Oil	**PPG200**	**Overall Froth % Solids (Cell 1 + Cell 2 + Cell 3)**
0.70	0.2	43.3, 44.2
	0.4	43.1, 43.6
	0.8	39.3, 40.3
1.05	0.2	43.1, 44.7
	0.4	42.6
	0.8	39.8
1.40	0.2	43.8, 44.5
	0.4	44.5, 44.9
	0.8	38.0, 38.6

Appendix II. Kitt Mine Plant Test Data.

Table II-1. Kitt Mine Plant Test Data - Relative Volumetric Flowrates for Ash and Coal Species in the Froth and Cell Products at a MIBC Dosage of 0.04 lb./ton and No. 2 Fuel Oil Dosage of 0.14 lb. / ton.

			Ash			**Coal**		
Stream	**Water**	**+ 48**	**48 X 100**	**- 100**	**+ 48**	**48 X 100**	**- 100**	**All Coal**
Feed	8.82	.0071	.0097	.108	.107	.138	.364	
Froth 1	0.68	.00063	.0011	.0074	.031	.052	.135	.22
Froth 2	0.54	.00046	.00084	.0057	.022	.037	.097	.16
Froth 3	0.34	.00029	.00053	.0036	.013	.019	.056	.088
Froth 4	0.10	.00007	.00016	.0012	.003	.0049	.015	.022
Cell 1	8.12	.0067	.0086	.100	.076	.087	.229	
Cell 2	7.60	.0063	.0078	.095	.054	.050	.132	
Cell 3	7.26	.0060	.0073	.091	.041	.030	.076	
Cell 4	7.16	.0059	.0071	.089	.038	.023	.061	

Table II-2. Kitt Mine Plant Test Data - Relative Volumetric Flowrates for Ash and Coal Species in the Froth and Cell Products at a MIBC Dosage of 0.04 lb./ton and No. 2 Fuel Oil Dosage of 0.21 lb. / ton.

		Ash			**Coal**			
Stream	**Water**	**+ 48**	**48 X 100**	**- 100**	**+ 48**	**48 X 100**	**- 100**	**All Coal**
Feed	9.08	.0063	.0095	.11	.099	.14	.376	
Froth 1	1.01	.00067	.0014	.011	.040	.070	.19	.30
Froth 2	0.42	.00027	.00051	.0046	.015	.024	.071	.11
Froth 3	0.20	.00011	.00023	.0020	.0056	.010	.031	.047
Froth 4	0.11	.00005	.00012	.0012	.0025	.0054	.017	.025
Cell 1	8.07	.0056	.0081	.10	.059	.069	.177	
Cell 2	7.65	.0054	.0076	.096	.045	.045	.106	
Cell 3	7.45	.0053	.0074	.094	.039	.034	.075	
Cell 4	7.34	.0052	.0072	.093	.036	.029	.058	

Table II-3. Kitt Mine Plant Test Data - Relative Volumetric Flowrates for Ash and Coal Species in the Froth and Cell Products at a MIBC Dosage of 0.04 lb./ton and No. 2 Fuel Oil Dosage of 0.35 lb. / ton.

			Ash			Coal		
Stream	**Water**	**+ 48**	**48 X 100**	**- 100**	**+ 48**	**48 X 100**	**- 100**	**All Coal**
Feed	7.73	.0067	.010	.11	.094	.13	.37	
Froth 1	0.60	.00044	.00090	.0068	.021	.043	.12	.19
Froth 2	0.42	.00025	.00053	.0047	.012	.024	.075	.11
Froth 3	0.31	.000092	.00027	.0035	.0048	.013	.057	.074
Froth 4	0.15	.000026	.00010	.0018	.0014	.0047	.028	.034
Cell 1	7.13	.0064	.0062	.0091	.11	.072	.088	
Cell 2	6.71	.0060	.0060	.0086	.10	.060	.064	
Cell 3	6.40	.0059	.0059	.0083	.099	.055	.052	
Cell 4	6.25	.0059	.0058	.0082	.097	.054	.047	

Table II-4. Kitt Mine Plant Test Data - Relative Volumetric Flowrates for Ash and Coal Species in the Froth and Cell Products at a MIBC Dosage of 0.04 lb./ton and No. 2 Fuel Oil Dosage of 0.42 lb. / ton.

			Ash			**Coal**		
Stream	**Water**	**+ 48**	**48 X 100**	**- 100**	**+ 48**	**48 X 100**	**- 100**	**All Coal**
Feed	9.67	.0067	.0095	.10	.11	.14	.37	
Froth 1	0.62	.00061	.0011	.0060	.031	.050	.12	.21
Froth 2	0.35	.00024	.00048	.0034	.013	.021	.063	.097
Froth 3	0.21	.00007	.00020	.0021	.0037	.0092	.039	.052
Froth 4	0.16	.00003	.00011	.0018	.0014	.0075	.030	.039
Cell 1	9.04	.0063	.0085	.098	.078	.087	.25	
Cell 2	8.70	.0060	.0080	.095	.065	.066	.18	
Cell 3	8.49	.0059	.0078	.093	.062	.057	.15	
Cell 4	8.32	.0059	.0077	.091	.060	.052	.12	

Table II-5. Kitt Mine Plant Test Data - Relative Volumetric Flowrates for Ash and Coal Species in the Froth and Cell Products at a MIBC Dosage of 0.06 lb./ton and No. 2 Fuel Oil Dosage of 0.14 lb. / ton.

			Ash			**Coal**		
Stream	**Water**	**+ 48**	**48 X 100**	**- 100**	**+ 48**	**48 X 100**	**- 100**	**All Coal**
Feed	7.59	.0067	.0090	.093	.10	.14	.40	
Froth 1	0.74	.00051	.0010	.0071	.024	.043	.13	.19
Froth 2	1.01	.00084	.0017	.011	.039	.062	.16	.26
Froth 3	0.40	.00046	.00089	.0045	.016	.022	.054	.092
Froth 4	0.14	.00025	.00046	.0023	.0054	.0062	.017	.029
Cell 1	6.85	.0062	.0080	.086	.077	.10	.27	
Cell 2	5.84	.0053	.0063	.075	.038	.038	.12	
Cell 3	5.43	.0049	.0054	.071	.023	.016	.062	
Cell 4	5.29	.0046	.0049	.068	.017	.010	.045	

Table II-6. Kitt Mine Plant Test Data - Relative Volumetric Flowrates for Ash and Coal Species in the Froth and Cell Products at a MIBC Dosage of 0.06 lb./ton and No. 2 Fuel Oil Dosage of 0.21 lb. / ton.

		Ash			**Coal**			
Stream	**Water**	**+ 48**	**48 X 100**	**- 100**	**+ 48**	**48 X 100**	**- 100**	**All Coal**
Feed	8.32	.0072	.010	.083	.11	.15	.40	
Froth 1	0.77	.00058	.0011	.0066	.027	.048	.13	.21
Froth 2	0.95	.00073	.0014	.0085	.033	.059	.15	.24
Froth 3	0.40	.00049	.00061	.0042	.018	.018	.057	.093
Froth 4	0.15	.00017	.00036	.0018	.0048	.0075	.019	.031
Cell 1	7.55	.0066	.0090	.076	.078	.10	.27	
Cell 2	6.60	.0059	.0076	.067	.045	.043	.12	
Cell 3	6.19	.0054	.0070	.064	.027	.025	.063	
Cell 4	6.04	.0052	.0067	.062	.022	.017	.044	

Table II-7. Kitt Mine Plant Test Data - Relative Volumetric Flowrates for Ash and Coal Species in the Froth and Cell Products at a MIBC Dosage of 0.06 lb./ton and No. 2 Fuel Oil Dosage of 0.35 lb. / ton.

			Ash			**Coal**		
Stream	**Water**	**+ 48**	**48 X 100**	**- 100**	**+ 48**	**48 X 100**	**- 100**	**All Coal**
Feed	8.73	.0077	.012	.095	.11	.14	.38	
Froth 1	0.66	.00059	.0010	.0070	.029	.047	.12	.20
Froth 2	0.65	.00054	.0010	.0065	.024	.042	.11	.18
Froth 3	0.32	.00024	.0005	.0035	.0099	.017	.050	.077
Froth 4	0.18	.00010	.0003	.0020	.0038	.0088	.027	.039
Cell 1	8.07	.0071	.011	.088	.078	.097	.26	
Cell 2	7.43	.0065	.0095	.081	.054	.055	.15	
Cell 3	7.11	.0063	.0090	.078	.044	.037	.096	
Cell 4	6.93	.0062	.0064	.078	.040	.033	.064	

Table II-8. Kitt Mine Plant Test Data - Relative Volumetric Flowrates for Ash and Coal Species in the Froth and Cell Products at a MIBC Dosage of 0.06 lb./ton and No. 2 Fuel Oil Dosage of 0.42 lb. / ton.

			Ash			**Coal**		
Stream	**Water**	**+ 48**	**48 X 100**	**- 100**	**+ 48**	**48 X 100**	**- 100**	**All Coal**
Feed	9.96	.0075	.010	.095	.11	.15	.38	
Froth 1	1.12	.0013	.0024	.012	.057	.093	.21	.35
Froth 2	0.49	.00058	.0010	.0050	.023	.034	.081	.14
Froth 3	0.25	.00024	.00044	.0027	.0083	.012	.037	.057
Froth 4	0.09	.00010	.00018	.0023	.0016	.0027	.0091	.013
Cell 1	8.84	.0062	.0078	.083	.049	.058	.17	
Cell 2	8.35	.0057	.0068	.078	.026	.023	.092	
Cell 3	8.10	.0054	.0064	.075	.018	.011	.055	
Cell 4	8.01	.0053	.0062	.073	.016	.0083	.046	

Appendix III. Kitt Mine Lab Test Data.

Table III-1. Overall Test Results for Lab Tests on Lower Kittanning Seam Coal From the Kitt Mine.

Test Number	Reagent Dosages (lb./ton)		Concentrates	
	MIBC	No. 2 Fuel Oil	% Ash	% Recovery
1	0.108	0.084	7.3	25.8
2		0.168	8.0	39.9
3		0.252	7.3	46.6
4		0.336	7.4	57.1
5		0.420	7.3	59.2
6		0.504	7.1	64.2
7		0.588	7.3	70.0
8		0.672	7.4	69.5
9	0.216	0.084	7.9	77.3
10		0.168	8.9	84.8
11		0.252	8.5	85.3
12		0.336	8.5	85.7
13		0.420	8.2	87.2
14		0.504	8.6	89.1
15		0.588	8.7	89.4
16		0.672	9.0	88.9
17	0.324	0.084	9.4	84.3
18		0.168	8.9	85.7
19		0.252	9.0	88.9
20		0.336	9.6	90.1
21		0.420	9.8	91.7
22		0.504	9.5	89.4
23		0.588	9.9	92.0
24		0.672	9.9	92.2

Table III-2. Results for Batch Flotation Tests with Kitt Mine Flotation Feed. These Tests with 0.108 lb. / ton of MIBC and Varying Fuel Oil Dosages.

Test No.	Prod.	Fuel Oil (lb. / ton)	Wt. %	Individual Wt. %			% Ash			% Wt. Rec.			% Coal Rec.			% Ash Rec.		
				+ 48	48 x 100	- 100	+ 48	48 x 100	- 100	+ 48	48 x 100	- 100	+ 48	48 x 100	- 100	+ 48	48 x 100	- 100
1	**Conc.**	.084	19.86	8.55	8.81	82.64	3.82	3.24	8.09	6.5	8.2	31.3	21.3	22.1	26.6	7.5	4.9	5.1
	Tails		80.14	30.58	24.50	44.91	11.73	15.53	37.04									
2	**Conc.**	.168	31.65	11.87	14.63	73.50	3.44	3.60	9.59	14.6	22.6	43.3	33.8	35.0	41.8	11.3	8.9	9.6
	Tails		68.35	32.24	23.19	44.58	12.47	17.03	41.56									
3	**Conc.**	.252	36.25	11.45	16.20	72.35	3.25	3.49	8.86	15.7	28.0	49.8	38.6	40.3	49.3	12.9	9.6	9.7
	Tails		63.75	34.85	23.68	41.47	12.47	18.63	46.78									
4	**Conc.**	.336	46.30	17.01	20.31	62.68	3.53	4.05	9.60	30.0	44.9	55.0	49.3	51.8	61.0	17.3	13.2	14.2
	Tails		53.70	34.18	21.53	44.29	14.51	23.01	50.11									
5	**Conc.**	.420	48.81	19.96	20.90	59.14	3.43	4.36	9.61	36.6	48.7	55.0	52.0	54.6	63.3	17.8	14.6	15.5
	Tails		51.19	32.97	20.98	46.05	15.06	24.27	50.13									
6	**Conc.**	.504	53.68	22.55	21.50	55.95	3.92	4.70	9.32	46.3	54.8	56.9	57.4	59.9	68.6	20.6	17.2	17.2
	Tails		46.32	30.31	20.58	49.12	17.52	21.19	51.85									
7	**Conc.**	.588	58.62	22.58	21.63	55.86	4.05	4.99	9.55	50.8	61.2	61.6	62.4	65.6	74.7	24.4	19.6	19.4
	Tails		41.28	30.96	19.48	49.56	17.83	29.17	56.37									
8	**Conc.**	.672	58.12	22.40	22.13	55.47	4.06	4.75	9.79	48.9	60.6	61.8	62.1	65.1	74.3	23.0	18.4	19.4
	Tails		41.88	32.44	20.00	47.56	18.78	29.26	56.62									

Table III-3. Results for Batch Flotation Tests with Kitt Mine Flotation Feed. These Tests with 0.216 lb. / ton of MIBC and Varying Fuel Oil Dosages.

Test No.	Prod.	Fuel Oil (lb. / ton)	Wt. %	Individual Wt. %			% Ash			% Wt. Rec.			% Coal Rec.			% Ash Rec.		
				+ 48	48 x 100	- 100	+ 48	48 x 100	- 100	+ 48	48 x 100	- 100	+ 48	48 x 100	- 100	+ 48	48 x 100	- 100
9	**Conc.**	.084	64.02	20.35	22.58	57.07	4.18	5.06	10.31	49.8	68.8	69.2	67.5	72.1	82.8	29.2	20.7	21.5
	Tails		35.98	36.47	18.23	45.30	18.05	34.51	66.96									
10	**Conc.**	.168	72.54	22.59	23.37	54.04	4.28	5.72	11.72	62.1	79.1	75.8	76.3	82.6	89.3	38.4	24.1	30.1
	Tails		27.46	38.07	16.29	45.64	22.33	47.68	71.98									
11	**Conc.**	.252	72.50	22.80	23.50	53.70	4.40	5.99	11.30	62.8	81.2	73.9	76.5	83.3	90.0	34.0	23.9	28.7
	Tails		27.50	35.57	14.34	50.09	22.49	50.35	74.11									
12	**Conc.**	.336	73.46	23.88	23.81	52.32	4.59	6.16	11.43	65.3	81.8	74.3	77.8	84.2	90.0	34.1	24.9	30.3
	Tails		26.54	35.10	14.71	50.20	24.53	51.38	72.63									
13	**Conc.**	.420	74.73	24.01	23.81	52.18	4.60	5.85	10.95	67.9	83.7	74.5	79.1	86.4	91.3	35.0	23.6	30.2
	Tails		25.27	33.54	13.70	52.76	25.27	56.12	74.75									
14	**Conc.**	.504	77.24	24.56	23.44	52.00	4.57	6.12	11.56	72.5	86.0	76.0	81.8	89.3	92.5	35.6	25.2	34.1
	Tails		22.76	31.67	12.90	55.43	28.10	61.69	75.80									
15	**Conc.**	.588	77.74	25.18	23.41	51.41	4.43	6.51	11.87	73.9	87.1	76.0	82.6	89.9	92.6	34.3	26.4	35.5
	Tails		22.26	31.07	12.15	56.78	29.57	63.35	75.38									
16	**Conc.**	.672	78.07	25.78	24.16	50.06	4.88	6.56	12.20	75.0	86.4	76.1	82.8	89.6	91.8	37.1	27.5	37.5
	Tails		21.93	30.54	13.52	55.94	29.48	61.53	75.25									

Table III-4. Results for Batch Flotation Tests with Kitt Mine Flotation Feed. These Tests with 0.324 lb. / ton of MIBC and Varying Fuel Oil Dosages.

Test No.	Prod.	Fuel Oil (lb. / ton)	Wt. %	Wt. %			% Ash			% Wt. Rec.			% Coal Rec.			% Ash Rec.		
				+ 48	48 x 100	- 100	+ 48	48 x 100	- 100	+ 48	48 x 100	- 100	+ 48	48 x 100	- 100	+ 48	48 x 100	- 100
17	**Conc.**	.084	70.28	19.09	24.43	56.48	4.38	5.91	12.63	49.7	78.9	77.5	73.4	80.6	89.6	36.4	23.1	28.2
	Tails		29.72	45.75	15.42	38.82	18.12	46.44	75.91									
18	**Conc.**	.168	71.49	19.15	24.66	56.18	4.15	5.82	11.83	52.0	82.5	76.8	74.6	83.3	90.6	36.2	21.7	27.8
	Tails		28.51	44.34	13.11	42.55	18.32	52.66	76.95									
19	**Conc.**	.252	76.41	23.37	23.64	52.99	4.48	6.24	12.19	67.3	85.8	77.3	80.4	88.7	92.7	37.1	24.8	33.7
	Tails		23.59	36.82	12.64	50.54	24.57	61.44	77.72									
20	**Conc.**	.336	78.25	23.66	23.59	52.75	4.76	6.63	13.17	70.1	87.3	78.7	82.3	90.6	93.3	39.5	26.9	38.0
	Tails		21.75	36.34	12.35	51.31	26.21	64.98	77.40									
21	**Conc.**	.420	80.50	25.11	23.66	51.23	4.94	6.77	13.50	75.0	88.5	80.1	85.1	92.7	94.4	39.2	28.6	41.5
	Tails		19.50	34.63	12.74	52.63	31.66	69.61	78.66									
22	**Conc.**	.504	77.17	22.45	23.49	54.06	4.46	6.32	12.90	66.5	86.4	78.7	81.1	88.8	93.2	37.6	26.2	35.7
	Tails		22.83	38.17	12.50	49.33	25.03	60.28	78.64									
23	**Conc.**	.588	80.84	25.13	23.12	51.75	4.78	7.16	13.67	76.9	89.2	79.4	85.6	93.4	94.5	38.4	29.5	42.2
	Tails		19.16	31.81	11.86	56.33	32.31	72.35	79.03									
24	**Conc.**	.672	81.17	25.13	23.18	51.70	5.03	6.83	13.60	78.2	89.2	79.4	86.1	93.3	94.7	39.0	29.3	42.6
	Tails		18.83	30.14	12.05	57.81	33.86	71.71	79.14									

Table III-5. Results for Batch Flotation Tests with Kitt Mine Flotation Feed. These Tests with 0.167 lb. / ton of MIBC and Varying Fuel Oil Dosages.

Test No.	Prod.	Fuel Oil (lb. / ton)	Wt. %	Wt. %			% Ash			% Wt. Rec.			% Coal Rec.			% Ash Rec.		
				+ 48	48 x 100	- 100	+ 48	48 x 100	- 100	+ 48	48 x 100	- 100	+ 48	48 x 100	- 100	+ 48	48 x 100	- 100
25	**Conc.**	0.672	82.12	27.27	21.96	50.77	4.05	7.11	12.93	86.4	89.2	77.4	89.3	94.8	95.1	28.2	29.8	42.9
	Tails		17.88	19.77	12.15	68.08	47.41	76.78	79.18									
26	**Conc.**	0.084	26.12	7.73	12.58	76.69	5.20	4.00	6.94	7.9	15.8	38.7	27.8	28.9	36.1	12.5	7.9	5.5
	Tails		73.88	31.70	23.72	44.58	12.85	16.53	41.82									
27	**Conc.**	1.340	78.11	26.99	24.58	48.43	5.12	6.33	11.52	81.7	88.7	72.0	84.0	90.3	93.1	33.8	26.1	34.9
	Tails		21.89	21.53	11.15	67.32	35.72	64.04	76.76									

Table III-6. Size / Specific Gravity Analysis Results for Batch Flotation Test No. 26 Using 0.167 lb. / ton of MIBC and 0.084 lb. / ton of No. 2 Fuel Oil.

Size (Mesh)	Product	Weight %	Density Fraction	Weight % in Fraction	% Ash	Coal Dist. in Fraction	% of Available Coal Present in Fraction
+ 48	**Conc.**	2.02	**+ 1.3**	1.89	2.59	8.35	10.16
			1.3 X 1.9	0.13	18.61	0.48	3.00
			- 1.9	0.00	n.a.	0.00	0.00
	Tails	23.42	**+ 1.3**	17.38	6.34	73.78	
			1.3 X 1.9	4.27	19.48	15.59	
			- 1.9	1.77	77.58	1.80	
48 X 100	**Conc.**	3.29	**+ 1.3**	3.96	2.31	16.15	20.13
			1.3 X 1.9	0.33	16.69	1.54	8.90
			- 1.9	0.00	n.a.	0.00	0.00
	Tails	17.52	**+ 1.3**	11.82	2.93	64.07	
			1.3 X 1.9	3.55	20.35	15.79	
			- 1.9	2.15	79.56	2.45	
- 100	**Conc.**	20.81	**+ 1.3**	17.93	2.42	48.85	92.01
			1.3 X 1.9	2.75	15.50	6.49	18.19
			- 1.9	0.13	64.17	0.13	1.16
	Tails	32.94	**+ 1.3**	1.59	4.51	4.24	
			1.3 X 1.9	13.08	20.12	29.17	
			- 1.9	18.27	78.19	11.12	

Table III-7. Size / Specific Gravity Analysis Results for Batch Flotation Test No. 25 Using 0.167 lb. / ton of MIBC and 0.672 lb. / ton of No. 2 Fuel Oil.

Size (Mesh)	Product	Weight %	Density Fraction	Weight % in Fraction	% Ash	Coal Dist. in Fraction	% of Available Coal Present in Fraction
+ 48	**Conc.**	22.39	**+ 1.3**	18.75	2.83	78.72	96.38
			1.3 X 1.9	3.64	15.60	13.27	79.32
			- 1.9	0.00	n.a.	0.00	0.00
	Tails	3.53	**+ 1.3**	0.71	3.54	2.96	
			1.3 X 1.9	1.11	27.85	3.46	
			- 1.9	1.71	78.48	1.59	
48 X 100	**Conc.**	18.03	**+ 1.3**	13.76	2.58	77.72	100.00
			1.3 X 1.9	3.88	18.37	18.36	95.39
			- 1.9	0.39	62.19	0.86	28.27
	Tails	2.17	**+ 1.3**	0.00	n.a.	0.00	
			1.3 X 1.9	0.27	43.3	0.89	
			- 1.9	1.90	80.3	2.17	
- 100	**Conc.**	41.70	**+ 1.3**	14.63	2.41	37.30	100.00
			1.3 X 1.9	24.89	17.80	54.22	100.00
			- 1.9	2.18	64.17	2.07	24.41
	Tails	12.18	**+ 1.3**	0.00	n.a.	0.00	
			1.3 X 1.9	0.00	n.a.	0.00	
			- 1.9	11.94	79.74	6.41	

Table III-8. Size / Specific Gravity Analysis Results for Batch Flotation Test No. 26 Using 0.167 lb. / ton of MIBC and 1.340 lb. / ton of No. 2 Fuel Oil.

Size (Mesh)	Product	Weight %	Density Fraction	Weight % in Fraction	% Ash	Coal Dist. in Fraction	% of Available Coal Present in Fraction
+ 48	**Conc.**	21.08	**+ 1.3**	17.89	2.08	74.94	90.74
			1.3 X 1.9	3.19	15.70	11.50	71.96
			- 1.9	0.00	n.a.	0.00	0.00
	Tails	4.71	**+ 1.3**	1.85	3.39	7.65	
			1.3 X 1.9	1.39	24.60	4.48	
			- 1.9	1.47	77.29	1.43	
48 X 100	**Conc.**	19.20	**+ 1.3**	15.36	2.81	79.49	
			1.3 X 1.9	3.54	18.46	15.37	
			- 1.9	0.30	59.26	0.65	
	Tails	2.44	**+ 1.3**	0.00	n.a.	0.00	100.00
			1.3 X 1.9	0.63	21.15	2.65	85.32
			- 1.9	1.81	80.96	1.84	26.18
- 100	**Conc.**	37.83	**+ 1.3**	34.43	2.51	85.93	100.00
			1.3 X 1.9	1.81	19.91	3.71	73.64
			- 1.9	1.59	62.47	1.53	16.91
	Tails	14.74	**+ 1.3**	0.00	n.a.	0.00	
			1.3 X 1.9	0.68	23.71	1.33	
			- 1.9	14.06	79.15	7.50	

Appendix IV. Panther Valley Laboratory Test Data.

Table IV-1. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 1.4 lb. / ton of PPG200 Frother and 0.7 lb. / ton of No. 2 Fuel Oil.

Product	Cum. Time (Sec.)	Wt. %	Cum. Wt. %	% Ash	Cum. % Ash	Cum. % Ash Rec.	% Coal	Cum. % Coal	Cum. % Coal Rec.
Froth 1	15	28.14	28.14	10.76	10.76	10.01	88.16	88.16	37.19
Froth 2	45	7.42	35.56	11.26	10.86	12.77	87.61	88.05	46.92
Froth 3	75	8.41	43.96	11.56	11.00	15.98	87.28	87.90	57.92
Froth 4	240	30.24	74.20	13.77	12.13	29.74	84.85	86.66	96.38
Tails		25.80	100.00	82.39	30.25	100.00	9.37	66.72	100.00

Table IV-2. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 0.7 lb. / ton of PPG200 Frother and 0.7 lb. / ton of No. 2 Fuel Oil.

Product	Cum. Time (Sec.)	Wt. %	Cum. Wt. %	% Ash	Cum. % Ash	Cum. % Ash Rec.	% Coal	Cum. % Coal	Cum. % Coal Rec.
Froth 1	15	32.04	32.04	10.97	10.97	11.31	87.93	87.93	42.81
Froth 2	45	15.44	47.47	11.25	11.06	16.89	87.63	87.83	63.36
Froth 3	90	9.68	57.16	12.90	11.37	20.91	85.81	87.49	75.98
Froth 4	210	14.98	72.13	16.76	12.49	28.99	81.56	86.26	94.55
Tails		27.87	100.00	79.20	31.08	100.00	12.88	65.81	100.00

Table IV-3. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 0.7 lb. / ton of PPG200 Frother and 0.35 lb. / ton of No. 2 Fuel Oil.

Product	Cum. Time (Sec.)	Wt. %	Cum. Wt. %	% Ash	Cum. % Ash	Cum. % Ash Rec.	% Coal	Cum. % Coal	Cum. % Coal Rec.
Froth 1	15	21.02	21.02	10.02	10.02	6.97	88.98	88.98	28.02
Froth 2	45	24.14	45.16	11.60	10.86	16.24	87.24	88.05	59.57
Froth 3	90	14.21	59.38	12.91	11.35	22.31	85.80	87.51	77.84
Froth 4	210	15.48	74.85	17.36	12.60	31.20	80.90	86.14	96.59
Tails		25.15	100.00	82.69	30.22	100.00	9.04	66.75	100.00

Table IV-4. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 1.4 lb. / ton of PPG200 Frother and 0.35 lb. / ton of No. 2 Fuel Oil.

Product	Cum. Time (Sec.)	Wt. %	Cum. Wt. %	% Ash	Cum. % Ash	Cum. % Ash Rec.	% Coal	Cum. % Coal	Cum. % Coal Rec.
Froth 1	15	26.47	26.47	10.65	10.65	9.30	88.29	88.28	35.07
Froth 2	45	17.54	44.02	12.32	11.32	16.43	86.45	87.55	57.82
Froth 3	90	14.32	58.33	12.69	11.65	22.42	86.04	87.18	76.30
Froth 4	270	17.52	75.85	17.83	13.08	32.72	80.39	85.61	97.43
Tails		24.15	100.00	84.47	30.32	100.00	7.08	66.65	100.00

Table IV-5. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 1.4 lb. / ton of DF1012 Frother and 0.7 lb. / ton of No. 2 Fuel Oil.

Product	Cum. Time (Sec.)	Wt. %	Cum. Wt. %	% Ash	Cum. % Ash	Cum. % Ash Rec.	% Coal	Cum. % Coal	Cum. % Coal Rec.
Froth 1	15	23.68	23.68	9.82	9.82	7.71	89.20	89.20	31.60
Froth 2	45	20.18	43.86	12.00	10.82	15.75	86.80	88.09	57.81
Froth 3	90	14.06	57.92	12.30	11.18	21.48	86.47	87.70	76.00
Froth 4	275	18.44	76.36	17.27	12.65	32.04	81.00	86.08	98.34
Tails		23.64	100.00	86.65	30.15	100.00	4.69	66.84	100.00

Table IV-6. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 0.7 lb. / ton of DF1012 Frother and 0.7 lb. / ton of No. 2 Fuel Oil.

Product	Cum. Time (Sec.)	Wt. %	Cum. Wt. %	% Ash	Cum. % Ash	Cum. % Ash Rec.	% Coal	Cum. % Coal	Cum. % Coal Rec.
Froth 1	15	22.45	22.45	9.90	9.90	7.33	89.11	89.11	30.02
Froth 2	45	22.07	44.52	11.85	10.87	15.95	86.97	88.05	58.82
Froth 3	90	11.22	55.74	12.31	11.16	20.50	86.46	87.73	73.37
Froth 4	240	18.46	74.19	15.81	12.31	30.13	82.61	86.45	96.25
Tails		25.81	100.00	82.11	30.33	100.00	9.68	66.64	100.00

Table IV-7. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 0.7 lb. / ton of DF1012 Frother and 0.35 lb. / ton of No. 2 Fuel Oil.

Product	Cum. Time (Sec.)	Wt. %	Cum. Wt. %	% Ash	Cum. % Ash	Cum. % Ash Rec.	% Coal	Cum. % Coal	Cum. % Coal Rec.
Froth 1	15	21.67	21.67	10.13	10.13	7.21	88.86	88.86	28.94
Froth 2	45	18.20	39.86	11.80	10.89	14.27	87.02	88.02	52.74
Froth 3	90	16.86	56.72	12.12	11.26	20.98	86.67	87.62	74.70
Froth 4	210	17.84	74.56	16.60	12.54	30.71	81.74	86.21	96.61
Tails		25.44	100.00	82.86	30.43	100.00	8.85	66.53	100.00

Table IV-8. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 1.4 lb. / ton of DF1012 Frother and 0.35 lb. / ton of No. 2 Fuel Oil.

Product	Cum. Time (Sec.)	Wt. %	Cum. Wt. %	% Ash	Cum. % Ash	Cum. % Ash Rec.	% Coal	Cum. % Coal	Cum. % Coal Rec.
Froth 1	15	25.56	25.56	9.98	9.98	8.54	89.02	89.02	33.89
Froth 2	45	18.60	44.16	12.37	10.99	16.24	86.39	87.91	57.83
Froth 3	90	16.30	60.46	12.61	11.42	23.12	86.13	87.43	78.74
Froth 4	210	16.47	76.94	18.68	12.98	33.42	79.45	85.72	98.24
Tails		23.06	100.00	86.25	29.88	100.00	5.13	67.13	100.00

Table IV-9. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 1.4 lb. / ton of DF1263 Frother and 0.7 lb. / ton of No. 2 Fuel Oil.

Product	**Cum. Time (Sec.)**	**Wt. %**	**Cum. Wt. %**	**% Ash**	**Cum. % Ash**	**Cum. % Ash Rec.**	**% Coal**	**Cum. % Coal**	**Cum. % Coal Rec.**
Froth 1	15	22.88	22.88	10.00	10.00	7.55	89.00	89.00	30.55
Froth 2	45	19.98	42.87	12.39	11.11	15.72	86.37	87.77	56.44
Froth 3	90	15.63	58.50	12.34	11.44	22.09	86.43	87.41	76.71
Froth 4	180	18.42	76.92	19.90	13.47	34.18	78.11	85.19	98.29
Tails		23.08	100.00	86.43	30.31	100.00	4.93	66.66	100.00

Table IV-10. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 0.7 lb. / ton of DF1263 Frother and 0.7 lb. / ton of No. 2 Fuel Oil.

Product	**Cum. Time (Sec.)**	**Wt. %**	**Cum. Wt. %**	**% Ash**	**Cum. % Ash**	**Cum. % Ash Rec.**	**% Coal**	**Cum. % Coal**	**Cum. % Coal Rec.**
Froth 1	15	11.78	11.78	8.79	8.79	3.44	90.33	90.33	15.91
Froth 2	45	25.64	37.42	11.05	10.34	12.86	87.85	88.63	49.57
Froth 3	90	26.32	63.74	12.22	11.12	23.56	86.56	87.77	83.61
Froth 4	180	11.94	75.68	20.15	12.54	31.55	77.84	86.21	97.49
Tails		24.32	100.00	84.64	30.08	100.00	6.90	66.92	100.00

Table IV-11. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 0.7 lb. / ton of DF1263 Frother and 0.35 lb. / ton of No. 2 Fuel Oil.

Product	Cum. Time (sec.)	Wt. %	Cum. Wt. %	% Ash	Cum. % Ash	Cum. % Ash Rec.	% Coal	Cum. % Coal	Cum. % Coal Rec.
Froth 1	15	20.64	20.64	9.52	9.52	6.50	89.53	89.53	27.68
Froth 2	45	36.35	56.99	11.73	10.93	20.60	87.10	87.98	75.12
Froth 3	90	15.32	72.31	15.77	11.96	28.59	82.65	86.85	94.10
Froth 4	180	4.13	76.44	34.28	13.16	33.27	62.29	85.52	97.95
Tails		23.56	100.00	85.63	30.23	100.00	5.81	66.74	100.00

Table IV-12. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 1.4 lb. / ton of DF1263 Frother and 0..35 lb. / ton of No. 2 Fuel Oil.

Product	Cum. Time (Sec.)	Wt. %	Cum. Wt. %	% Ash	Cum. % Ash	Cum. % Ash Rec.	% Coal	Cum. % Coal	Cum. % Coal Rec.
Froth 1	15	25.04	25.04	10.31	10.31	8.74	88.66	88.66	32.88
Froth 2	45	15.42	40.46	12.39	11.10	15.20	86.37	87.79	52.62
Froth 3	90	21.15	61.61	13.06	11.77	24.55	85.63	87.05	79.45
Froth 4	150	17.14	78.76	20.44	13.66	36.42	77.52	84.97	99.14
Tails		21.24	100.00	88.43	29.55	100.00	2.73	67.50	100.00

Table IV-13. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 2.0 lb. / ton of DF400 Frother and 0.7 lb. / ton of No. 2 Fuel Oil.

Product	**Cum. Time (Sec.)**	**Wt. %**	**Cum. Wt. %**	**% Ash**	**Cum. % Ash**	**Cum. % Ash Rec.**	**% Coal**	**Cum. % Coal**	**Cum. % Coal Rec.**
Froth 1	15	28.02	28.02	10.32	10.32	9.65	88.65	88.65	37.04
Froth 2	45	23.02	51.04	13.06	11.56	19.69	85.63	87.29	66.44
Froth 3	90	16.11	67.15	13.66	12.06	27.04	84.97	86.73	86.85
Froth 4	150	10.11	77.26	21.24	13.26	34.21	76.64	85.41	98.40
Tails		22.74	100.00	86.65	29.95	100.00	4.69	67.05	100.00

Table IV-14. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 1.0 lb. / ton of DF400 Frother and 0.7 lb. / ton of No. 2 Fuel Oil.

Product	**Cum. Time (Sec.)**	**Wt. %**	**Cum. Wt. %**	**% Ash**	**Cum. % Ash**	**Cum. % Ash Rec.**	**% Coal**	**Cum. % Coal**	**Cum. % Coal Rec.**
Froth 1	15	28.12	28.12	10.13	10.13	9.39	88.86	88.86	37.48
Froth 2	45	19.66	47.77	12.59	11.14	17.56	86.15	87.74	62.89
Froth 3	90	18.00	65.77	13.21	11.71	25.40	85.47	87.12	85.97
Froth 4	170	10.66	76.43	24.13	13.44	33.88	73.46	85.22	97.72
Tails		23.57	100.00	85.04	30.32	100.00	6.46	66.65	100.00

Table IV-15. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 1.0 lb. / ton of DF400 Frother and 0.35 lb. / ton of No. 2 Fuel Oil.

Product	Cum. Time (Sec.)	Wt. %	Cum. Wt. %	% Ash	Cum. % Ash	Cum. % Ash Rec.	% Coal	Cum. % Coal	Cum. % Coal Rec.
Froth 1	15	23.98	23.98	10.15	10.15	8.05	88.84	88.84	31.91
Froth 2	45	29.28	53.25	12.51	11.45	20.17	86.24	87.41	69.73
Froth 3	90	18.52	71.78	14.78	12.31	29.22	83.74	86.46	92.97
Froth 4	130	4.76	76.54	29.37	13.37	33.85	67.69	85.29	97.80
Tails		23.46	100.00	85.22	30.23	100.00	6.26	66.75	100.00

Table IV-16. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 2.0 lb. / ton of DF400 Frother and 0.35 lb. / ton of No. 2 Fuel Oil.

Product	Cum. Time (Sec.)	Wt. %	Cum. Wt. %	% Ash	Cum. % Ash	Cum. % Ash Rec.	% Coal	Cum. % Coal	Cum. % Coal Rec.
Froth 1	15	28.21	28.21	10.31	10.31	9.77	88.66	88.66	37.20
Froth 2	45	22.77	50.99	13.22	11.61	19.87	85.46	87.23	66.15
Froth 3	90	15.12	66.10	13.83	12.12	26.89	84.79	86.67	85.21
Froth 4	180	11.72	77.83	21.36	13.51	35.30	76.50	85.14	98.55
Tails		22.17	100.00	86.91	29.79	100.00	4.40	67.24	100.00

Table IV-17. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 1.0 lb. / ton of MIBC Frother and 0.7 lb. / ton of No. 2 Fuel Oil.

Product	Cum. Time (Sec.)	Wt. %	Cum. Wt. %	% Ash	Cum. % Ash	Cum. % Ash Rec.	% Coal	Cum. % Coal	Cum. % Coal Rec.
Froth 1	15	27.31	27.31	10.80	10.80	9.94	88.12	88.12	35.74
Froth 2	45	25.05	52.37	12.12	11.43	20.16	86.67	87.43	67.99
Froth 3	90	19.83	72.20	13.41	11.98	29.12	85.25	86.83	93.09
Froth 4	150	4.56	76.76	18.33	12.35	31.93	79.84	86.41	98.50
Tails		23.24	100.00	86.95	29.69	100.00	4.36	67.34	100.00

Table IV-18. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 0.5 lb. / ton of MIBC Frother and 0.7 lb. / ton of No. 2 Fuel Oil.

Product	Cum. Time (Sec.)	Wt. %	Cum. Wt. %	% Ash	Cum. % Ash	Cum. % Ash Rec.	% Coal	Cum. % Coal	Cum. % Coal Rec.
Froth 1	15	26.35	26.35	9.59	9.59	8.83	89.45	89.45	34.41
Froth 2	45	21.42	47.78	10.98	10.21	17.05	87.62	88.77	61.90
Froth 3	90	8.97	56.74	10.84	10.31	20.44	88.08	88.66	73.42
Froth 4	200	15.82	72.56	11.66	10.61	26.89	87.17	88.33	93.55
Tails		27.44	100.00	76.27	28.62	100.00	16.10	68.52	100.00

Table IV-19. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 0.5 lb. / ton of MIBC Frother and 0.35 lb. / ton of No. 2 Fuel Oil.

Product	Cum. Time (Sec.)	Wt. %	Cum. Wt. %	% Ash	Cum. % Ash	Cum. % Ash Rec.	% Coal	Cum. % Coal	Cum. % Coal Rec.
Froth 1	15	20.85	20.85	9.73	9.73	6.63	89.30	89.30	28.08
Froth 2	45	19.86	40.71	11.67	10.68	14.19	87.16	88.26	54.18
Froth 3	90	14.16	54.87	11.36	10.85	19.45	87.50	88.06	72.86
Froth 4	150	17.61	72.48	12.61	11.28	26.70	86.13	87.59	95.73
Tails		27.52	100.00	81.56	30.62	100.00	10.28	66.32	100.00

Table IV-20. Results for Batch Flotation Test with Panther Valley Mine Flotation Feed Using 1.0 lb. / ton of MIBC Frother and 0.35 lb. / ton of No. 2 Fuel Oil.

Product	Cum. Time (Sec.)	Wt. %	Cum. Wt. %	% Ash	Cum. % Ash	Cum. % Ash Rec.	% Coal	Cum. % Coal	Cum. % Coal Rec.
Froth 1	15	24.97	24.97	10.46	10.46	8.84	88.49	88.49	32.75
Froth 2	45	18.32	43.29	11.79	11.02	16.14	87.03	87.87	56.37
Froth 3	90	13.01	56.30	12.51	11.37	21.65	86.24	87.50	73.00
Froth 4	200	18.92	75.22	13.97	12.02	30.59	84.63	86.78	96.73
Tails		24.78	100.00	82.80	29.56	100.00	8.92	67.49	100.00

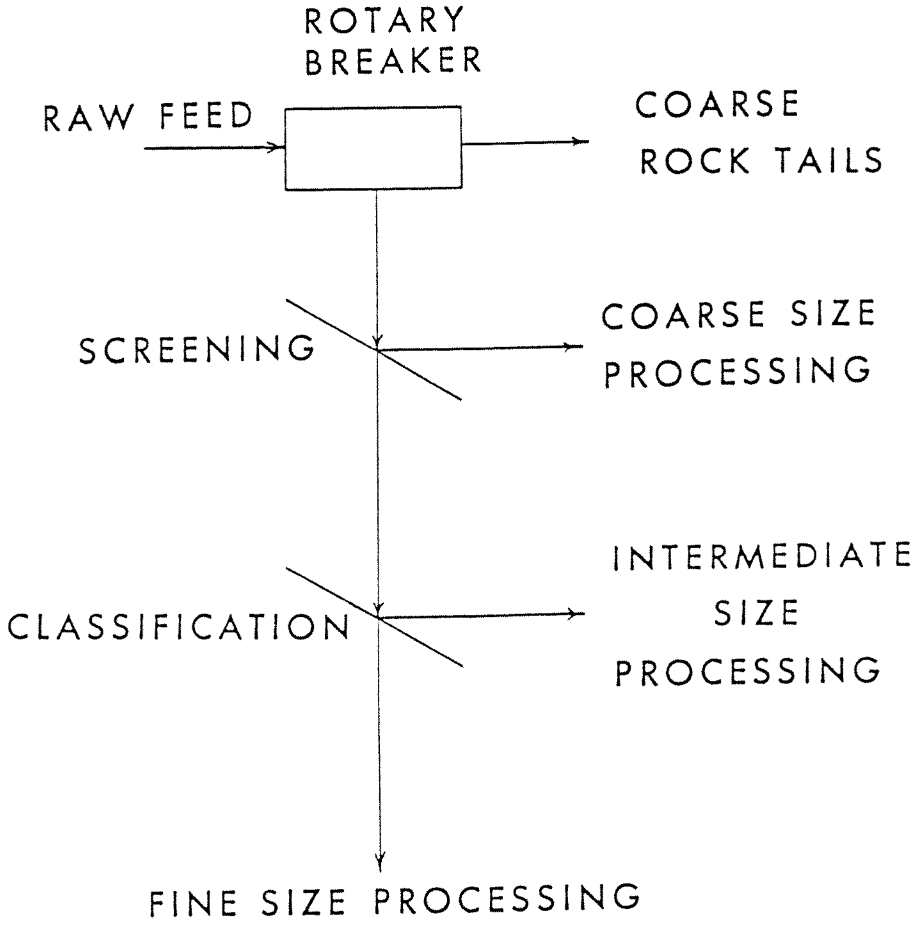


Figure 1.1. General Coal Preparation Plant Flowsheet.

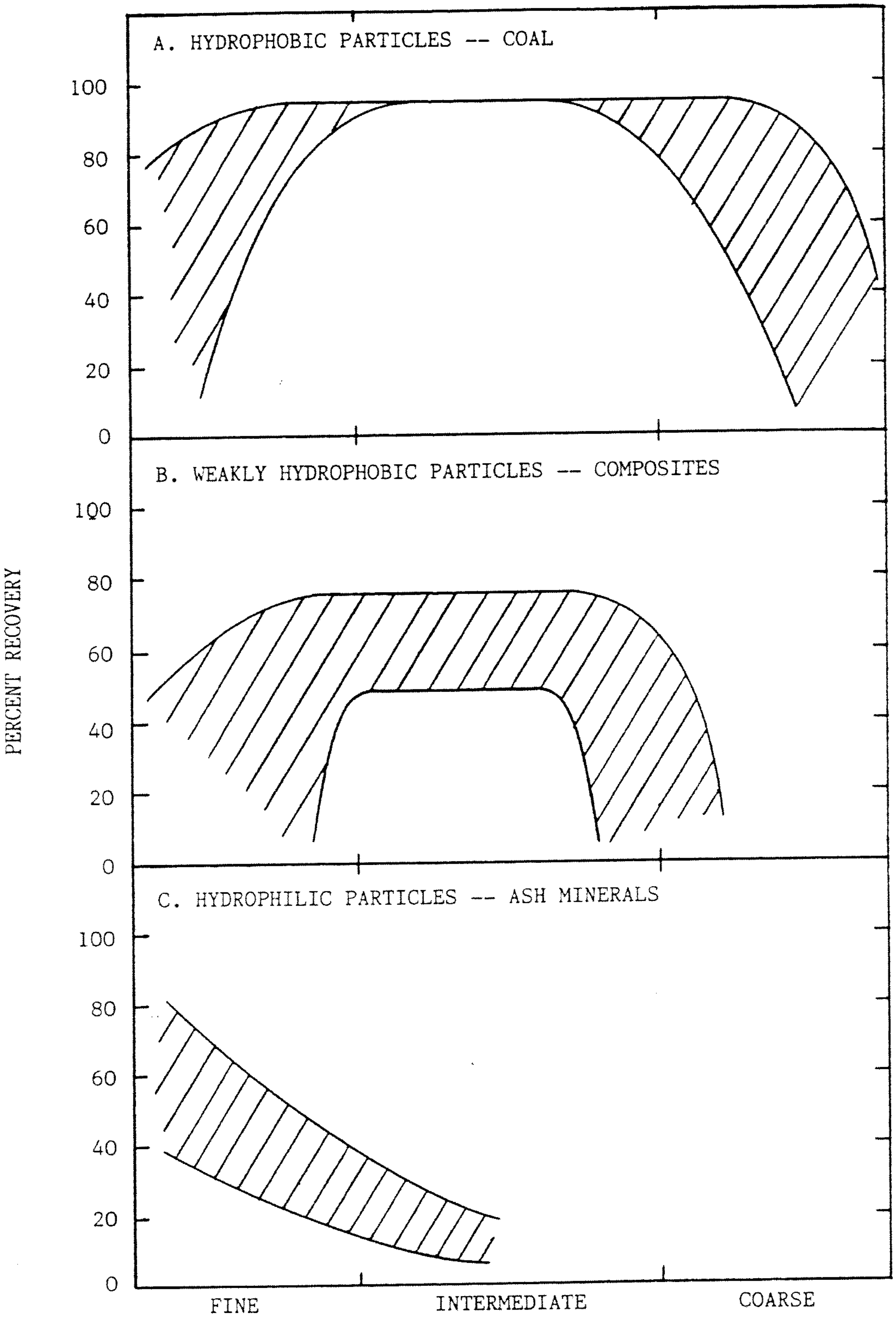


Figure 1.2. Recovery – Size Response for Particles in Flotation.

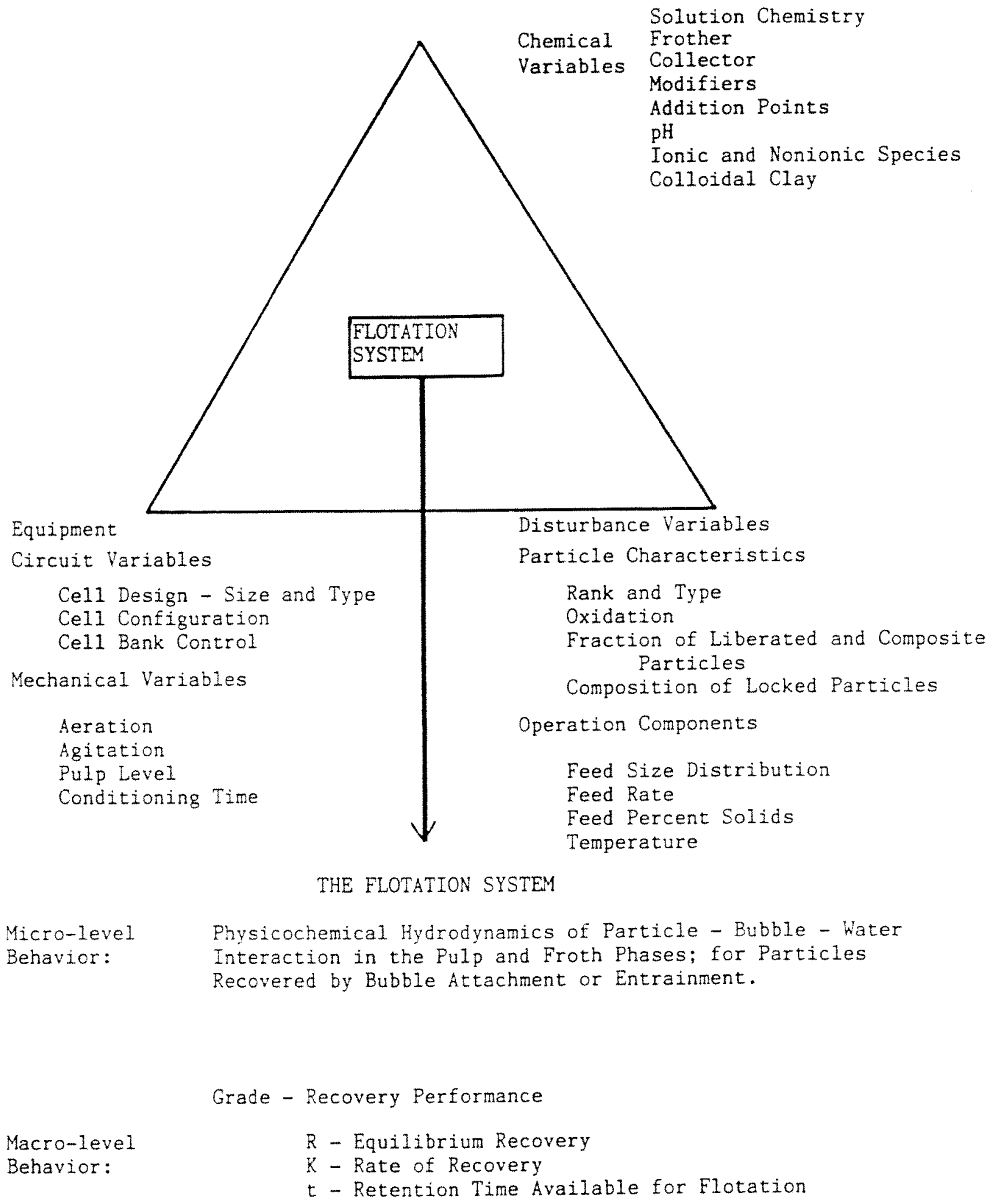


Figure 1.3. An Outline of the General Relationship Between Fundamental Physicochemical Phenomena, Independent Process Variables, and Grade - Recovery Performance in Flotation (Seitz and Kawatra, 1985a; Klimpel, 1985).

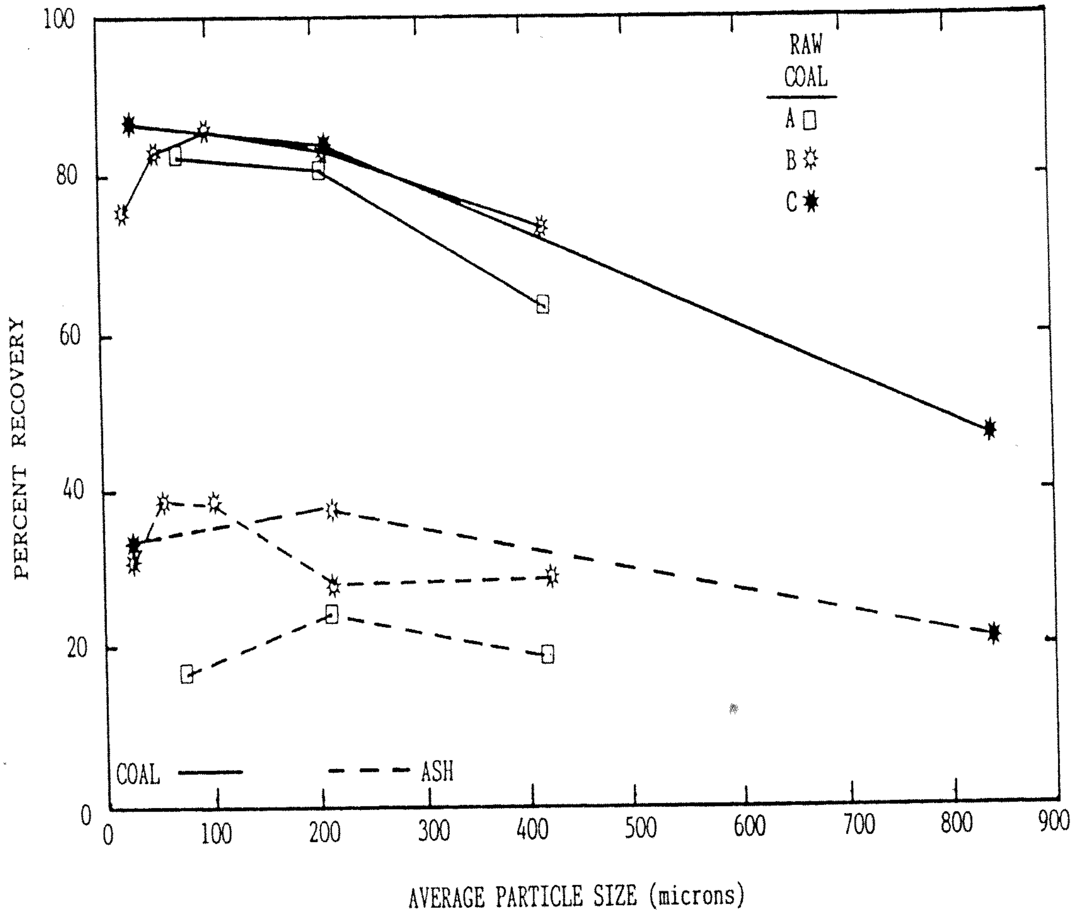


Figure 2.1. The Recovery – Size Behavior of Coal and Ash in Three Industrial Coal Flotation Circuits: A. Lower Kittanning Seam Coal (Kitt Mine – see Appendix II), B. Blend of Lower Kittanning and Upper Freeport Seam Coals (Canturbury Mine), and C. Mammoth Seam Coal (Panther Valley Mine (see Appendix I). Data from this dissertation and Kawatra, Seitz, and Suardini (1984).

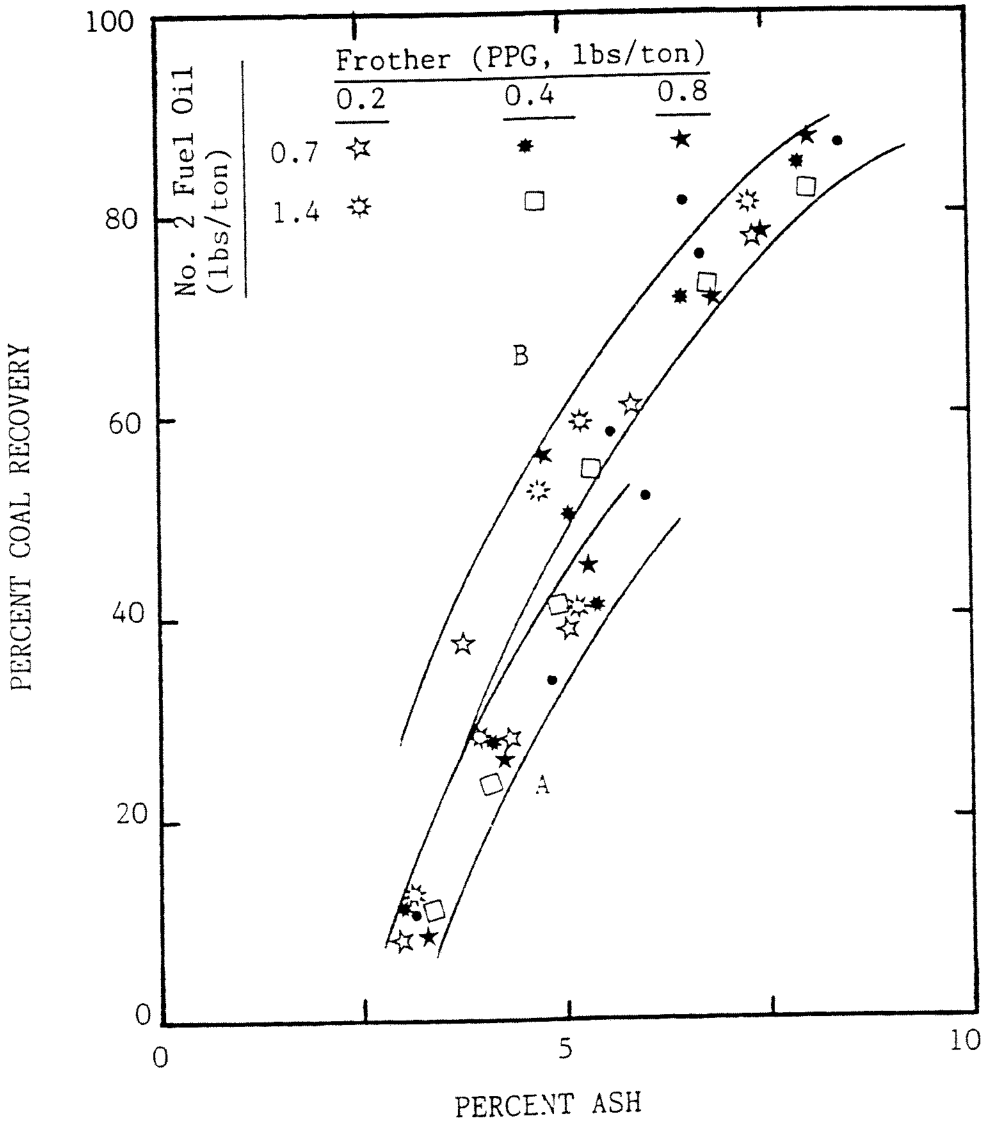


Figure 2.2. Grade – Recovery Performance of the Panther Valley Preparation Plant Flotation Circuit for 14 X 28 Mesh (A) and 48 X 65 Mesh (B) Size Fractions at Various Frother and No. 2 Fuel Oil Additional Levels.

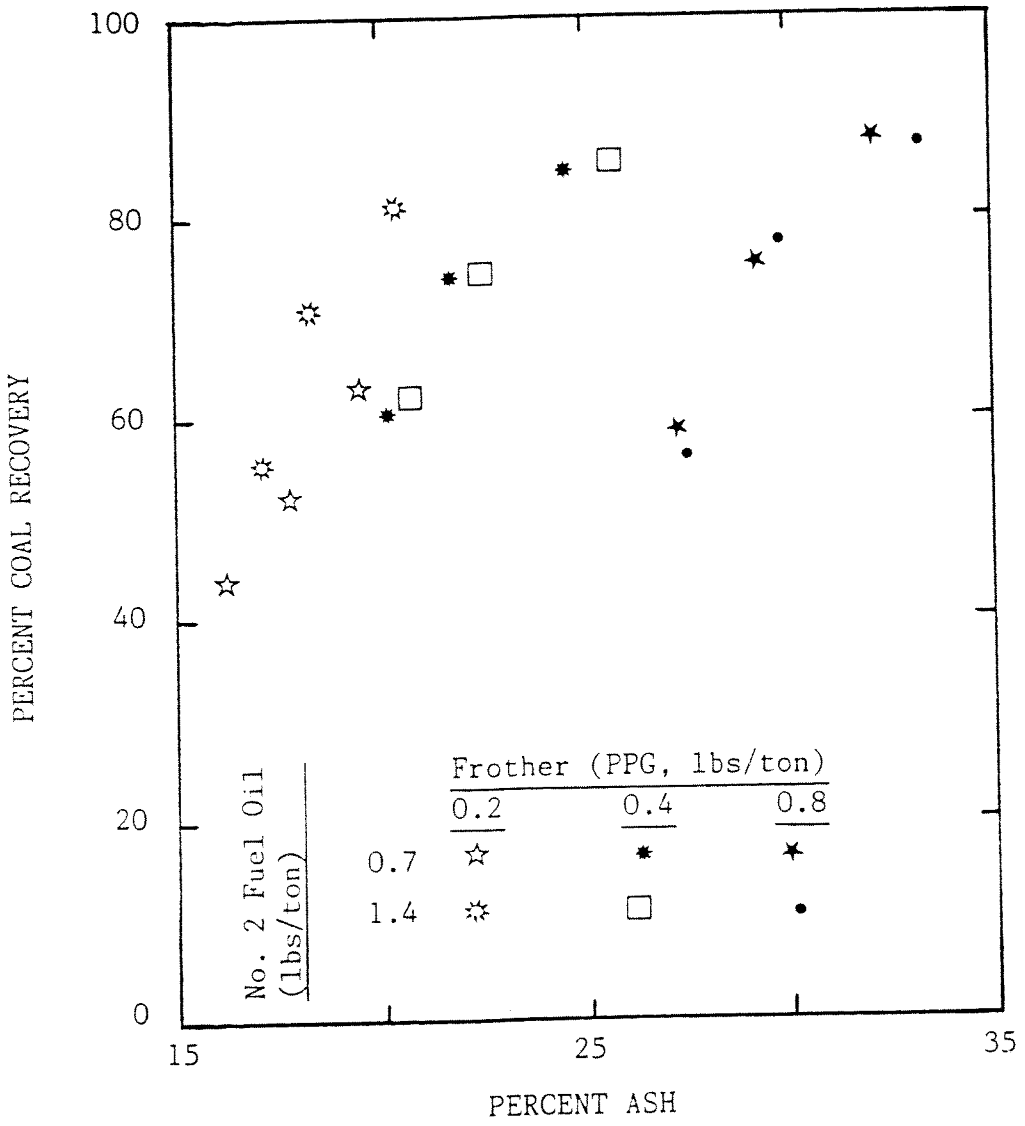


Figure 2.3. Grade – Recovery Performance of the Panther Valley Preparation Plant Flotation Circuit for – 200 Mesh Size Fraction at Various Frother and No. 2 Fuel Oil Additional Levels.

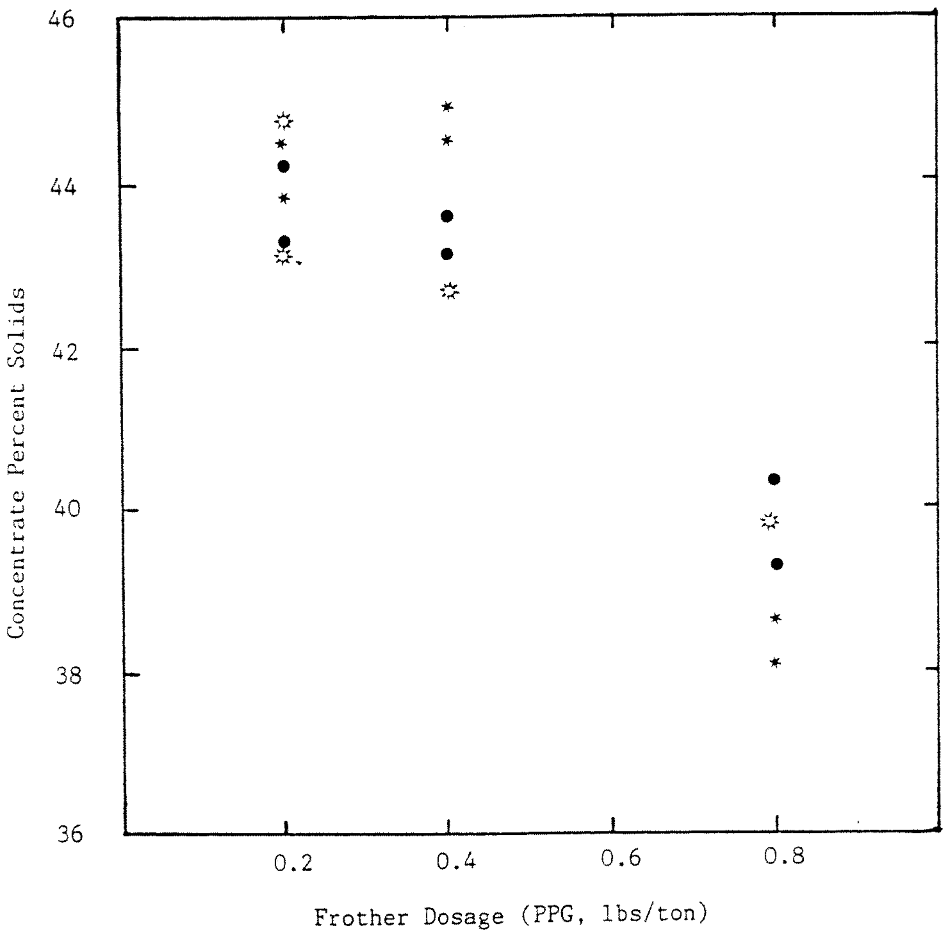


Figure 2.4. **The Effect of Frother and Fuel Oil Dosage on Concentrate Percent Solids for the Panther Valley Preparation Plant Flotation Circuit.**

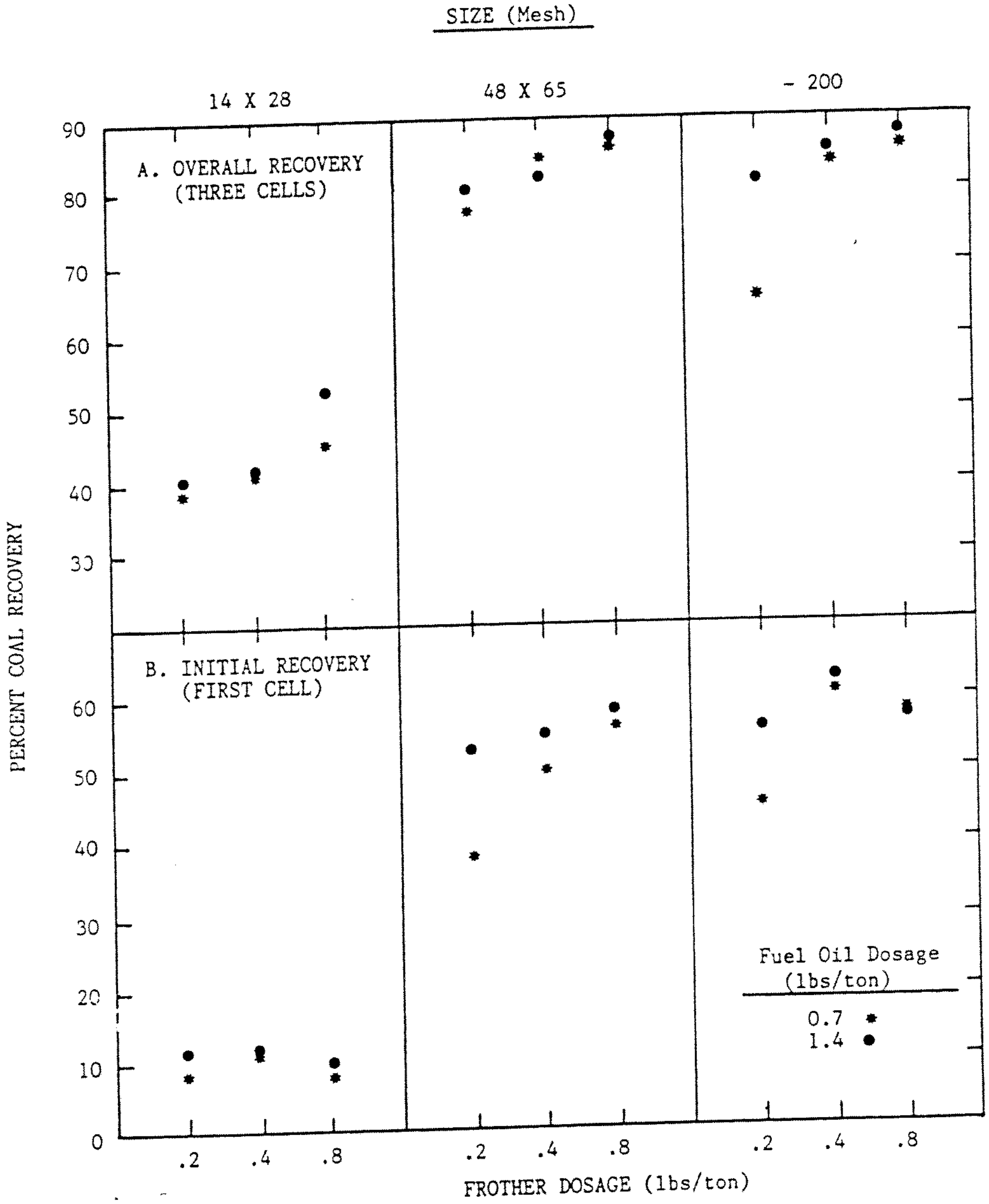


Figure 2.5. Coal Recovery – Reagent Dosage Response for Mammoth Seam Coal in the Panther Valley Preparation Plant Tests. Frother = PPG-200 and Collector = No. 2 Fuel Oil. A. Overall Recovery from Three Cells in the Bank and B. Initial Recovery from First Cell in the Bank.

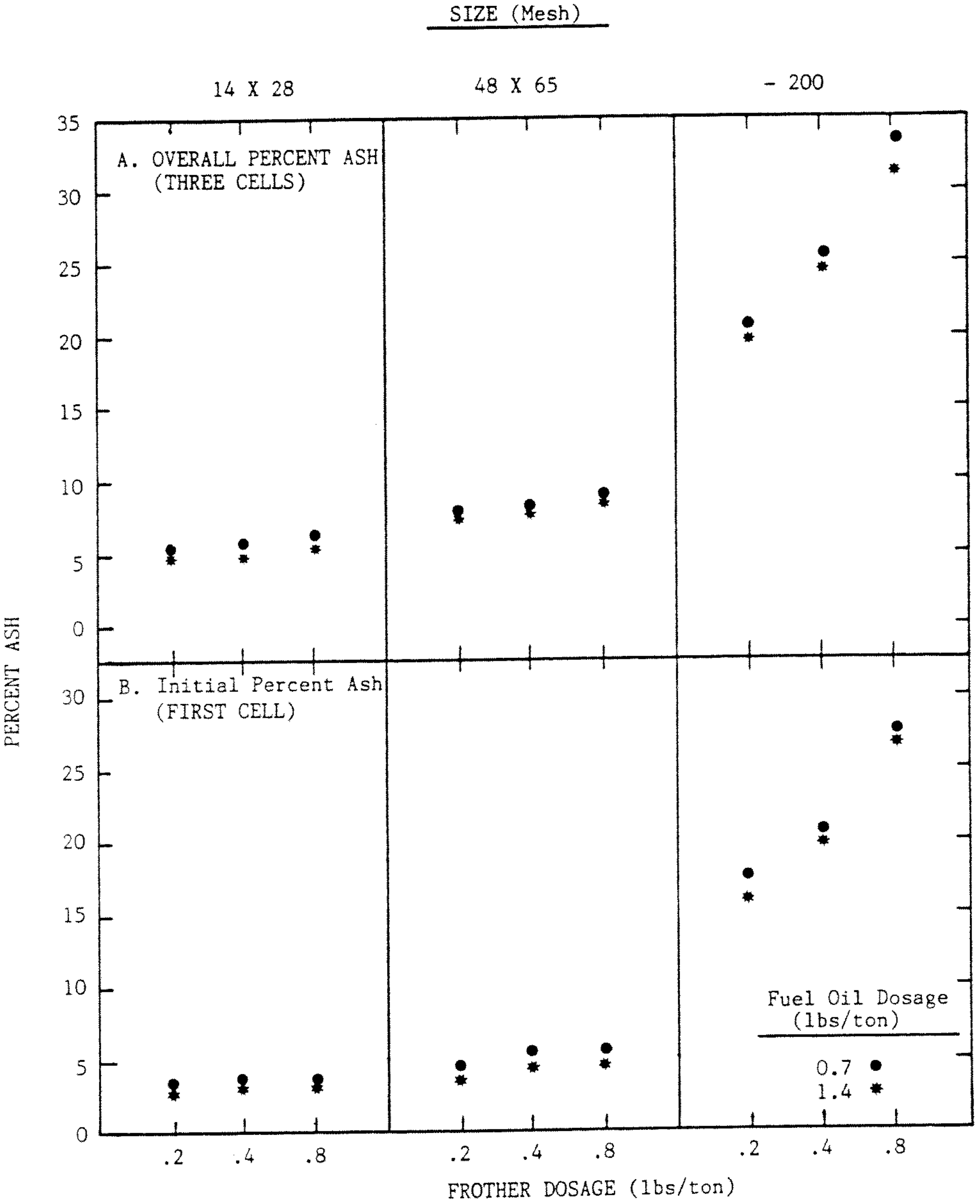


Figure 2.6. Percent Ash - Reagent Dosage Response for Mammoth Seam Coal in the Panther Valley Preparation Plant Tests. Frother = PPG-200 and Collector = No. 2 Fuel Oil. A. Overall Percent Ash from Three Cells in the Bank and B. Initial Percent Ash from First Cell in the Bank.

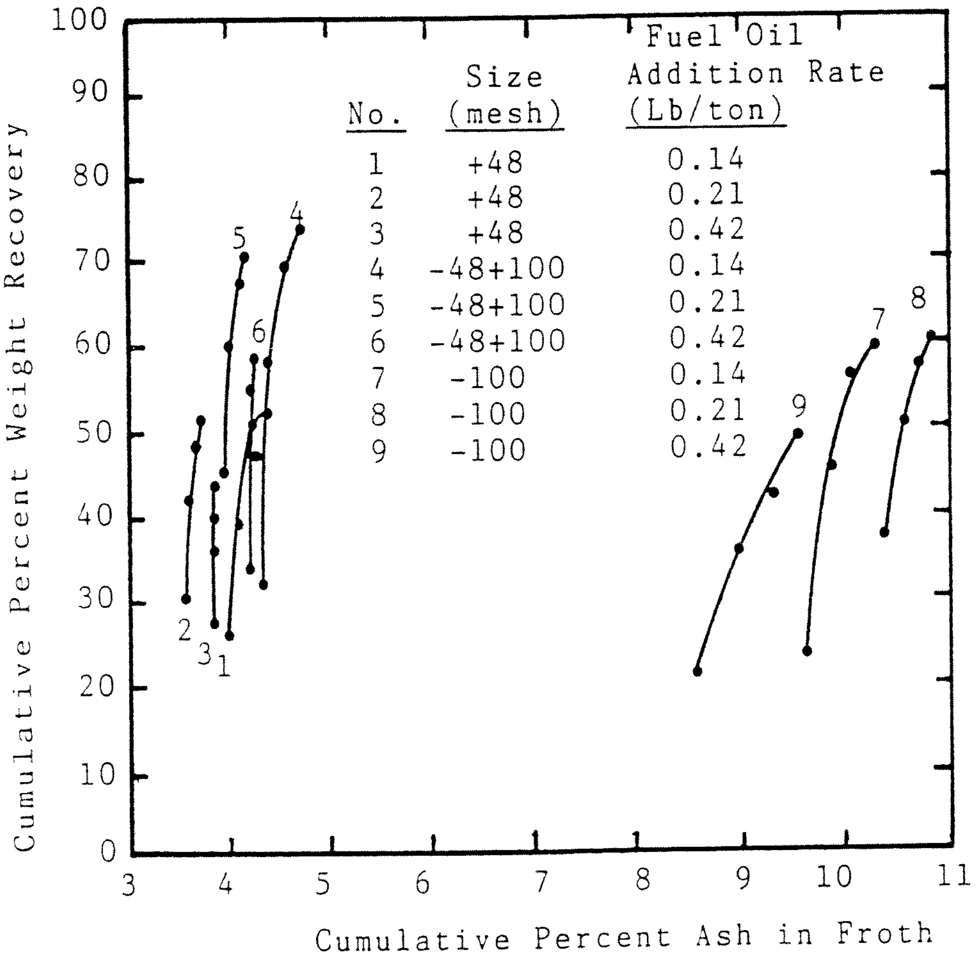


Figure 2.7a. Grade – Recovery Performance of the Kitt Mine Preparation Plant Flotation Circuit for Individual Size Fractions at a MIBC Addition Rate of 0.04 lb./ton and Fuel Oil Addition Rates of 100, 150, and 300 ml/min. (0.14, 0.21, and 0.42 lb./ton, respectively).

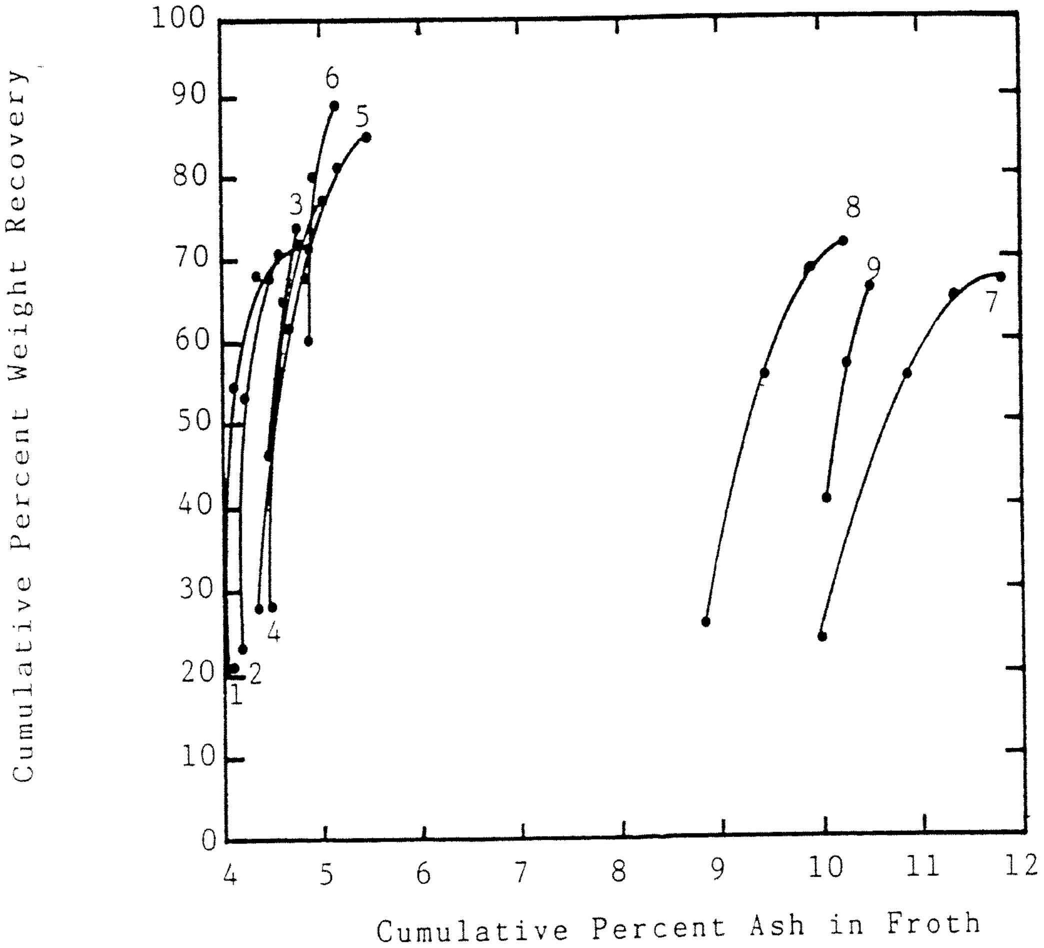


Figure 2.7b. **Grade – Recovery Performance of the Kitt Mine Preparation Plant Flotation Circuit for Individual Size Fractions at a MIBC Addition Rate of 0.06 lb./ton and Fuel Oil Addition Rates of 100, 150, and 300 ml/min. (0.14, 0.21, and 0.42 lb./ton, respectively).**

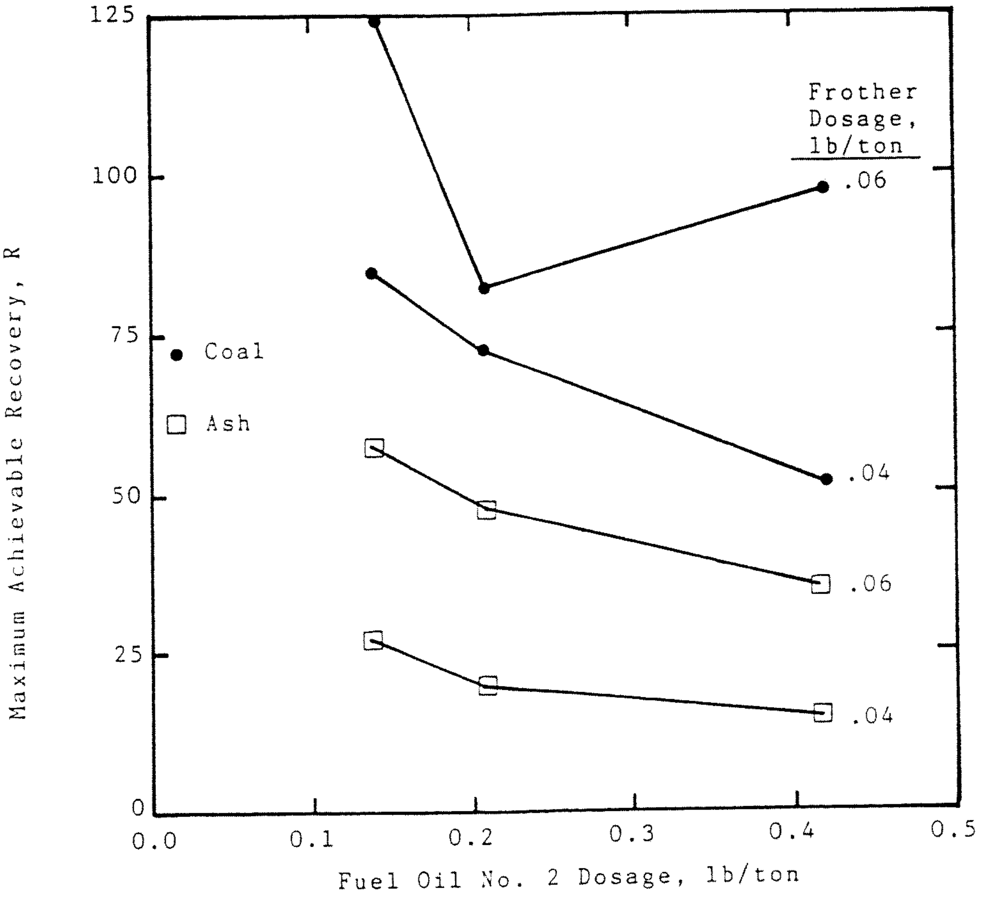


Figure 2.8a. The Effect of Frother and Collector Dosage on the Maximum Achievable Recovery of the Individual Size Fractions of a Lower Kittanning Seam Coal. A. + 48 Mesh Fraction.

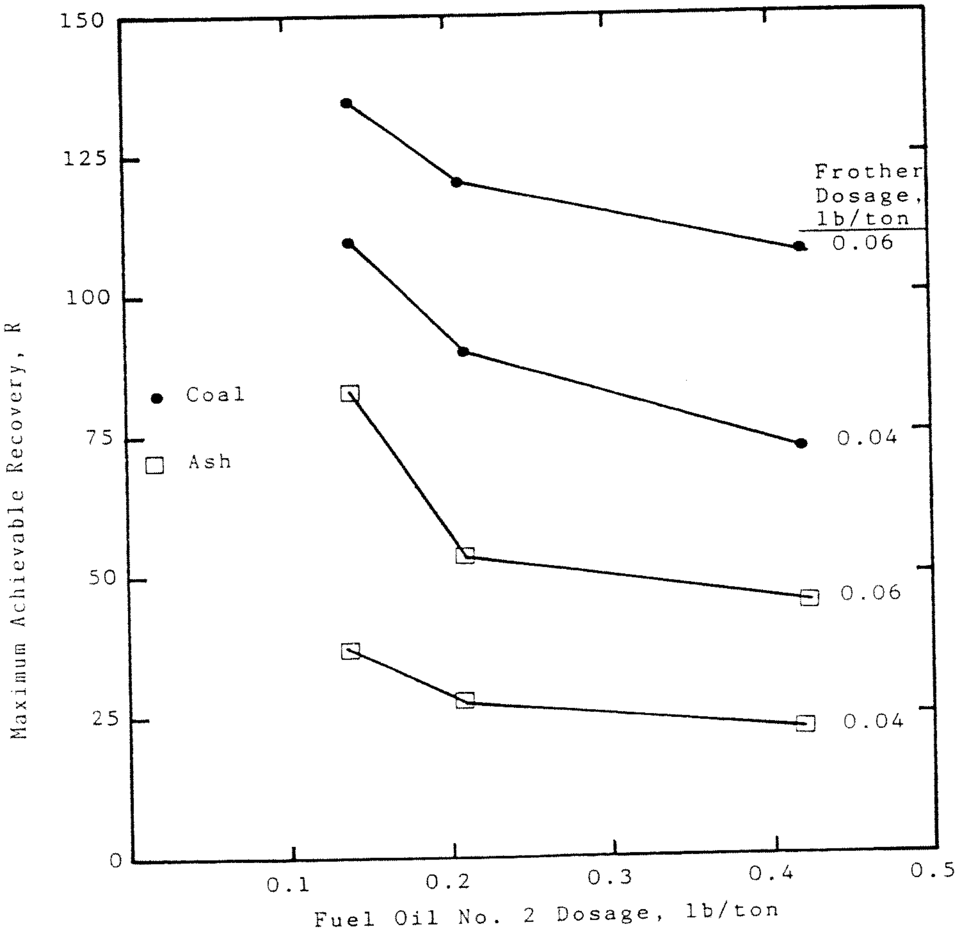


Figure 2.8b. The Effect of Frother and Collector Dosage on the Maximum Achievable Recovery of the Individual Size Fractions of a Lower Kittanning Seam Coal. A. 48 X 100 Mesh Fraction.

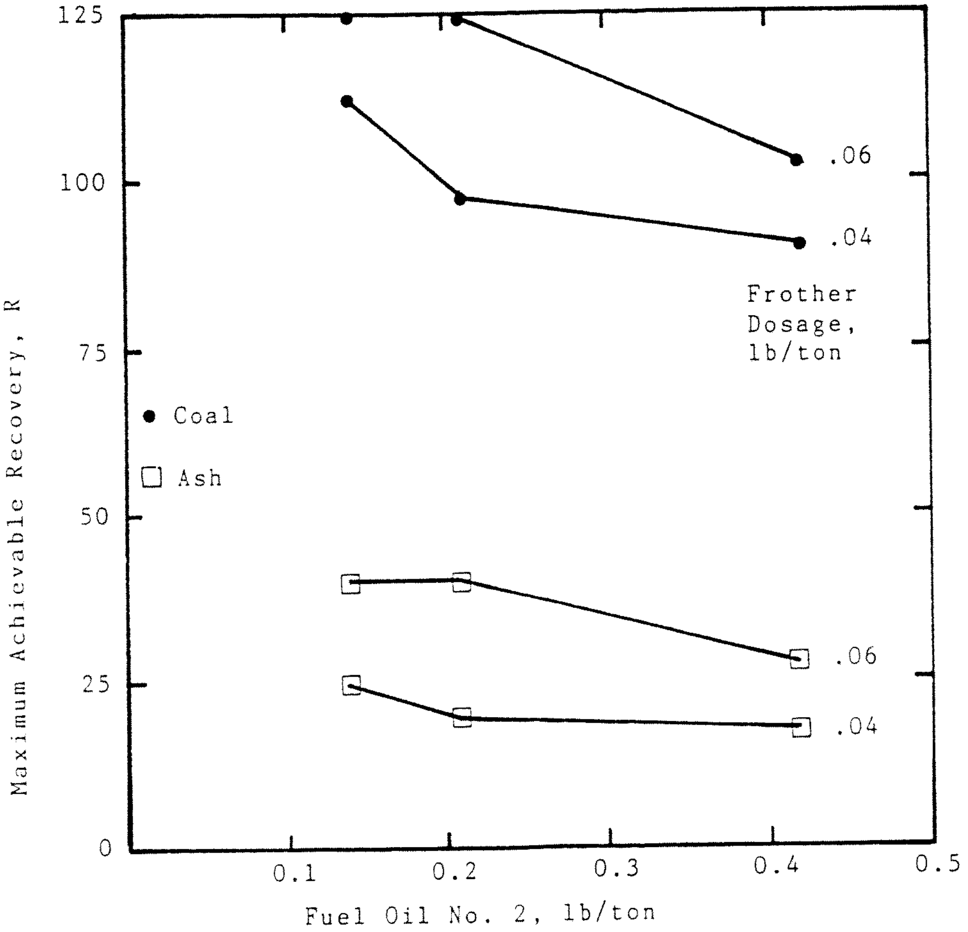


Figure 2.8c. The Effect of Frother and Collector Dosage on the Maximum Achievable Recovery of the Individual Size Fractions of a Lower Kittanning Seam Coal. A. - 100 Mesh Fraction.

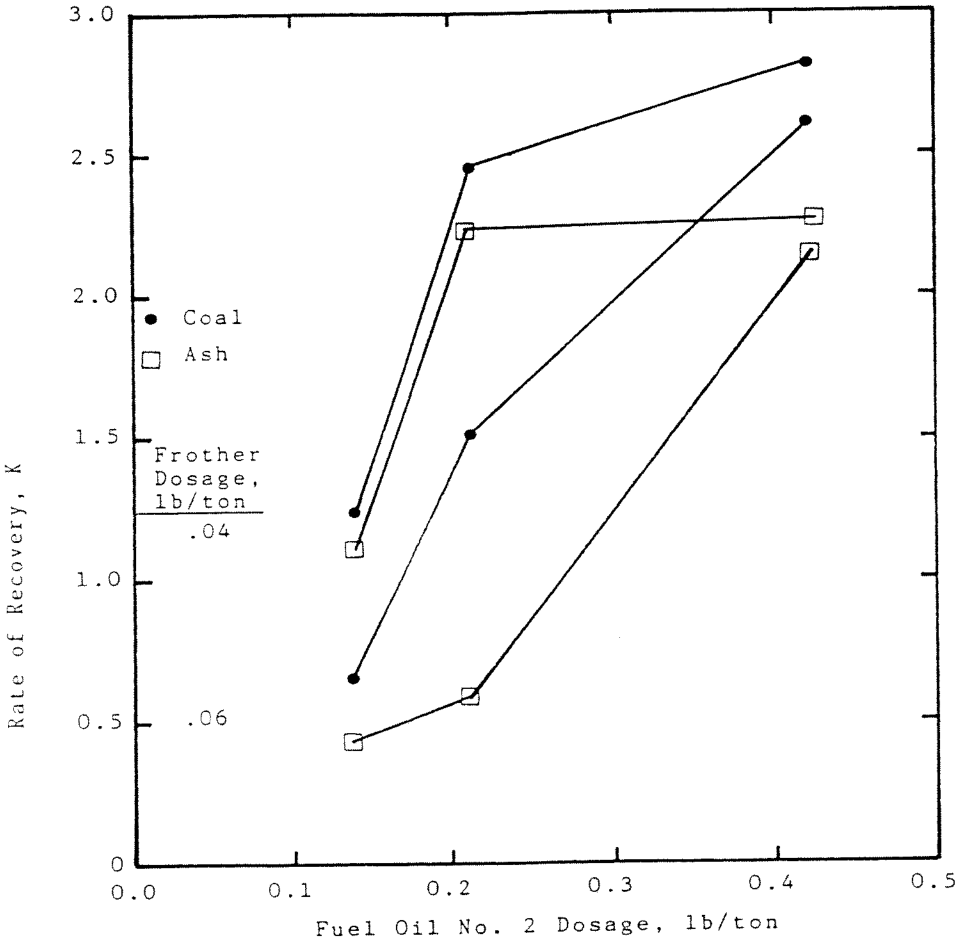


Figure 2.9a. The Effect of Frother and Collector Dosage on the Rate of Recovery of the Individual Size Fractions of a Lower Kittanning Seam Coal. A. + 48 Mesh Fraction.

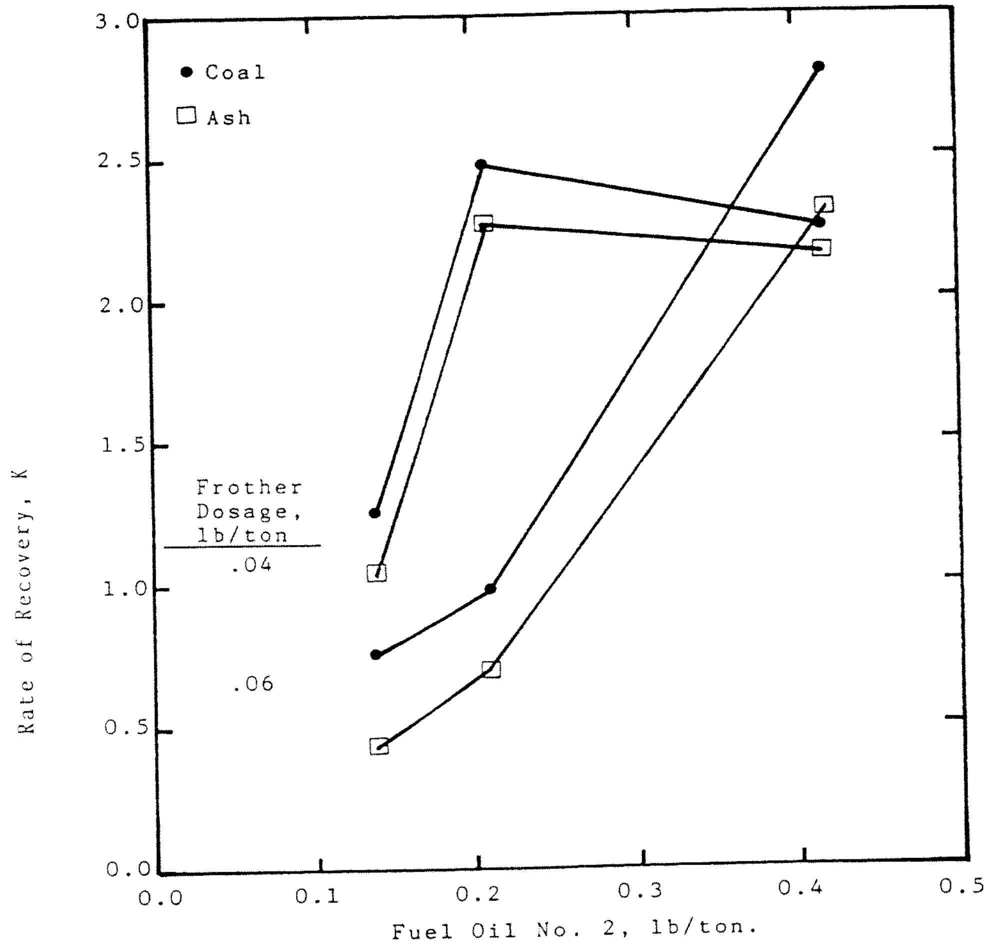


Figure 2.9b. The Effect of Frother and Collector Dosage on the Rate of Recovery of the Individual Size Fractions of a Lower Kittanning Seam Coal. A. 48 X 100 Mesh Fraction.

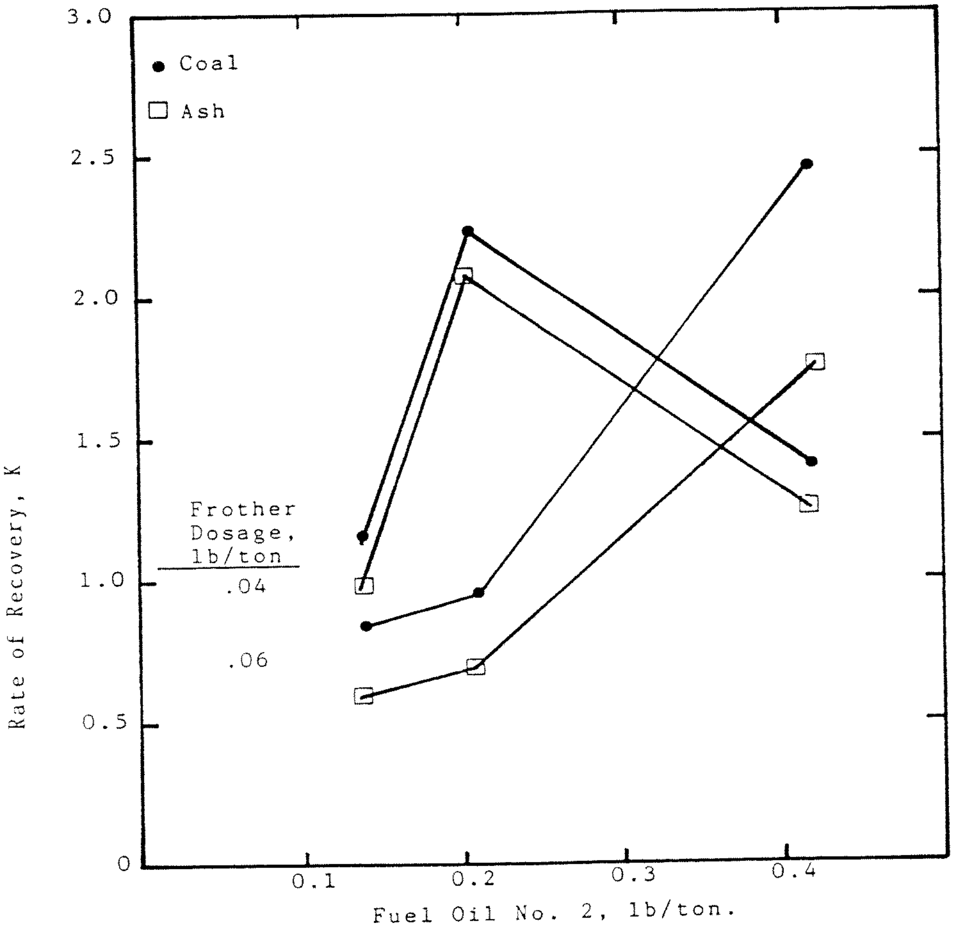


Figure 2.9c. The Effect of Frother and Collector Dosage on the Rate of Recovery of the Individual Size Fractions of a Lower Kittanning Seam Coal. A. - 100 Mesh Fraction.

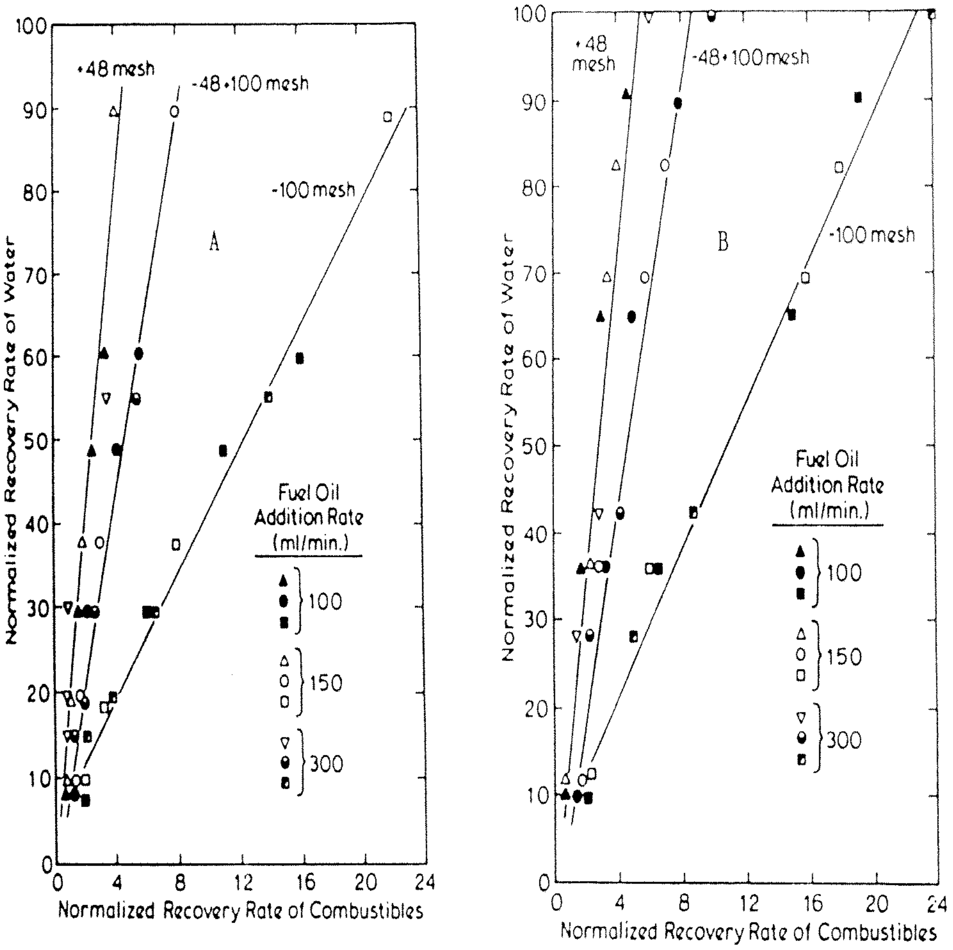


Figure 2.10. Relationship Between Water Recovery and Combustibles Recovery for Individual Size Fractions at MIBC Dosages of A. 0.04 and B. 0.06 lb./ton. All Test Data was Normalized to a Solids Feed Rate of 100. Fuel Oil Dosages of 0.14, 0.21, and 0.42 lb./ton (100, 150, and 300 ml/min., respectively).

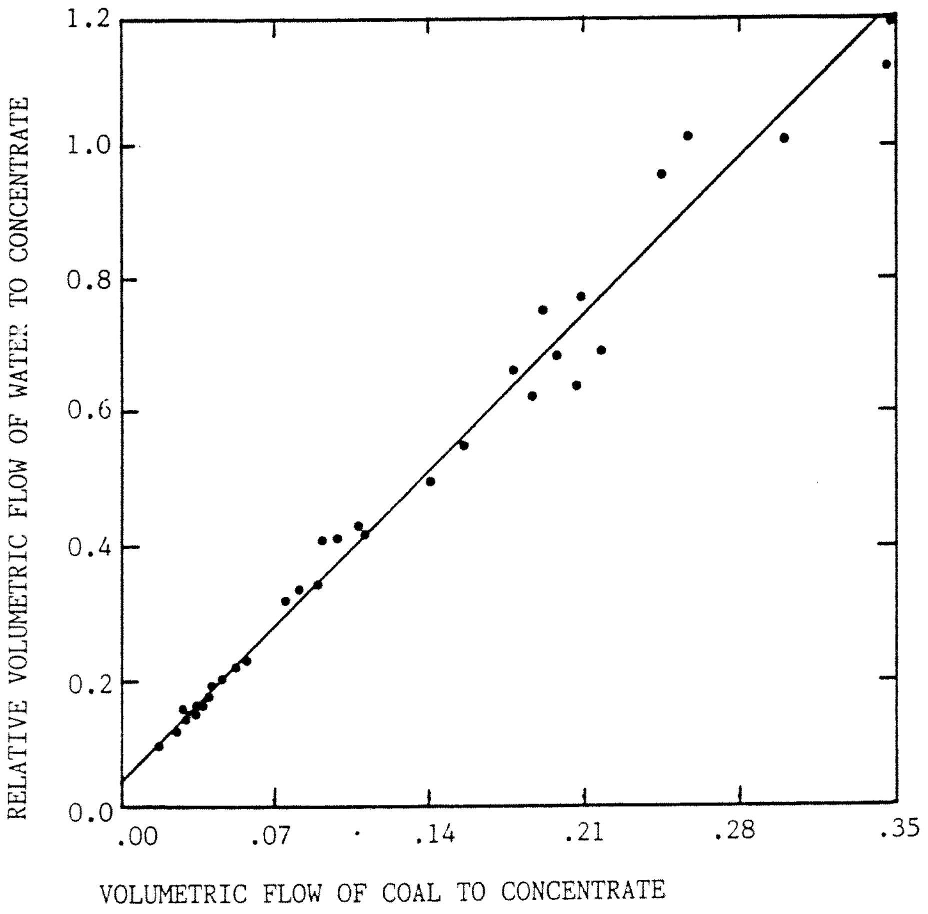


Figure 2.11. Relationship Between Water Recovery and Coal Recovery at the Kitt Mine. Data Points for all MIBC (0.04 and 0.06 lb./ton) and Fuel Oil (0.14, 0.21, 0.35, and 0.42 lb./ton) Reagent Combinations.

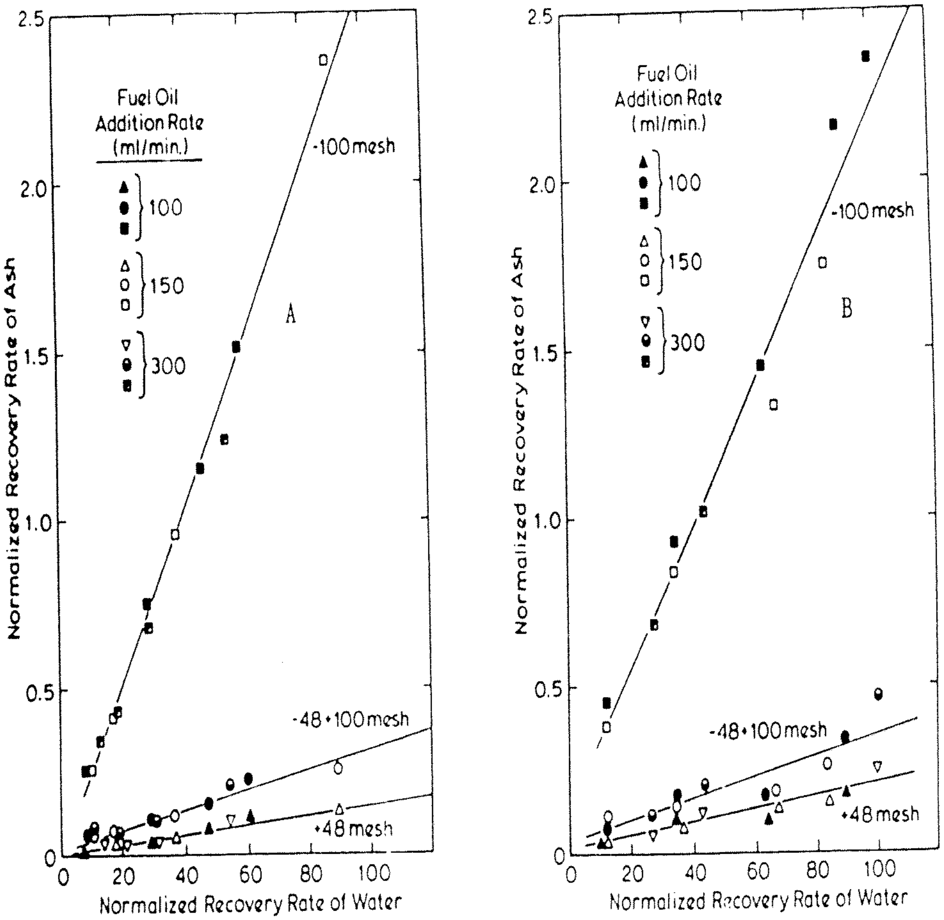


Figure 2.12. Relationship Between Ash Recovery and Water Recovery for Individual Size Fractions at MIBC Dosages of A. 0.04 and B. 0.06 lb./ton. All Test Data was Normalized to a Solids Feed Rate of 100. Fuel Oil Dosages of 0.14, 0.21, and 0.42 lb./ton (100, 150, and 300 ml/min., respectively).

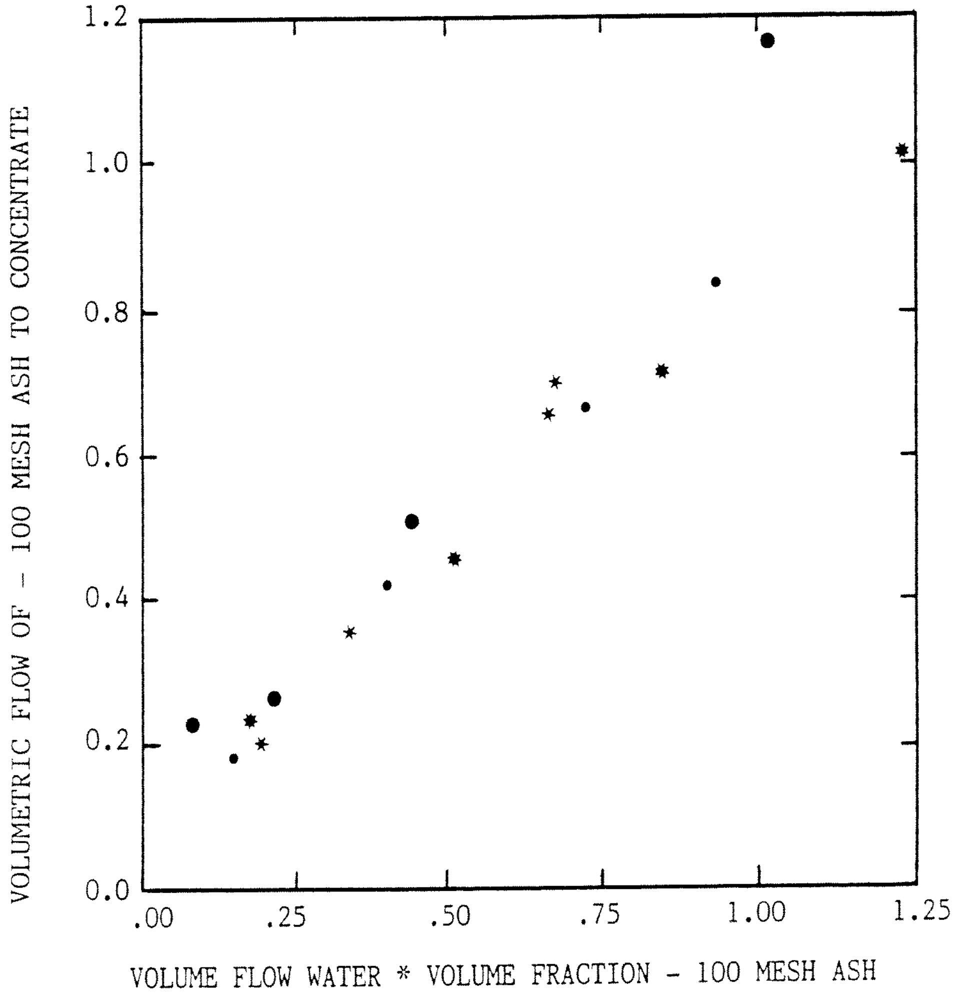


Figure 2.13a. Relationship Between Volumetric Flow of – 100 Mesh Ash into the Concentrate and Volumetric Flow of Water * Volume Fraction of – 100 Mesh Ash in the Pulp. A. MIBC Dosage of 0.04 lb./ton and Fuel Oil Dosages of 0.14, 0.21, 0.35, and 0.42 lb./ton.

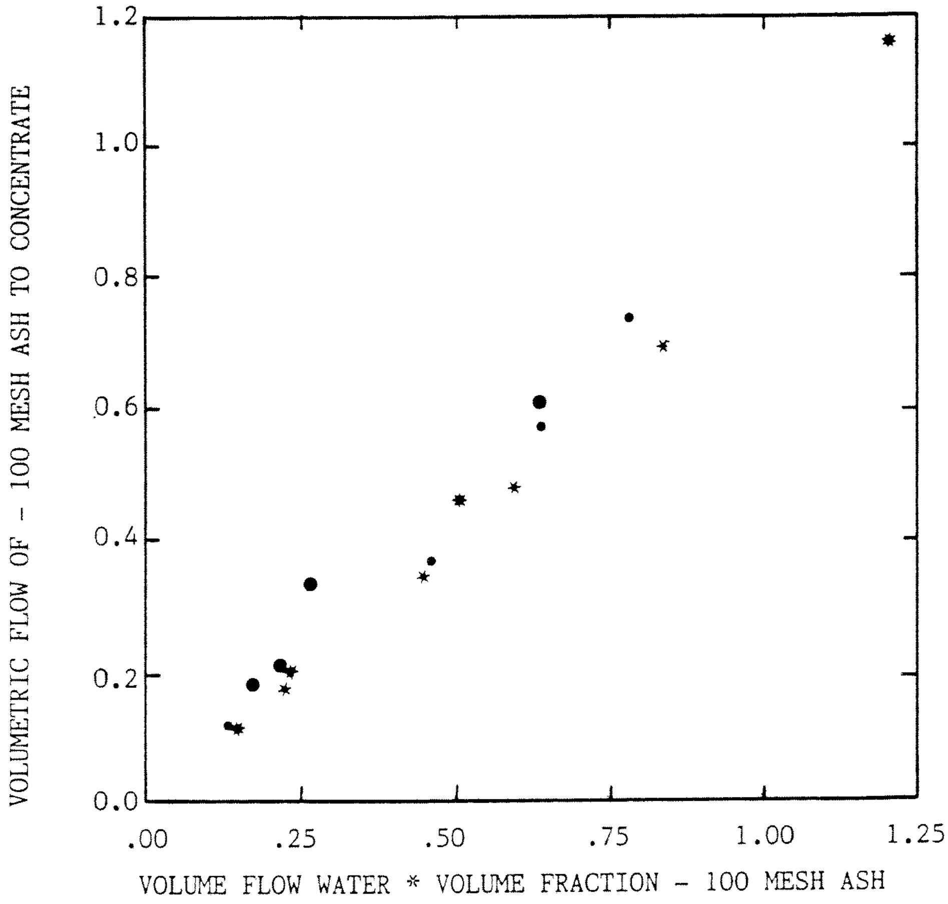


Figure 2.13b. Relationship Between Volumetric Flow of – 100 Mesh Ash into the Concentrate and Volumetric Flow of Water * Volume Fraction of – 100 Mesh Ash in the Pulp. B. MIBC Dosage of 0.06 lb./ton and Fuel Oil Dosages of 0.14, 0.21, 0.35, and 0.42 lb./ton.

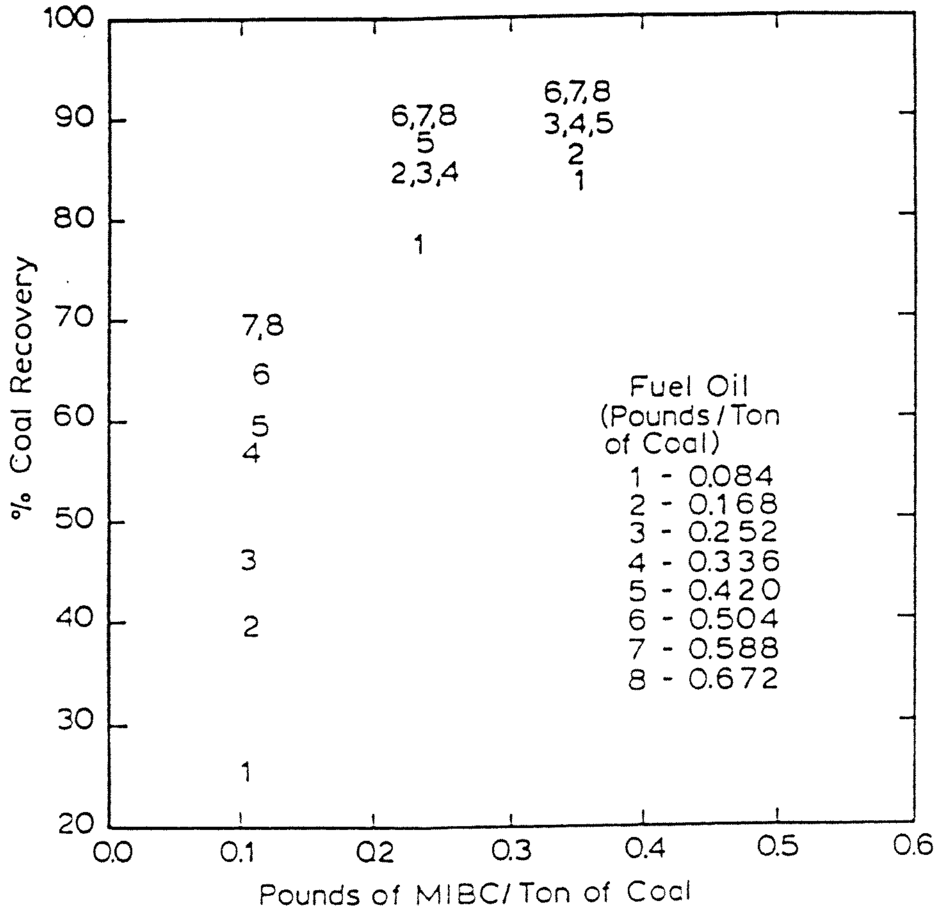


Figure 2.14. The Effect of MIBC Addition Level on the Percent Coal Recovery at Different Fuel Oil Addition Levels (lab tests on samples from the Kitt Mine Preparation Plant) (Kawatra and Seitz, 1984).

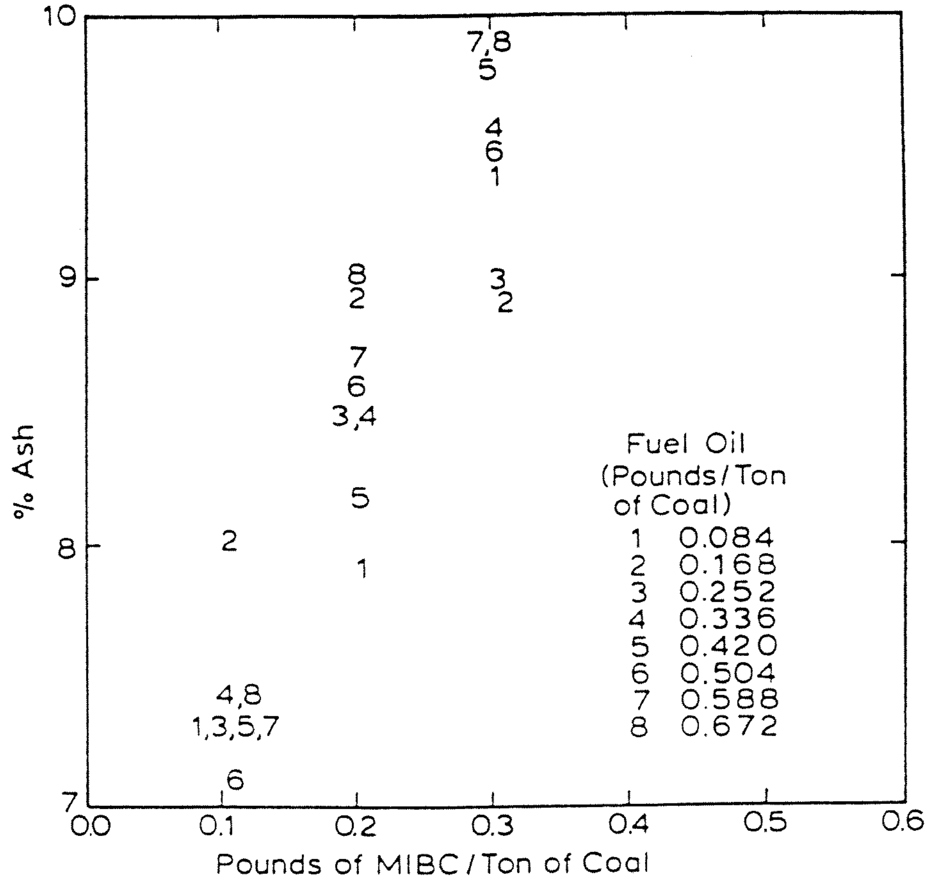


Figure 2.14. The Effect of MIBC Addition Level on the Concentrate **Percent** Ash **Recovery at Different Fuel Oil Addition** Levels (lab tests on samples from the Kitt Mine Preparation Plant) (Kawatra and Seitz, 1984).

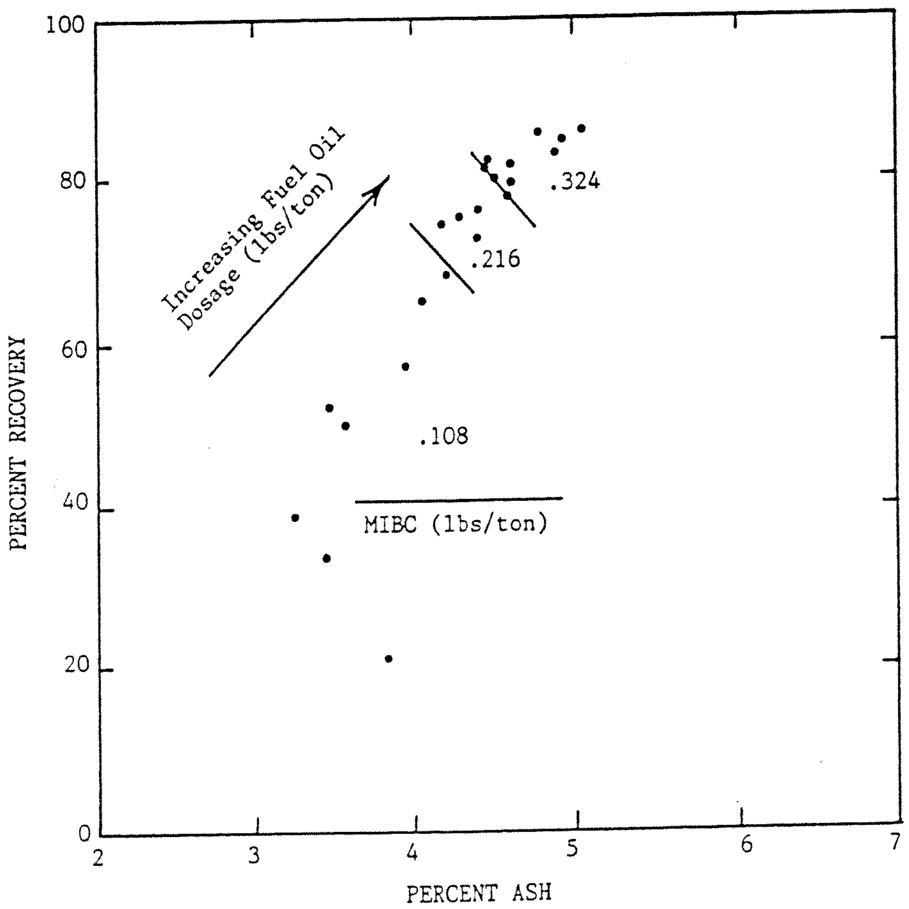


Figure 2.16a. Grade – Recovery Response for + 48 Mesh Fraction of Lower Kittanning Seam Coal in Laboratory Tests. Fuel Oil Dosage (lb./ton) was Increased from 0,.084 to 0.672 in Equal Increments for Each MIBC Dosage Level.

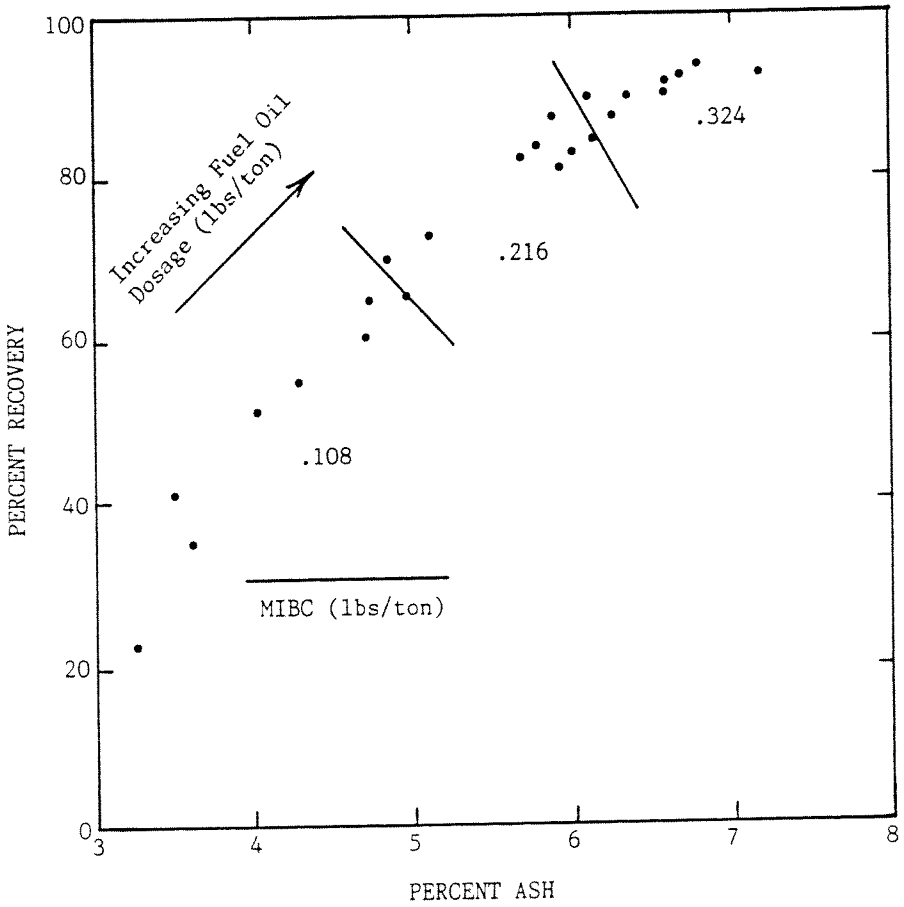


Figure 2.16b. Grade – Recovery Response for 48 X 100 Mesh Fraction of Lower Kittanning Seam Coal in Laboratory Tests. Fuel Oil Dosage (lb./ton) was Increased from 0,.084 to 0.672 in Equal Increments for Each MIBC Dosage Level.

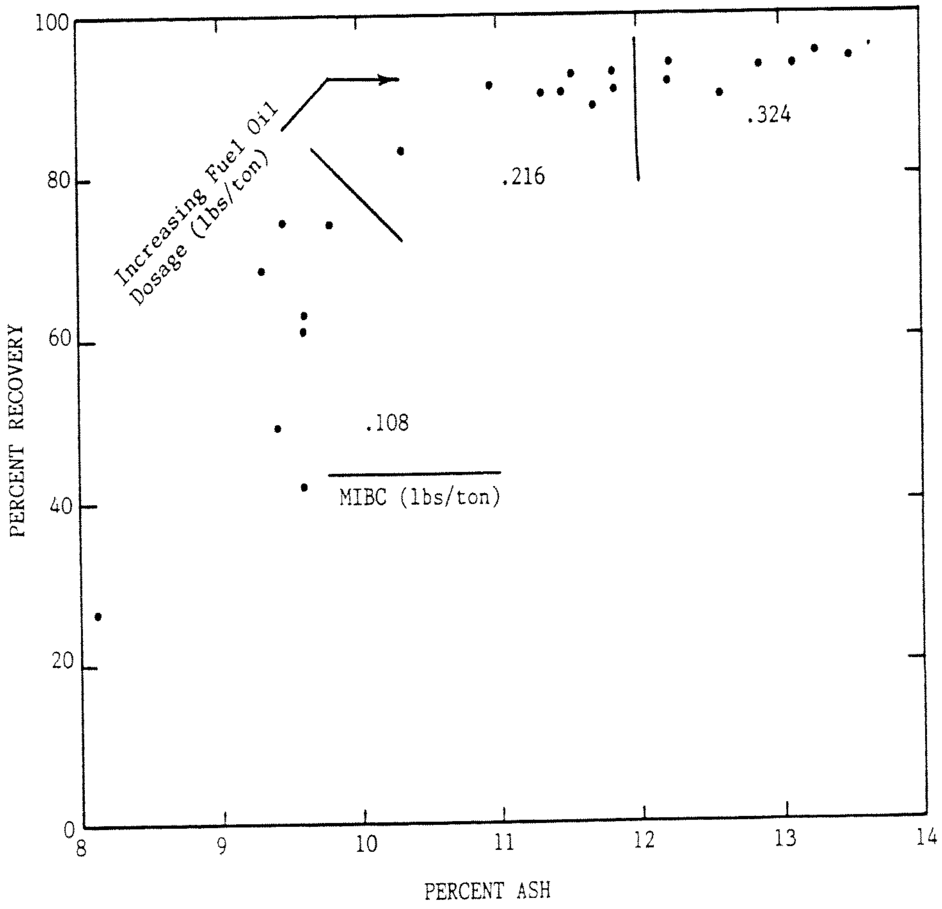


Figure 2.16c. Grade – Recovery Response for - 100 Mesh Fraction of Lower Kittanning Seam Coal in Laboratory Tests. Fuel Oil Dosage (lb./ton) was Increased from 0,.084 to 0.672 in Equal Increments for Each MIBC Dosage Level.

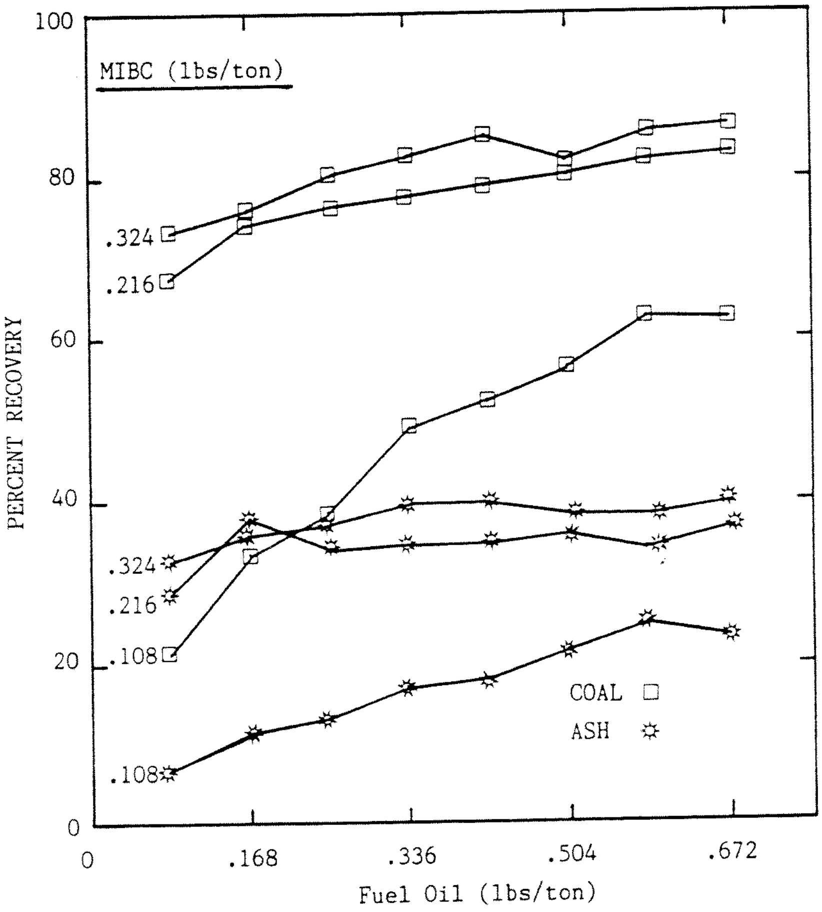


Figure 2.17a. Recovery – Dosage Response for + 48 Mesh Fraction of Lower Kittanning Seam Coal in Laboratory Tests.

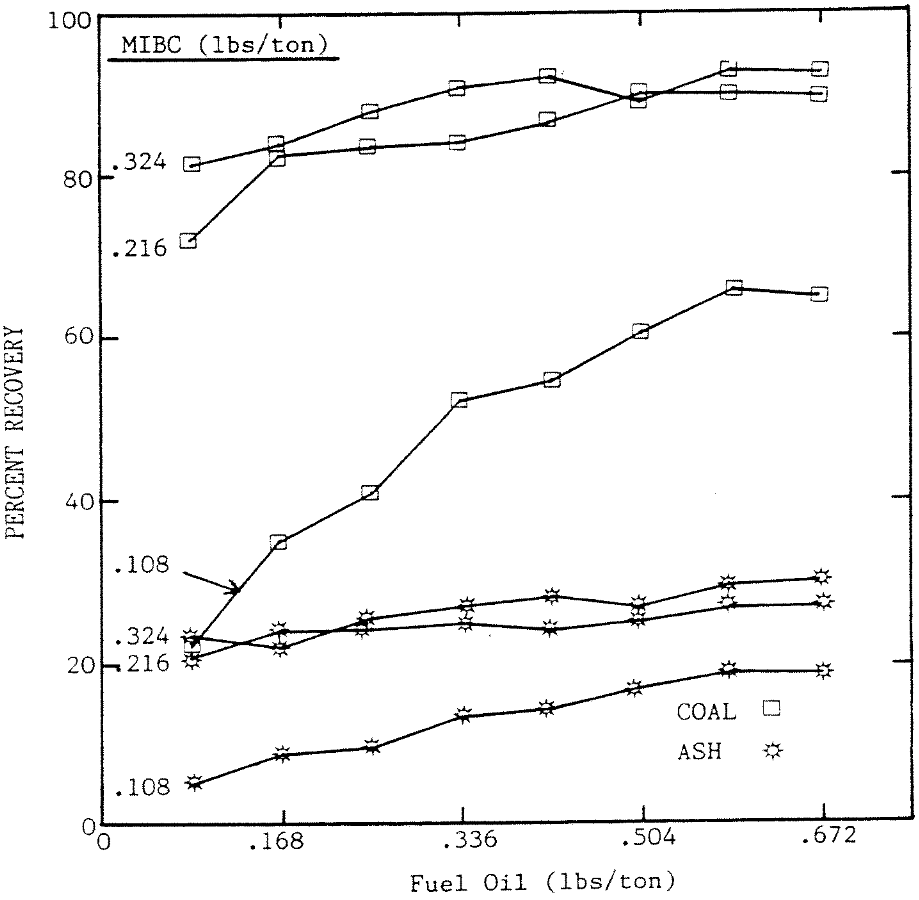


Figure 2.17b. Recovery – Dosage Response for 48 X 100 Mesh Fraction of Lower Kittanning Seam Coal in Laboratory Tests.

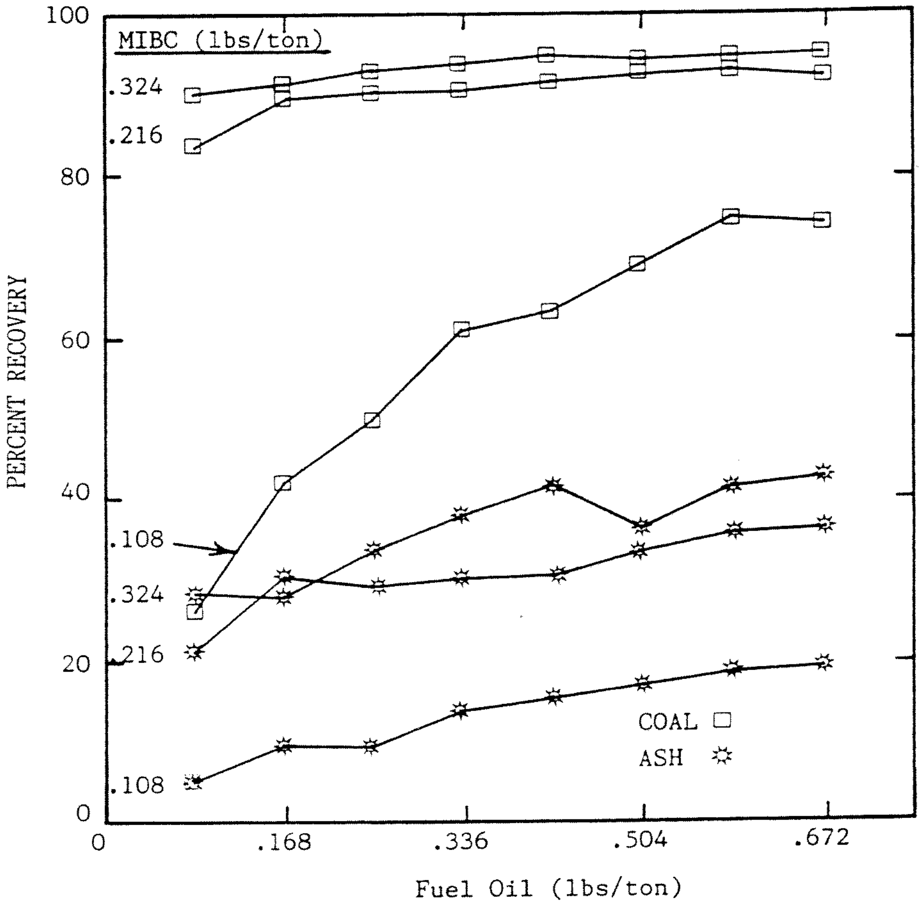


Figure 2.17c. **Recovery – Dosage Response for - 100 Mesh Fraction of Lower Kittanning Seam Coal in Laboratory Tests.**

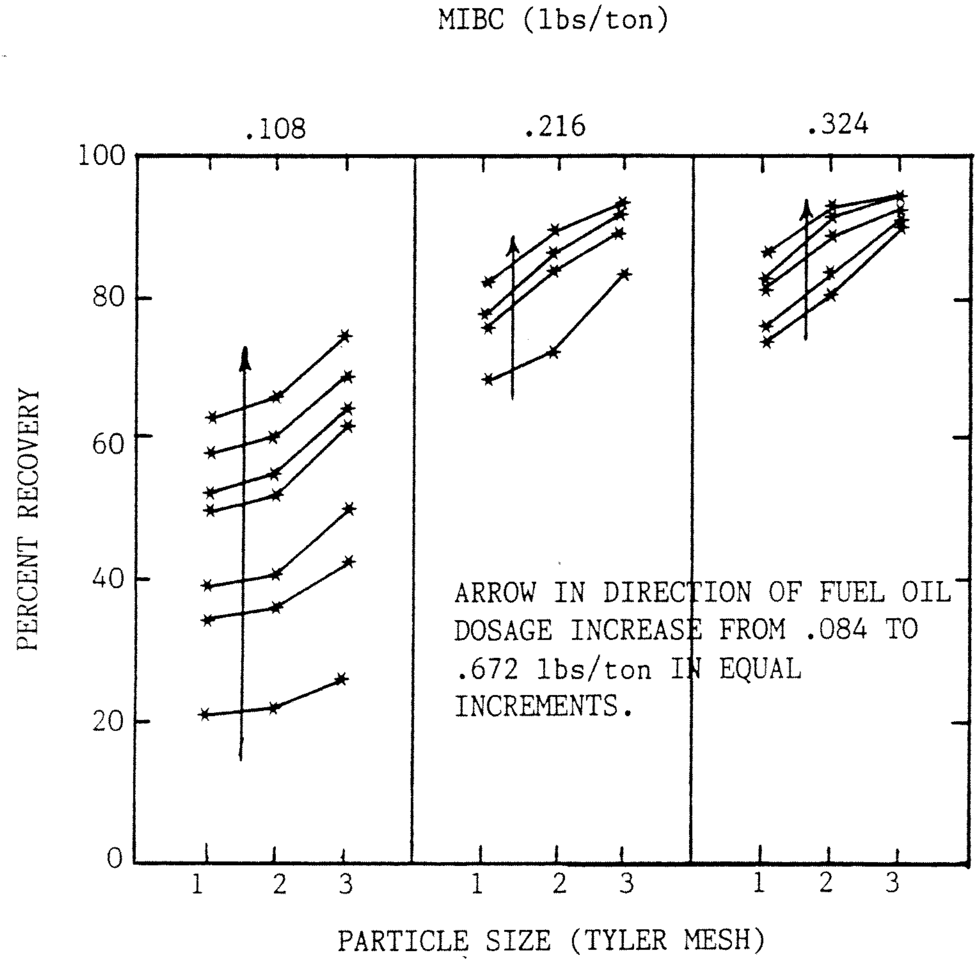


Figure 2.18. Recovery – Size Response for Lower Kittanning Seam Coal as a Function of Frother (MIBC) and Collector (No. 2 Fuel Oil) Dosages in Laboratory Tests. 1. + 48, 2. 48 X 100, and 3. – 100 Mesh.

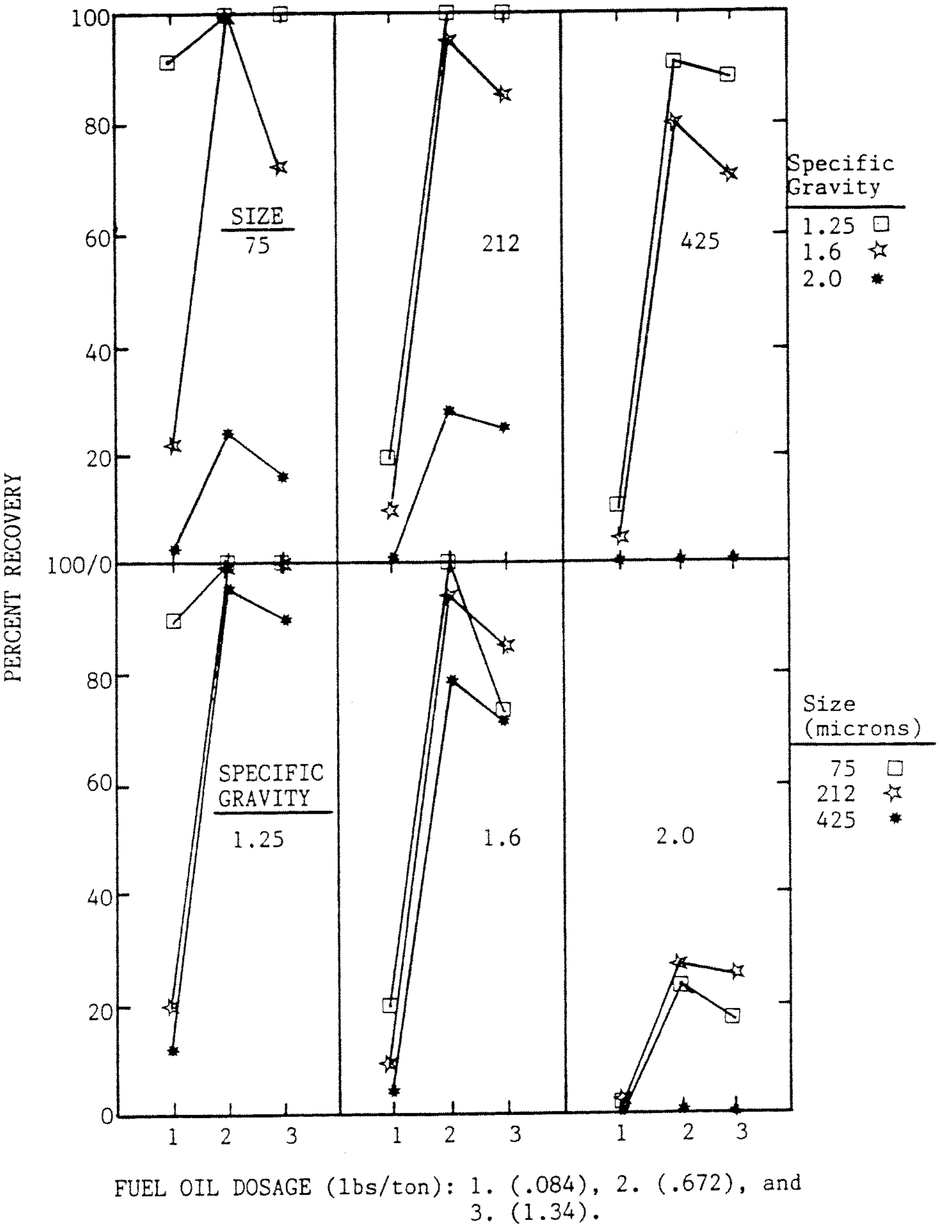


Figure 2.19. Recovery – Fuel Oil Dosage Response for Lower Kittanning Seam Coal in Laboratory Tests as a Function of Specific Gravity and Size.

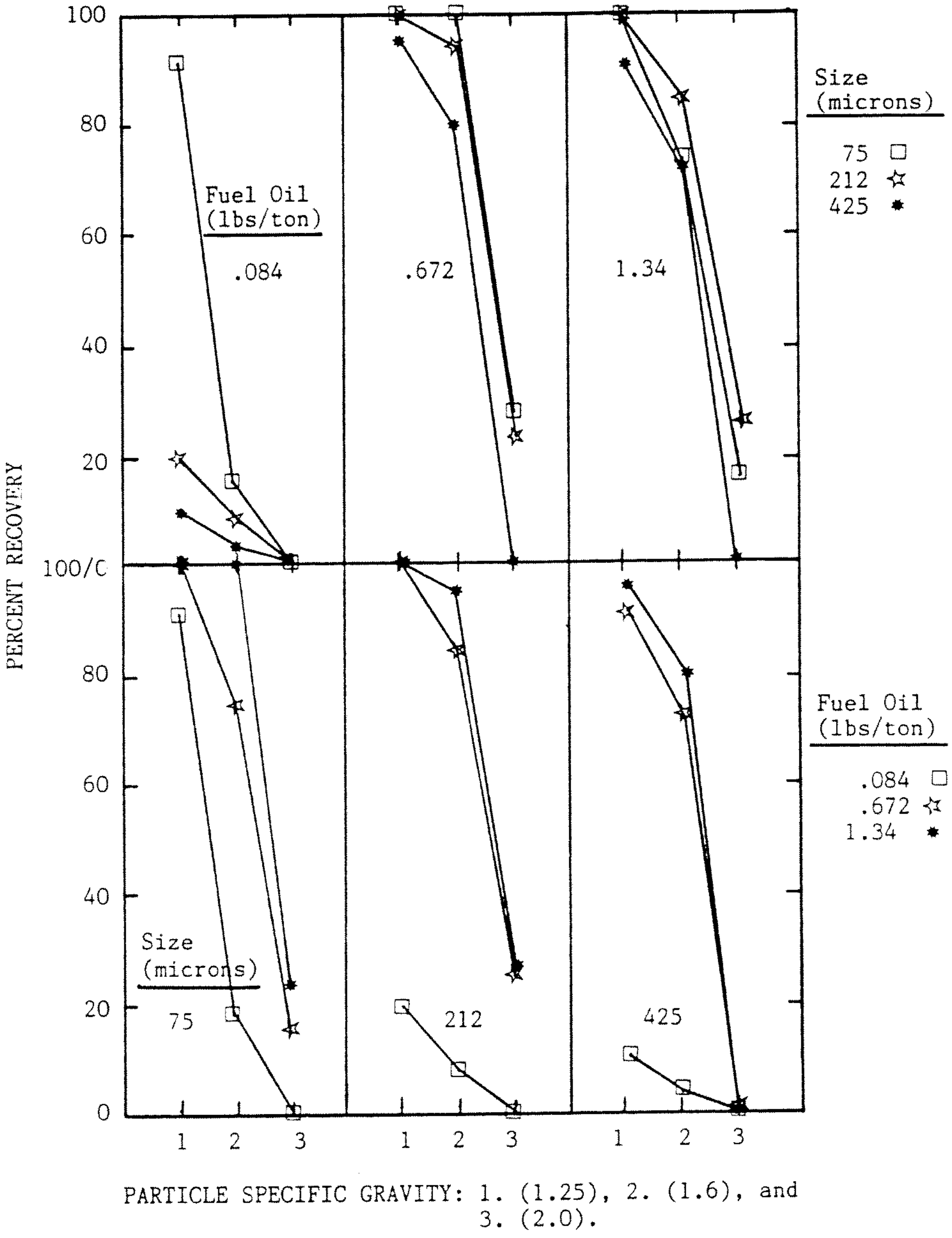


Figure 2.20. Recovery – Specific Gravity Response for Lower Kittanning Seam Coal in Laboratory Tests as a Function of Fuel Oil Dosage and Particle Size.

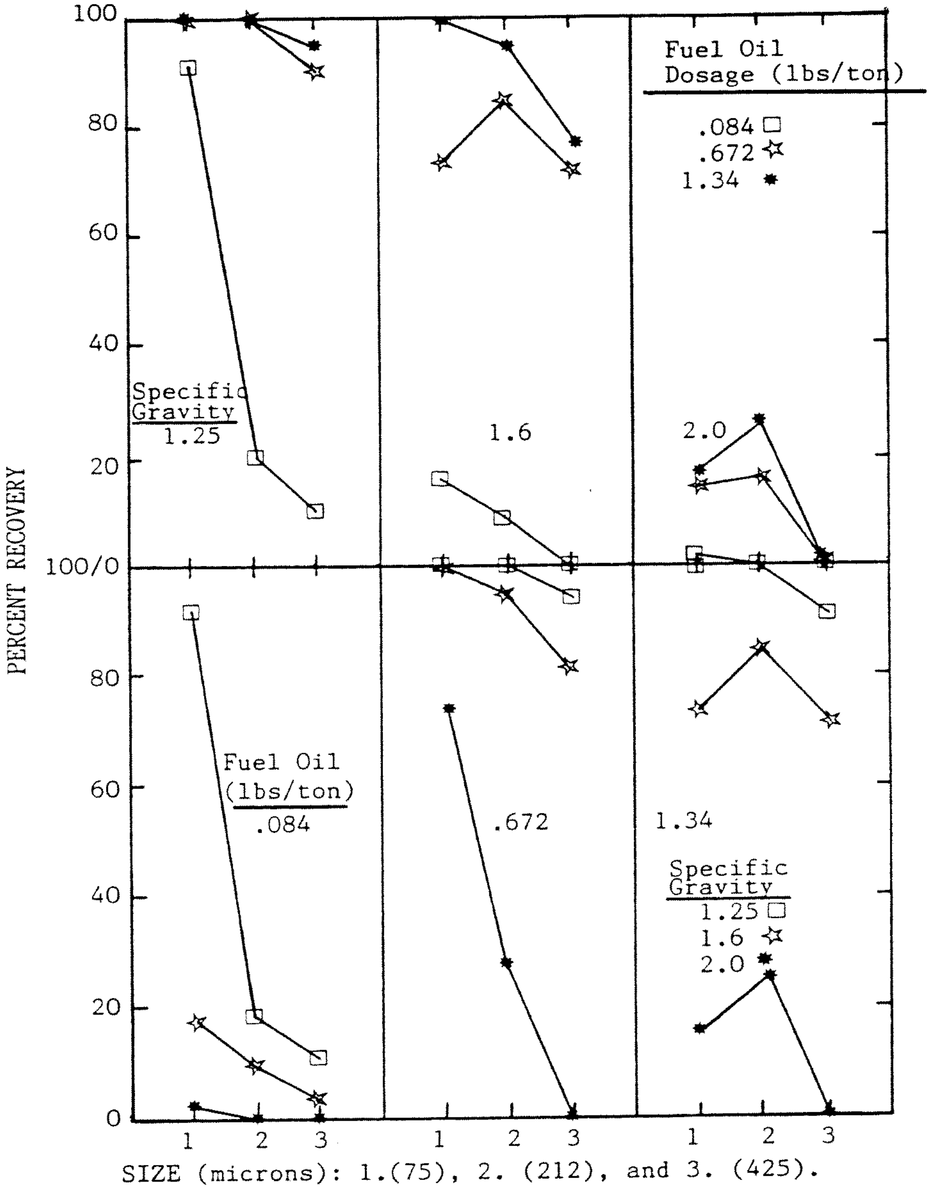


Figure 2.21. Recovery – Size Response for Lower Kittanning Seam Coal in Laboratory Tests as a Function of Fuel Oil Dosage and Specific Gravity.

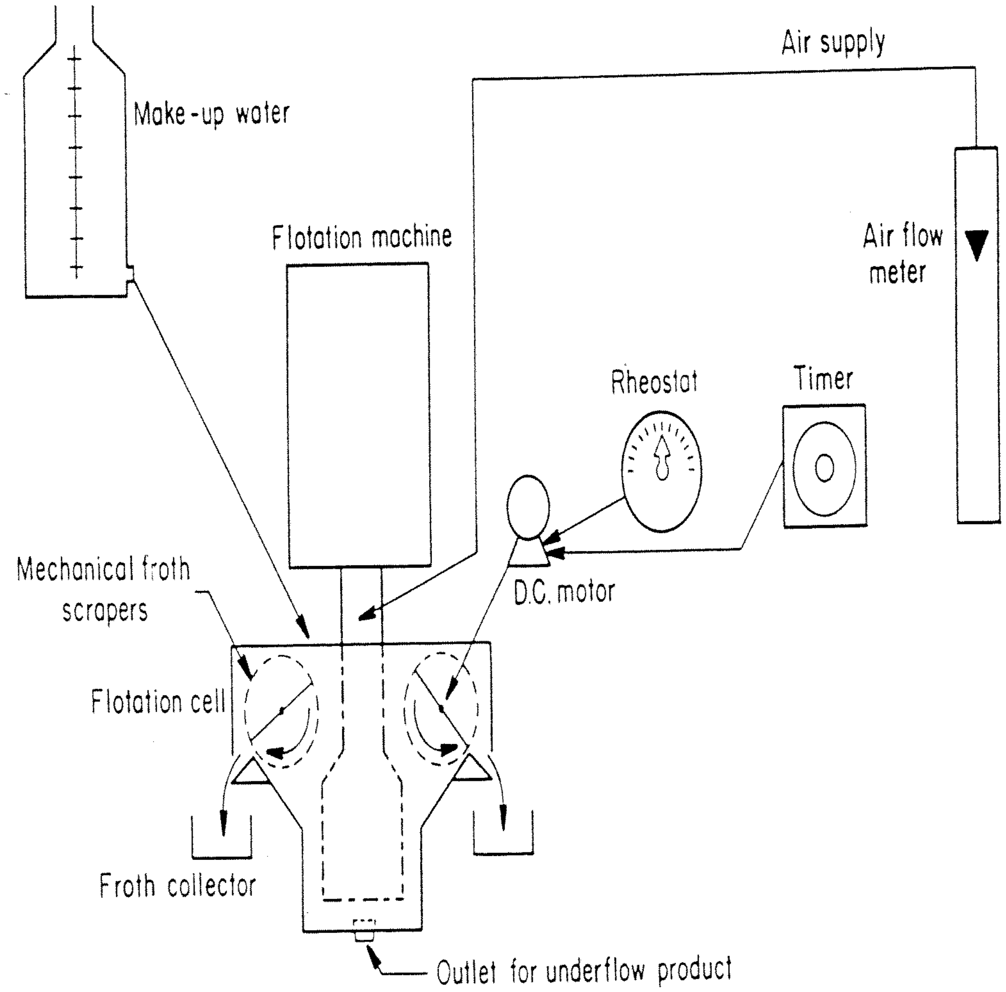


Figure 2.22. Laboratory Batch Flotation Unit with Mechanical Froth Scrapers.

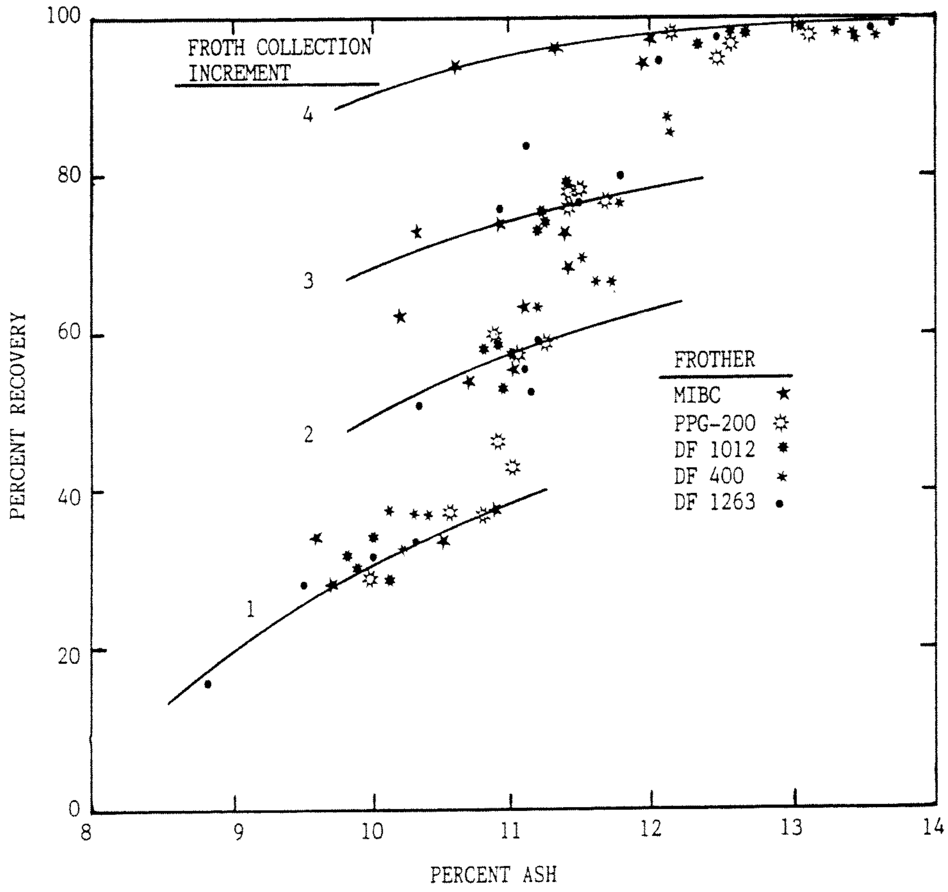


Figure 2.23. Grade – Recovery Response for Mammoth Seam Coal in Laboratory Tests where Frother Type and Dosage were Varied.

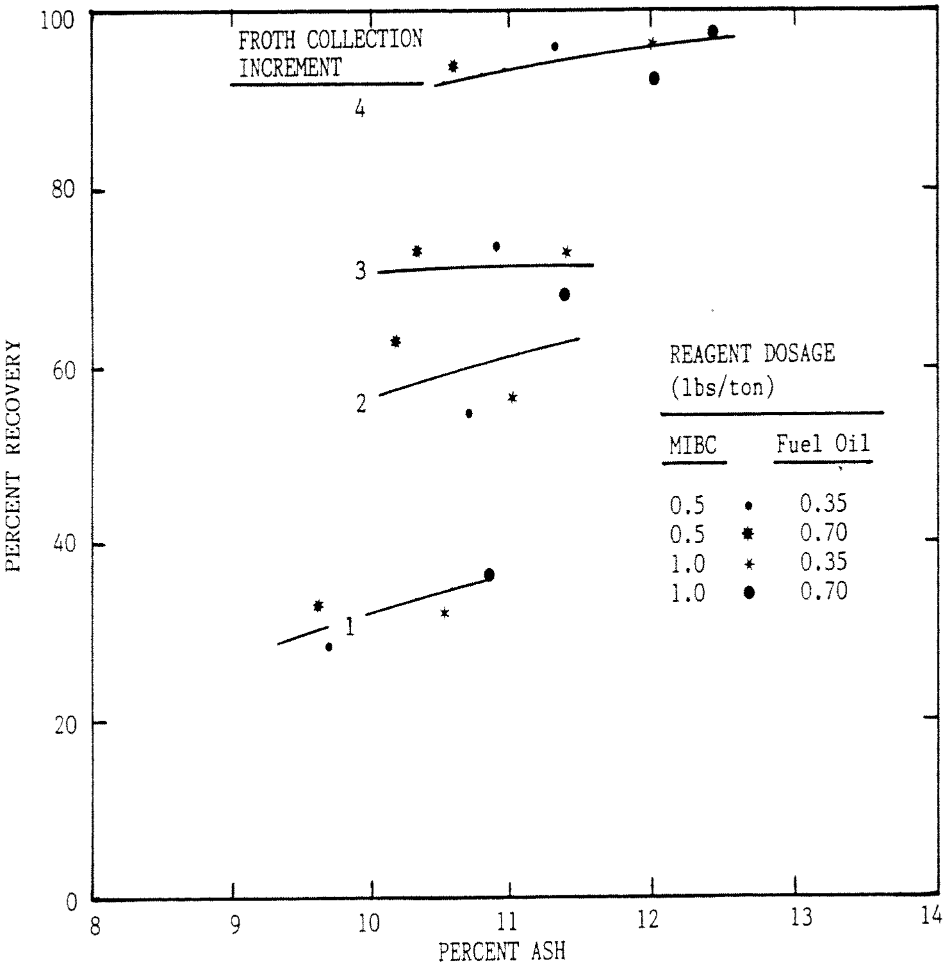


Figure 2.24. Grade – Recovery Response for Mammoth Seam Coal in Laboratory Tests Using MIBC: Frother and Collector Dosage Varying.

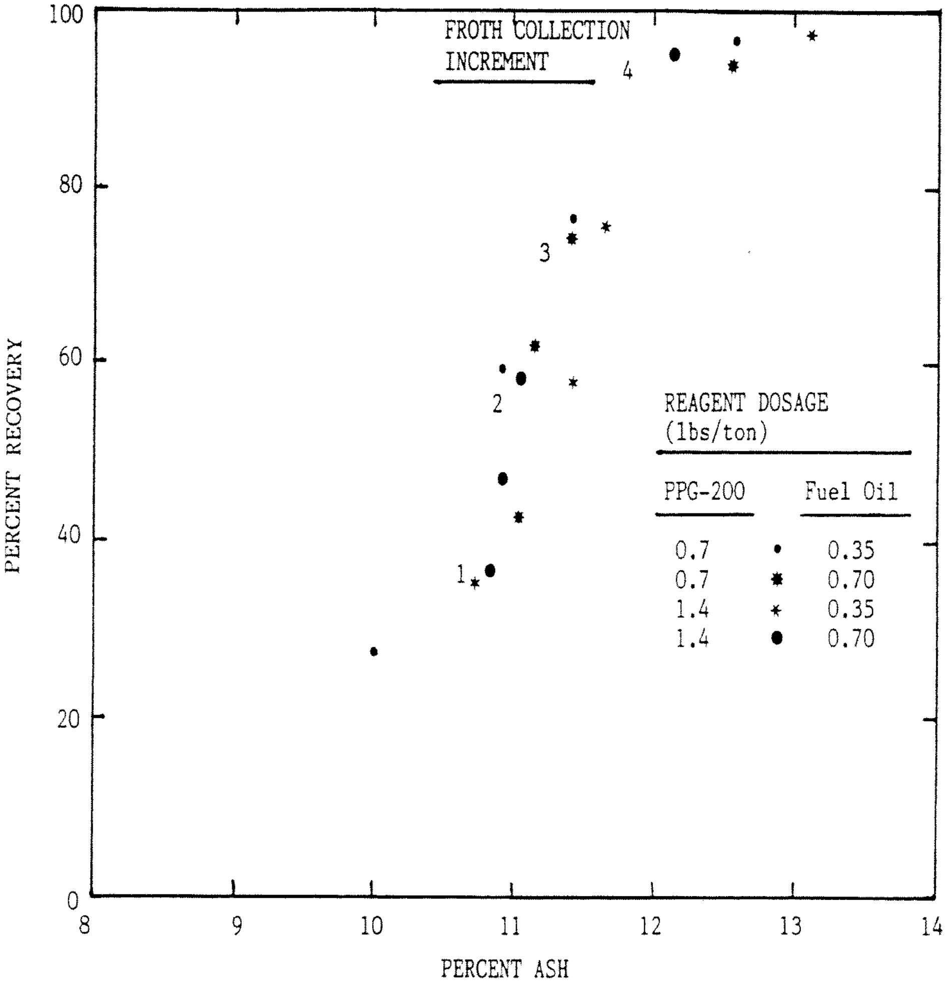


Figure 2.25. **Grade – Recovery Response for Mammoth Seam Coal in Laboratory Tests Using PPG-200: Frother and Collector Dosage Varying.**

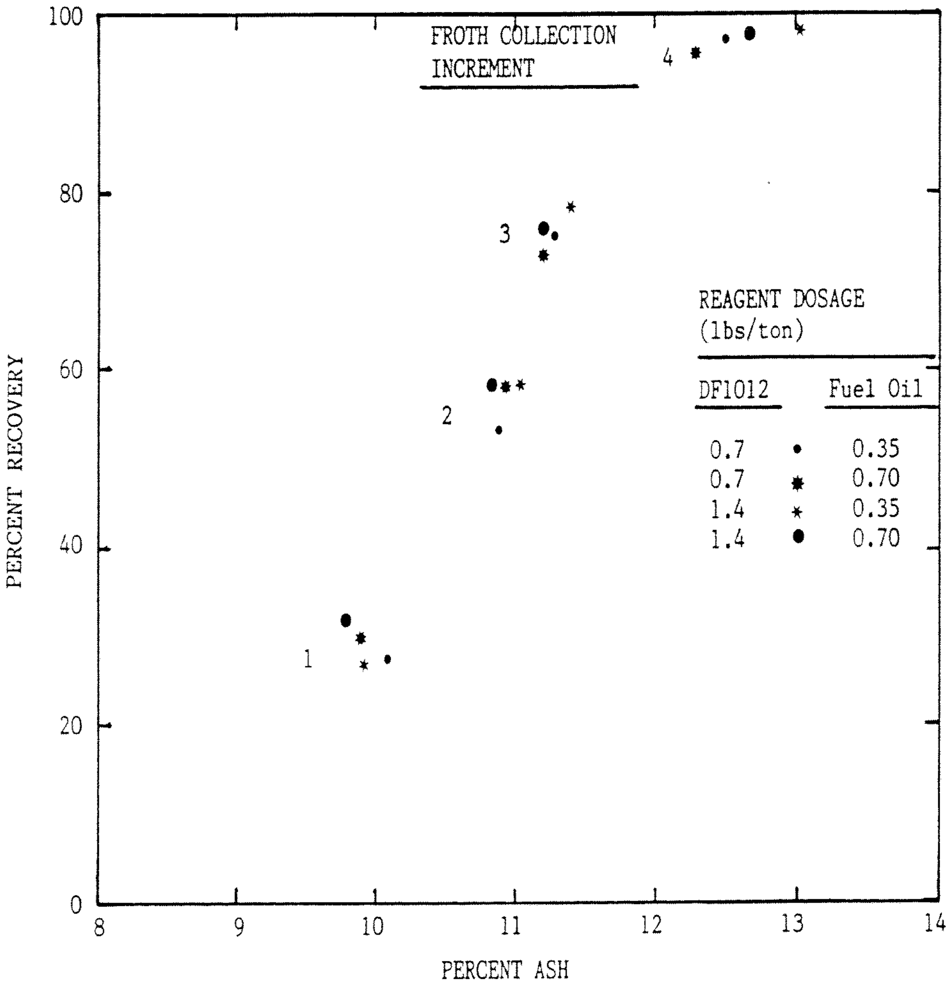


Figure 2.26. Grade – Recovery Response for Mammoth Seam Coal in Laboratory Tests Using DF1012: Frother and Collector Dosage Varying.

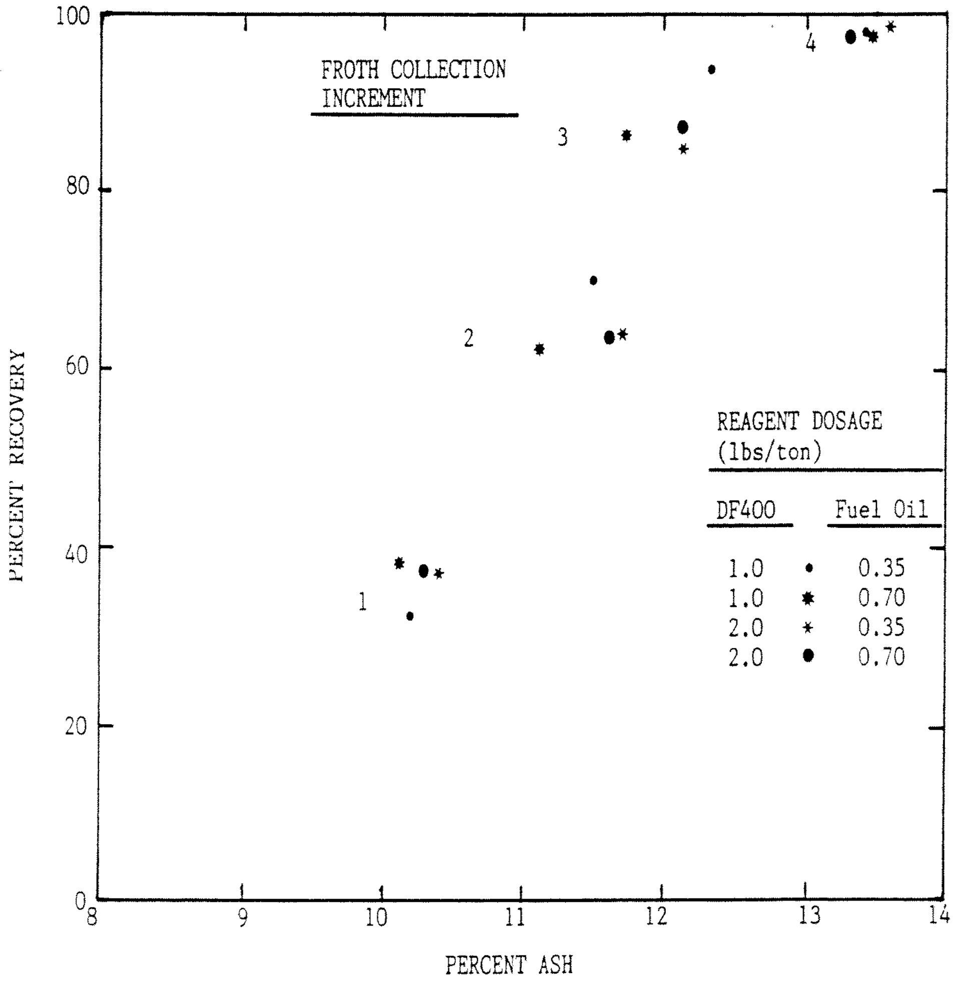


Figure 2.27. Grade – Recovery Response for Mammoth Seam Coal in Laboratory Tests Using DF400: Frother and Collector Dosage Varying.

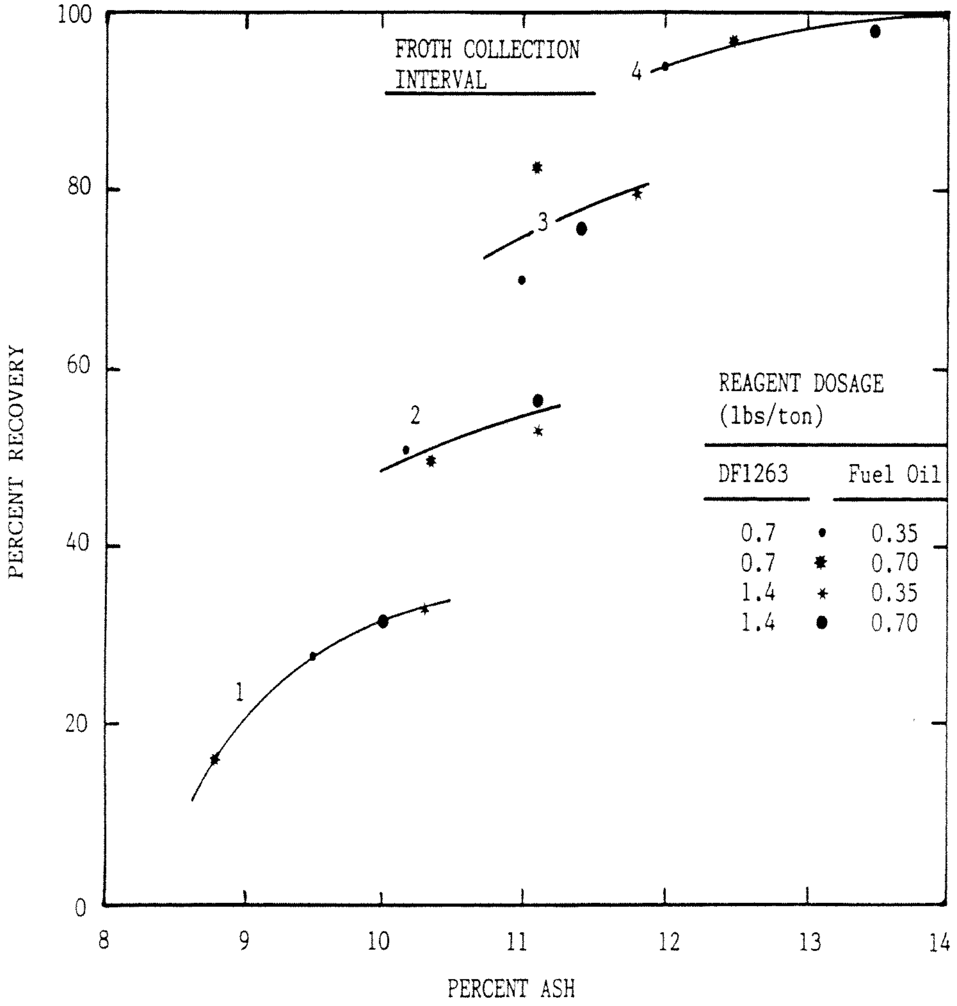


Figure 2.28. Grade – Recovery Response for Mammoth Seam Coal in Laboratory Tests Using DF1263: Frother and Collector Ddosage Varying.

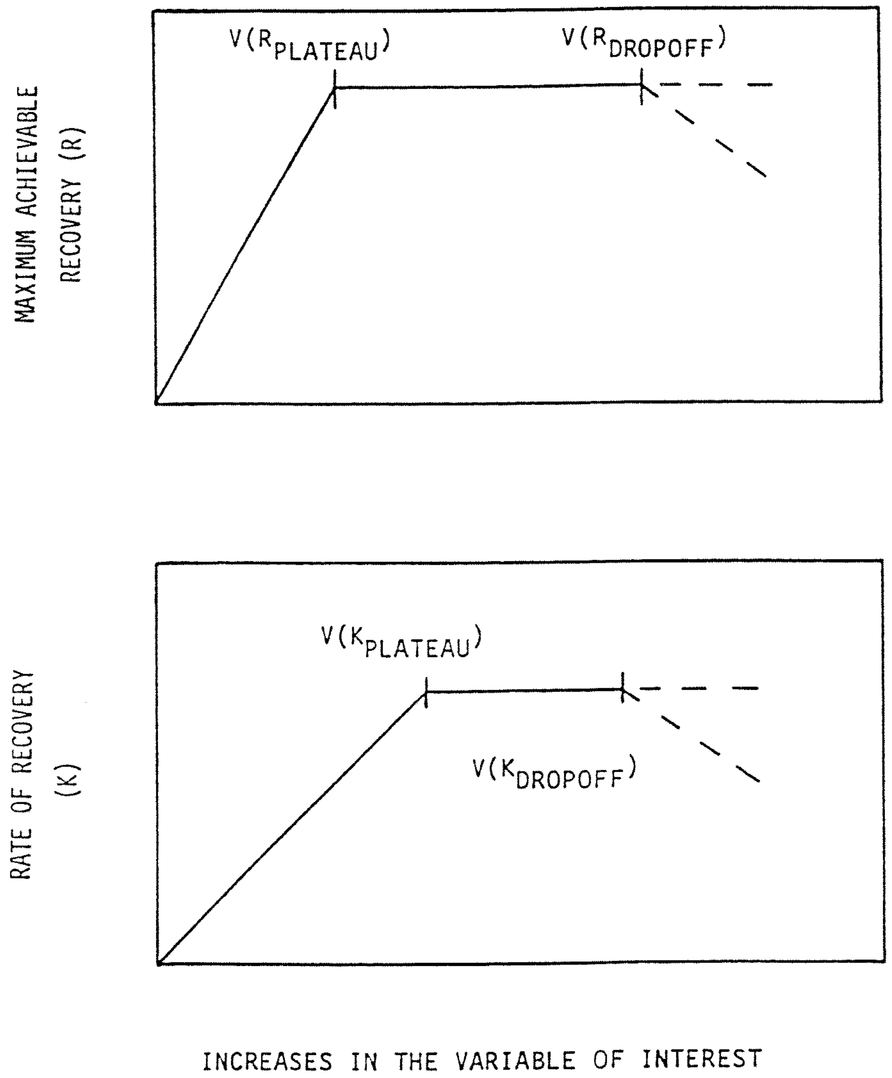


Figure 3.1. The Typical Effect of Increases in Independent Variables on the Rate of Recovery, K, and the Equilibrium Recovery, R; Where V (R-plateau or K-plateau) Refers to the Value of the Variable Required to Reach the Plateau and V (R-drop-off or K-drop-off) Refers to the Value of the Variable at Which the Plateau Ends (Seitz and Kawatra, 1985).

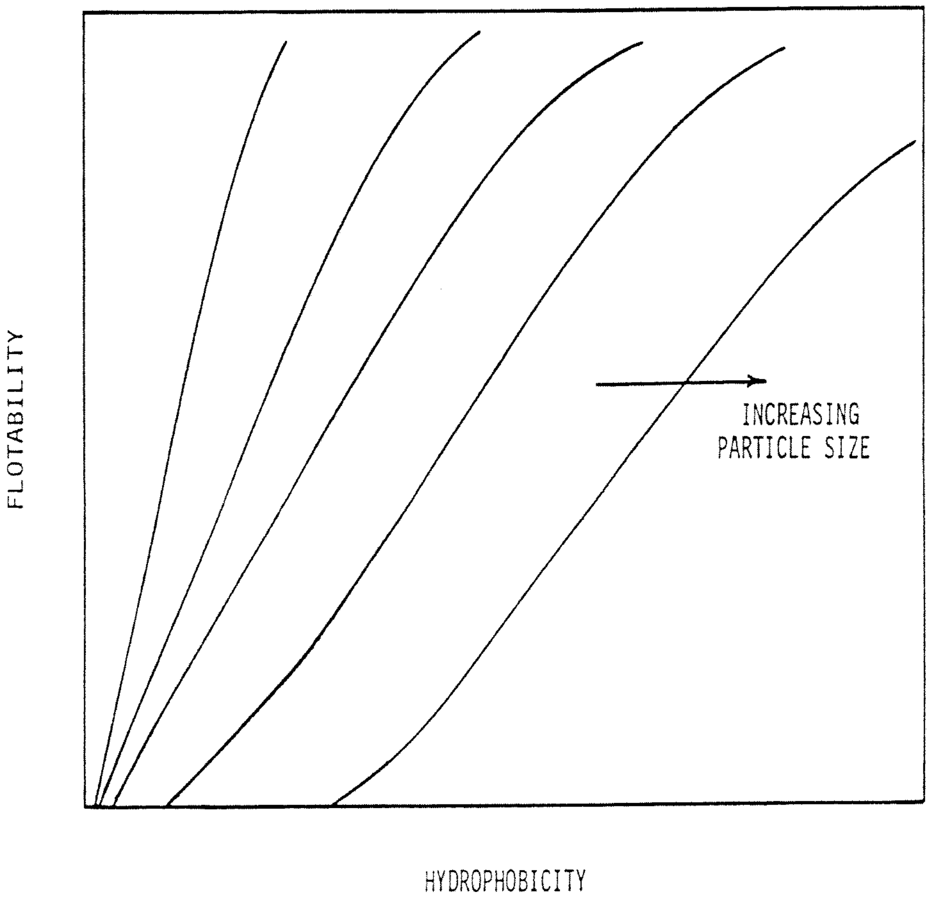


Figure 3.2. A Qualitative Representation of the Influence of Particle Size on the Relationship Between Flotability and Hydrophobicity (after Trahar, 1981; Seitz and Kawatra, 1985).

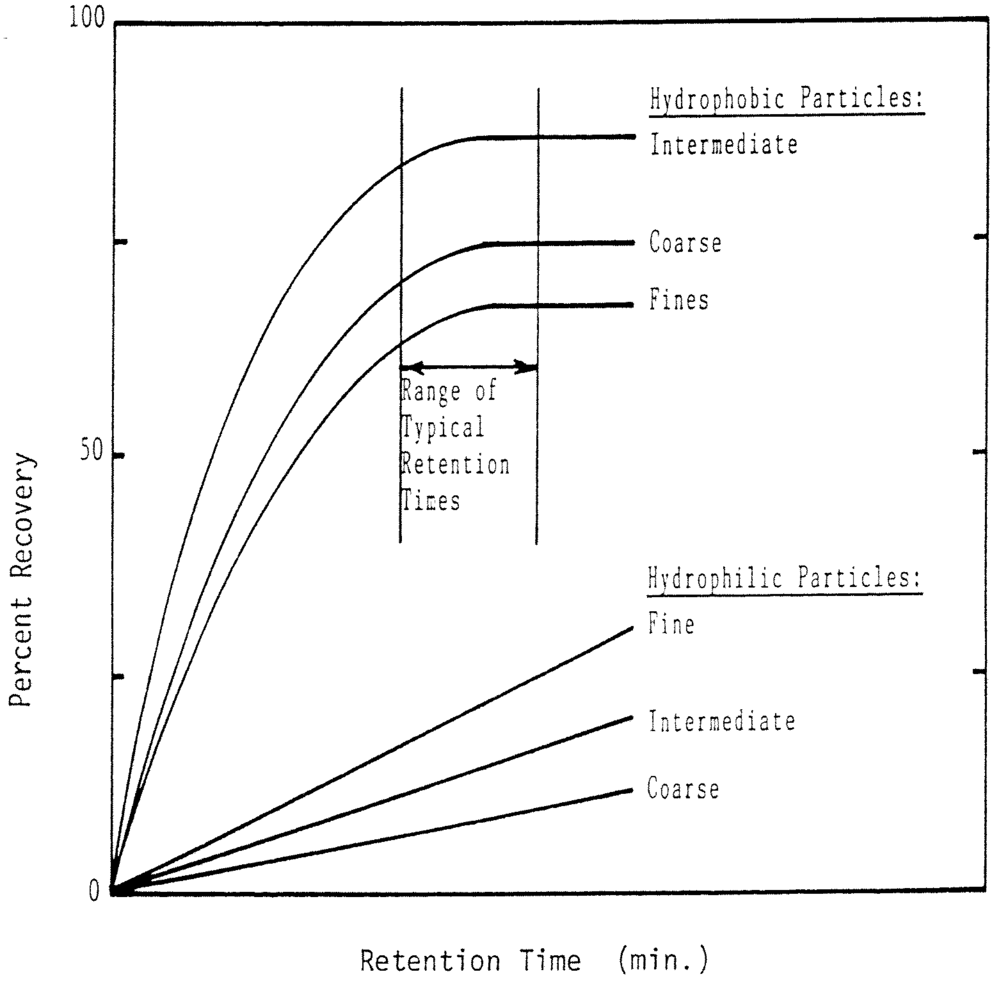


Figure 3.3. Typical Recovery – Time Profile of the Behavior of Fine, Intermediate, and Coarse Size Ranges of Hydrophobic (Coal) and Hydrophilic (Gangue) Particles in Flotation.

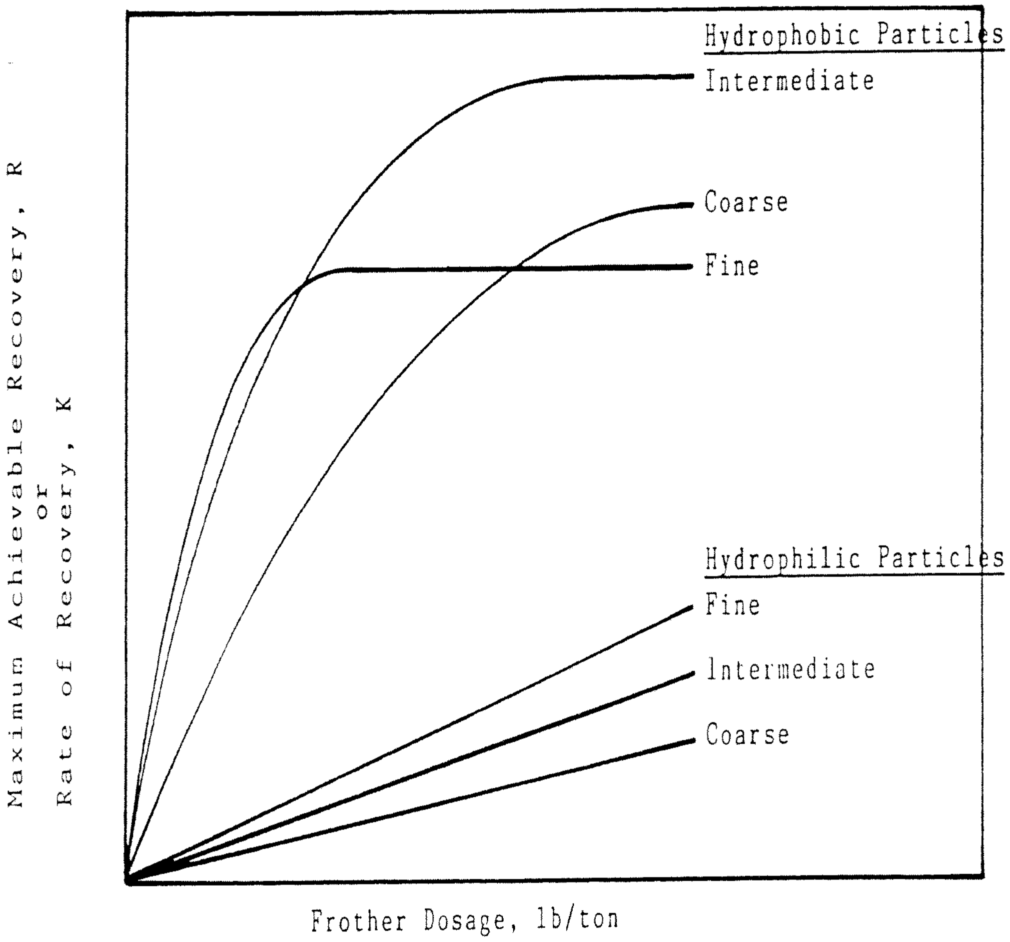


Figure 3.4. The Typical Relationship Between Frother Dosage and Maximum Achievable Recovery, R, or Rate of Recovery, K; for Fine, Intermediate, and Coarse Hydrophobic and Hydrophilic Particles in Flotation.

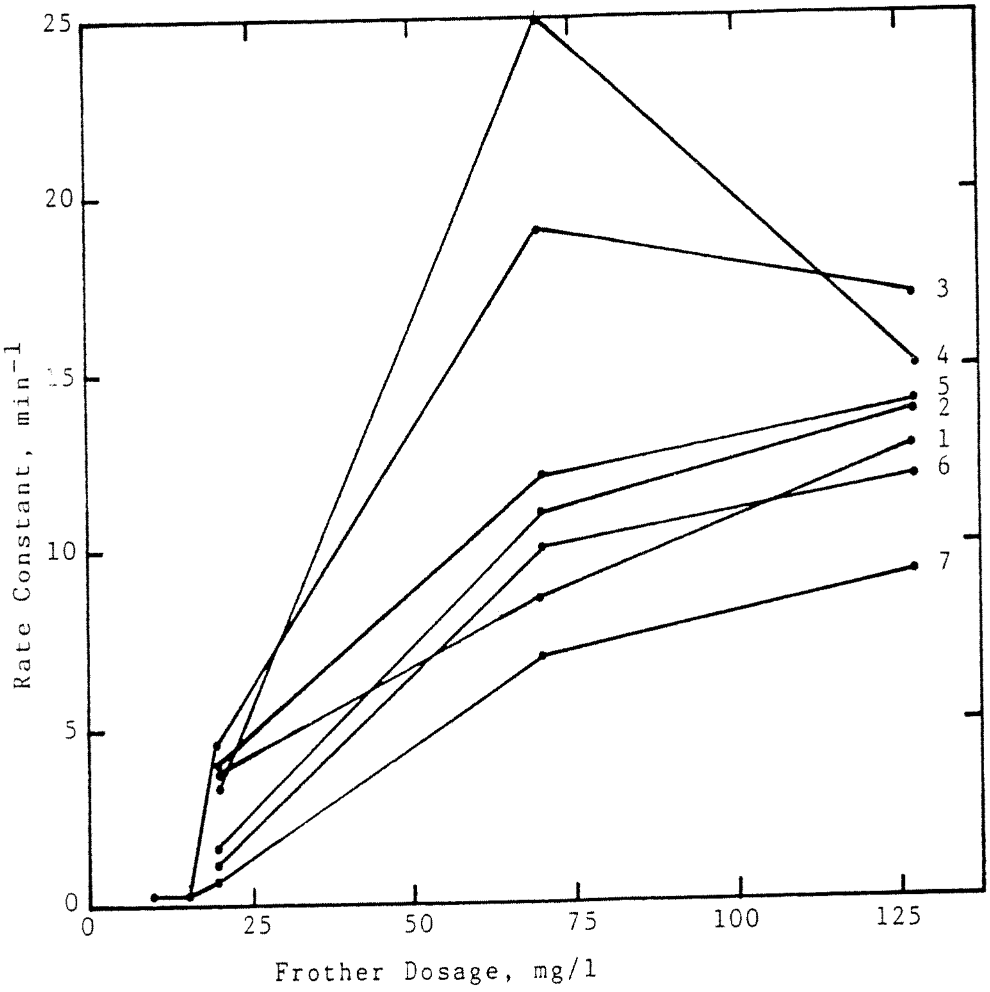


Figure 3.5. The Effect of Frother Dosage on the Rate of Recovery of Different Size Fractions of a 92.5 % Carbon Coal, Using m-Cresol as a Frother (after Safvi, 1959). 1. 33, 2. 76, 3. 105, 4. 153, 5. 211, 6. 300, and 7. 420 microns.

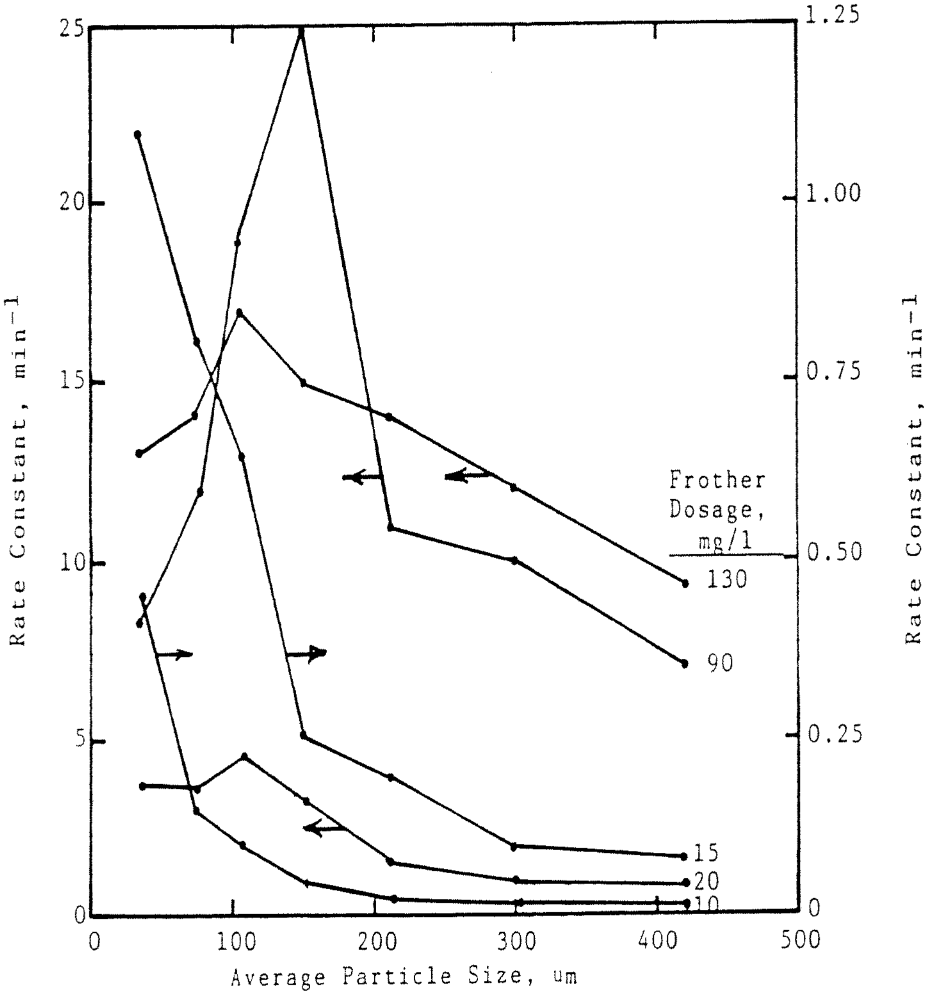


Figure 3.6. The Effect of Frother Dosage on the Rate of Recovery – Size Behavior of a 92.5 % Carbon Coal Using m-Cresol as a Frother (after Safvi, 1959).

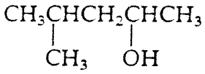
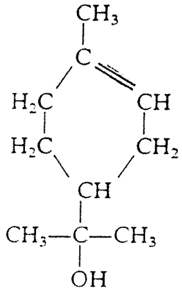
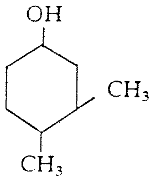
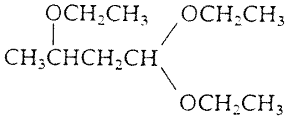
Type	Formula	Water solubility
Aliphatic Alcohols R = Alkyl with 5 to 8 carbon atoms	R—OH	Slight
MIBC	 $CH_3\underset{\underset{CH_3}{\vert}}{C}HCH_2\underset{\underset{OH}{\vert}}{C}HCH_3$	
Pine oils Terpineols		Slight
Cresylic acid		Slight
Alkoxyparaffins 1,1,3-triethoxybutane		Slight
Polyglycolethers Dowfroth Aerofroth	$R(OR')_xOH$	Miscible at low x to partial solubility at higher x

Table 3.3. Typical Compounds Used as Frothers in Flotation.