COAL SURFACE CONTROL FOR ADVANCED FINE COAL FLOTATION

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Quarterly Report No. 11
April 1 through June 30, 1991

Prepared By

University of California, Berkeley
Columbia University
University of Utah
Praxis Engineers, Inc.

Prepared For

U.S. Department of Energy
Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania

July 30, 1991

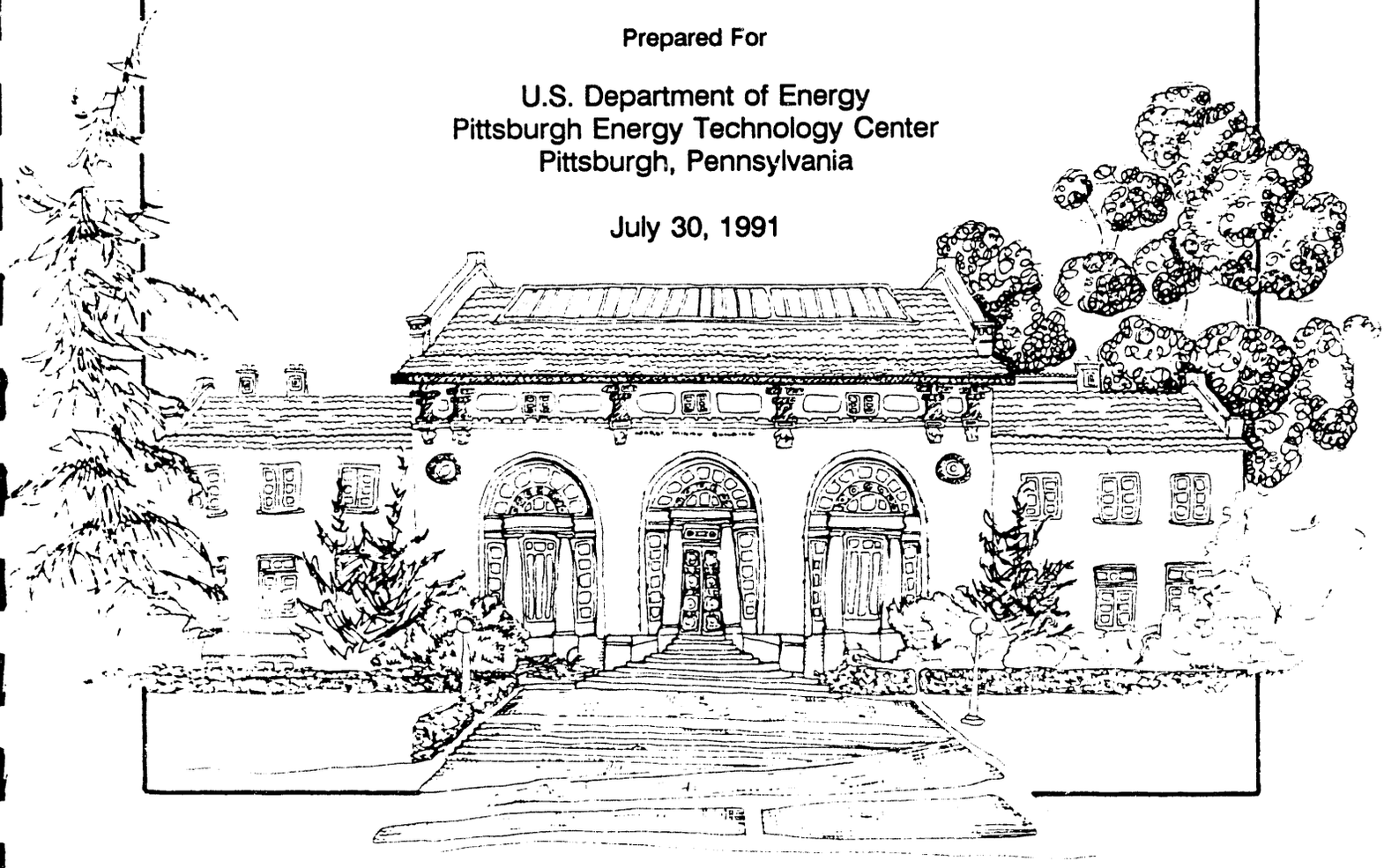

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TABLE OF CONTENTS

1.0 INTRODUCTION 1

1.1 Scope of this document 3

1.2 Overall Project Scope and Objectives 3

2.0 pH EFFECT ON COAL FLOTATION 5

2.1 Electrokinetics 5

2.2 Flotation tests 10

3.0 SURFACE MODIFICATION 13

3.1 Pyrite Depression 13

3.2 Reverse Flotation with Xanthate and Aerofloat 25 Promoter 21

3.3 Enhancement of Coal Hydrophobicity 26

4.0 COLUMN FLOTATION 33

5.0 FLOTATION KINETICS 36

5.1 Flotation Kinetics of 200-mesh Ground Coal 36

5.2 Effect of particle topsize of the feed on separation efficiency and flotation kinetics. 44

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LIST OF FIGURES

Figure 1.1 - Project organizational chart 2

Figure 2.1 - Zeta potential versus pH curve for i) coal sample prepared under non-precipitation conditions (sodium hydroxide addition in the mill) and aged for different time intervals and ii) coal sample prepared under precipitation conditions (sodium hydroxide addition in the cell). 6

Figure 2.2 - Zeta potential versus pH curve for i) coal sample prepared under non-precipitation conditions (sodium hydroxide addition in the mill), ii) coal sample prepared under precipitation conditions (sodium hydroxide addition in the cell), and iii) precipitate formed from the supernatant of the coal slurry. 7

Figure 2.3 - Effect of pH on the concentration of dissolved inorganic species - supernatant of Pittsburgh No. 8 coal slurry prepared by grinding coal at natural pH. 8

Figure 2.4 - Zeta potential versus pH curve for precipitates from i) coal slurry supernatant, ii) solution prepared using synthetic mixture of pure salts of different cationic species, and iii) $FeCl_2$ solution and iv) $MgCl_2$ solution. . . . 9

Figure 2.5 - Effects of washing and the presence of inorganic species on selectivity achieved during flotation of wet-ground 200 mesh Pittsburgh No. 8 coal. . . 11

Figure 2.6 - Effect of washing on coal-pyrite zeta potential. 11

Figure 3.1 - Flowsheet of the experiment. 14

Figure 3.2 - Effect of grinding with GMTG on combustible matter recovery and ash and pyritic sulfur rejection in the flotation of Illinois No. 6 coal. 16

Figure 3.3 - Effect of grinding with GMTG on combustible matter recovery and ash and pyritic sulfur rejection in the flotation of Pittsburgh No. 8 coal. 17

Figure 3.4 - Effect of grinding with GMTG on combustible matter recovery and ash and pyritic sulfur rejection in the flotation of Upper Freeport PA coal. 18

Figure 3.5 - Comparison of the effect of ethylene glycol (EG) and polyethylene glycol 200 (PEG-200) on the flotation of wet-ground minus 200 mesh Upper Freeport PA coal. 27

Figure 3.6 - Comparison of the effect of ethylene glycol and polyethylene glycol 200 (PEG-200) on the flotation of wet-ground minus 200 mesh Upper Freeport PA coal. 29

Figure 3.7 - Effect of pentylether on the flotation separation efficiency of wet-ground minus 200-mesh Upper Freeport PA coal. 30

Figure 3.8 - Comparison of the effect of dipentyamine (DPA) and butylamine (BA) on the flotation of wet-ground minus 200-mesh Upper Freeport PA coal. 32

Figure 3.9 - Effect of pentylether (PE), dipentylamine (DPA) and butylamine (BA) on the flotation of wet-ground minus 200-mesh Upper Freeport PA coal. 32

Figure 4.1 - Effect of bubble size on the rejection of pyrite from Pittsburgh No. 8 coal. . 34

Figure 4.2 - Effect of bubble size on the rejection of non-pyritic minerals from Pittsburgh No. 8 coal. 34

Figure 4.3 - Effect of wash water on the rejection of pyrite from Pittsburgh No. 8 coal - tests with coarse frit. 35

Figure 4.4 - Effect of wash water on the rejection of pyrite from Pittsburgh No. 8 coal - tests with medium frit. 35

Figure 5.1 - The combustible material recovery of plus 400 and minus 400-mesh size fractions of minus 200-mesh Illinois No. 6 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics. 41

Figure 5.2 - The combustible material recovery of plus 400 and minus 400-mesh size fractions of minus 200-mesh Pittsburgh No. 8 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics. 41

Figure 5.3 - The combustible material recovery of plus 400 and minus 400-mesh size fractions of minus 200-mesh Upper Freeport PA coal as a function of flotation time along with the fitting curves of the classical first-order kinetics. 42

Figure 5.4 - Flotation recoveries of combustible materials, ash and pyritic sulfur of minus 200-mesh Illinois No. 6 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics. 43

Figure 5.5 - Flotation recoveries of combustible materials, ash and pyritic sulfur of minus 200-mesh Pittsburgh No. 8 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics. 43

Figure 5.6 - Flotation recoveries of combustible materials, ash and pyritic sulfur of minus 200-mesh Upper Freeport PA coal as a function of flotation time along with the fitting curves of the classical first-order kinetics. 44

Figure 5.7 - The combustible material recovery of 28-, 100- and 200-mesh Illinois No. 6 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics. 47

Figure 5.8 - The combustible material recovery of 28-, 100- and 200-mesh Pittsburgh No. 8 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics. 47

Figure 5.9 - The combustible material recovery of 28-, 100- and 200-mesh Upper Freeport PA coal as a function of flotation time along with the fitting curves of the classical first-order kinetics. 48

LIST OF TABLES

Table 3.1 - Collector and frother dosages for the three coals. 15

Table 3.2 - Two-stage flotation results for Illinois No. 6 coal with GMTG addition. . . . 18

Table 3.3 - Two-stage flotation results for Illinois No. 6 coal without GMTG addition. . 19

Table 3.4 - Single-stage flotation results for 200 mesh Illinois No. 6 with GMTG addition. 19

Table 3.5 - Two-stage flotation results for Pittsburgh No. 8 coal with GMTG addition. . 19

Table 3.6 - Two-stage flotation results for Pittsburgh No. 8 coal without GMTG addition. 20

Table 3.7 - Single-stage flotation results for Illinois No. 6 coal without GMTG addition. 20

Table 3.8 - Two-stage flotation results for Upper Freeport PA coal with GMTG addition. 20

Table 3.9 - Two-stage flotation results for Upper Freeport PA coal without GMTG addition. 21

Table 3.10 - Flotation of pyrite from Illinois No. 6 coal 200 mesh grind as a function of MIBC addition in the presence of 0.57 lb/Ton potassium ethyl xanthate (KEX) at pH 8 ± 0.5. 22

Table 3.11 - Flotation of pyrite from Illinois No. 6 coal 200 mesh grind as a function of MIBC addition in the presence of 0.57 lb/T potassium ethyl xanthate (KEX) at pH 4 ± 0.1. Frother conditioning time: 15 seconds. 23

Table 3.12 - Step flotation of pyrite from Illinois No. 6 coal 200 mesh grind in the presence of potassium ethyl xanthate (KEX) and MIBC at pH 4 ± 0.1. . . . 24

Table 3.13 - Step flotation results for pyrite flotation from Illinois No. 6 coal at 200 mesh grind in the presence of potassium ethyl xanthate (KEX), hydrogen peroxide (H_2O_2), and 0.78 lb/T of MIBC. 25

Table 3.14 - Step flotation results for pyrite flotation from Illinois No. 6 coal at 200 mesh grind in the presence of Aerofloat 25 Promoter, hydrogen peroxide (H_2O_2), and MIBC. 26

Table 3.15 - Flotation results of ethylene glycol (EG) for wet-ground minus 200-mesh Upper Freeport PA coal. 27

Table 3.16 - Flotation results of polyethylene glycol 200 (PEG-200) for wet-ground minus 200-mesh Upper Freeport PA coal. 28

Table 3.17 - Flotation test results with polyethylene glycol (PEG-400) on wet-ground minus 200-mesh Upper Freeport PA coal. 28

Table 3.18 - Flotation test results with polyethylene glycol (PEG-1000) on wet-ground minus 200-mesh Upper Freeport PA coal. 28

Table 3.19 - Flotation test results with polyethylene glycol (PEG-6000) on wet-ground minus 200-mesh Upper Freeport PA coal. 28

Table 3.20 - Flotation test results of pentylether for wet-ground minus 200-mesh Upper Freeport PA coal. 30

Table 3.21 - Flotation results of dipentylamine for wet-ground minus 200 mesh Upper Freeport PA coal. 31

Table 3.22 - Flotation results of butylamine for wet-ground minus 200-mesh Upper Freeport PA coal. 31

Table 5.1 - Combustible material recovery (CMR), ash and pyritic sulfur rejection, and separation efficiency of 200-mesh Illinois No. 6 coal (dodecane 4.92 lb/T and MIBC 0.98 lb/T at pH 4.0). 37

Table 5.2 - Combustible material recovery (CMR), ash and pyritic sulfur rejection, and separation efficiency of 200-mesh Pittsburgh No. 8 coal (dodecane 1.92 lb/T and MIBC 0.30 lb/T at pH 3.6). 38

Table 5.3 - Combustible material recovery (CMR), ash and pyritic sulfur rejection, and separation efficiency of 200-mesh Upper Freeport PA coal (dodecane 0.24 lb/T and MIBC 0.26 lb/T at pH 3.4). 38

Table 5.4 - Yield, ash, total sulfur and pyritic sulfur content of different size fractions of 200-mesh Illinois No. 6, Pittsburgh No. 8 and Upper Freeport PA coals. . . 39

Table 5.5 - Combustible material recovery (CMR), ash and pyritic sulfur rejection, and separation efficiency of Illinois No. 6 coal for different grind sizes (dodecane 4.92 lb/T and MIBC 0.98 lb/T at pH about 4.5). 45

Table 5.6 - Combustible material recovery (CMR), ash and pyritic sulfur rejection, and separation efficiency of Pittsburgh No. 8 coal for different grind sizes (dodecane 1.92 lb/T and MIBC 0.30 lb/T at pH about 3.4). 45

Table 5.7 - Combustible material recovery (CMR), ash and pyritic sulfur rejection, and separation efficiency of Upper Freeport PA coal for different grind sizes (dodecane 0.24 lb/T and MIBC 0.26 lb/T at pH about 3.4). 46

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1.0 INTRODUCTION

Historically, coal surface characterization and control have not been considered critical to coal cleaning because of prior emphasis on maintaining particle size as coarse as possible. However, the current goal of near-total removal of pyritic sulfur necessitates fine grinding of coal to liberate pyrite. At these fine sizes coal surface behavior plays an increasingly dominant role and consequently the need for surface characterization and control is critical.

In order to investigate the properties of coal surfaces and their role in coal flotation, DOE awarded a contract entitled "Coal Surface Control for Advanced Fine Coal Flotation" to the University of California at Berkeley in October 1988. The main goal of the project is to characterize the surface and control the behavior of coal during advanced flotation processing in order to achieve an overall objective of near-total pyritic sulfur removal with a high Btu recovery. Also, investigation of the effects of weathering on the surface characteristics of coal is another important aspect of this project. This information will serve to support the engineering development of advanced flotation technology conducted by ICF Kaiser Engineers, Inc. as part of DOE PETC's Acid Rain Control Initiative.

The project team consists of research and engineering groups at Berkeley, Columbia University, the University of Utah and Praxis Engineers, Inc., with the University of California acting as the prime contractor. The organizational chart for this project is presented in Figure 1.1, which also identifies key project personnel.

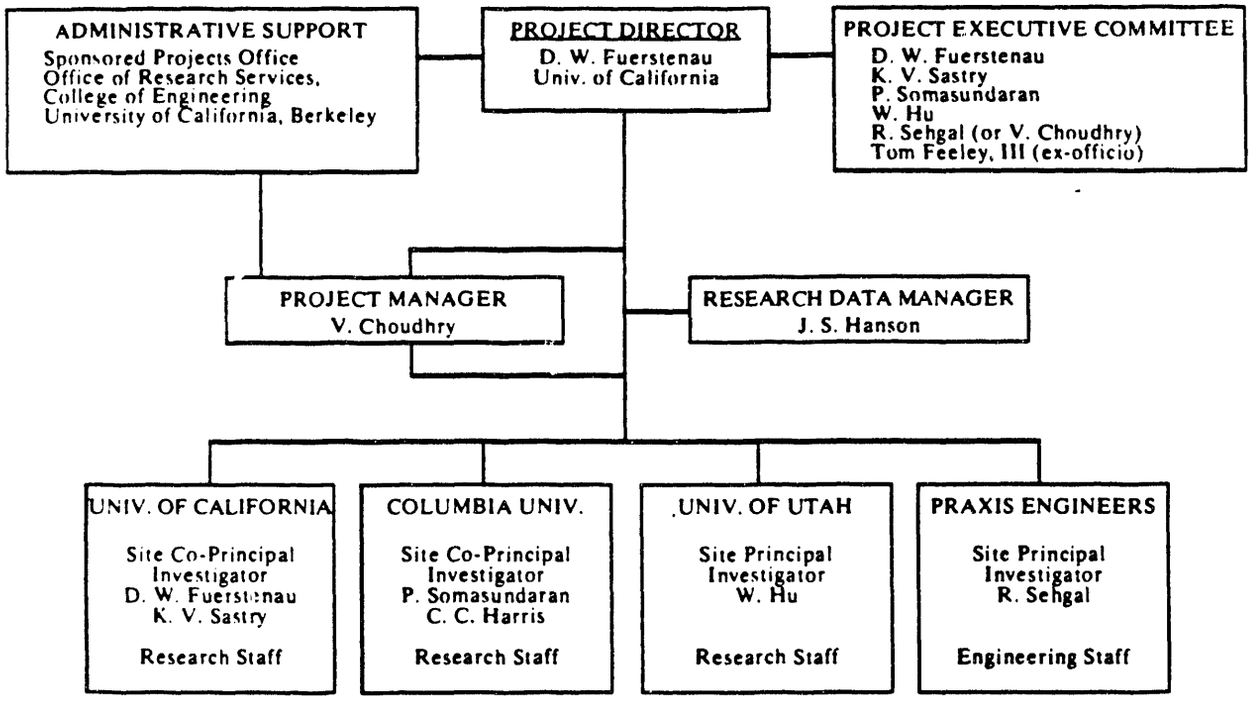

Figure 1.1 - Project organizational chart

1.1 Scope of this document

This document is the eleventh quarterly report prepared in accordance with the project reporting requirements covering the performance period from April 1, 1991 to June 30, 1991. This report presents the results of the technical work undertaken as part of this project by the University of California at Berkeley, Columbia University, the University of Utah and Praxis Engineers, Inc. during this period. The results of work conducted during this period are compiled together based on research topic rather than by location and reported here.

1.2 Overall Project Scope and Objectives

The primary objective in the scope of this research project is to develop advanced flotation methods for coal cleaning in order to achieve near total pyritic-sulfur removal at 90% Btu recovery, using coal samples procured from three major U.S. coal seams. Concomitantly, the ash content of these coals is to be reduced to 6% or less. Investigation of mechanisms for the control of coal and pyrite surfaces prior to fine coal flotation is the main aspect of the project objectives. The results of this research are to be made available to ICF Kaiser Engineers who are currently working on the Engineering Development of Advanced Flotation under a separate contract with DOE under the Acid Rain Control Initiative program.

As a part of this contract, large quantities of coal samples were procured from six major seams identified by DOE for use in this project for advanced flotation and weathering studies. Samples of the same coals have also been supplied to the University of Pittsburgh for selective agglomeration coal surface control research under a separate contract by DOE. In addition, coal samples of the three base coals were supplied to ICF Kaiser Engineers and Southern Company Services for bench-scale test work on their project. Coal samples were also supplied to a number of other organizations for research on DOE funded projects. Collection and preparation of a large sample for distribution for research projects served the purpose of providing uniform and

identical samples. This will make comparative evaluation of the results of various processes being funded by DOE relatively easy.

A second major objective is to investigate factors involved in the progressive weathering and oxidation of coal that had been exposed to varying degress of weathering, namely, open to the atmosphere, covered and in an "argon-inerted" atmosphere, over a period of twelve months. After regular intervals of weathering, samples of the three base coals (Illinois No. 6, Pittsburgh No. 8 and Upper Freeport PA) were collected and shipped to both the University of Pittsburgh and the University of California at Berkeley for characterization studies of the weathered material.

2.0 pH EFFECT ON COAL FLOTATION

The role of pH on the flotation behavior of Pittsburgh No. 8 coal has been studied extensively. During the initial research effort, it was found that at mildly basic pH's (pH ≈ 8) the efficiency of coal flotation increased slightly. This was observed for Pittsbugh No. 8 coal but not for the other two base coals. More electrokinetics and flotation tests were completed during this past quarter to further delineate the role of pH in coal flotation.

2.1 Electrokinetics

The measurements of the zeta potential of Pittsburgh No. 8 coal were continued and metal-hydroxide precipitates were contined during this reporting period in order to determine the mechanism by which pH influences the flotation of coal from pyrite. Experimental results reported previously showed that, in the pH range of 5 to 10, the zeta potential of coal samples prepared under precipitation conditions (sodium hydroxide added to the grinding mill) was less negative compared to that of the sample prepared under non-precipitation conditions (sodium hydroxide addition to the flotation cell). This effect may be attributed to: i) differences in the ionic strength of the medium, ii) differences in aging time*, and/or iii) precipitation of metal-hydroxide complexes on the coal surface (in the case of samples prepared under precipitation conditions).

Conductivity measurements of the supernatants of the slurries prepared under the two conditions showed that the ionic strengths were different. Therefore, zeta potential values were recomputed for a constant ionic strength value of 0.03 M (based on a monovalent salt such as KNO_3 or NaCl) and the results obtained are shown in Figure 2.1. It can be seen from this figure that the zeta potentials of the coal sample prepared under precipitation conditions are less negative than those of samples prepared under the non-precipitation conditions, indicating that

* Aging time for the coal sample prepared under non-precipitation conditions (addition of sodium hydroxide in the mill) was about two hours more than that for the sample prepared under precipitation conditions (sodium hydroxide addition in the cell).

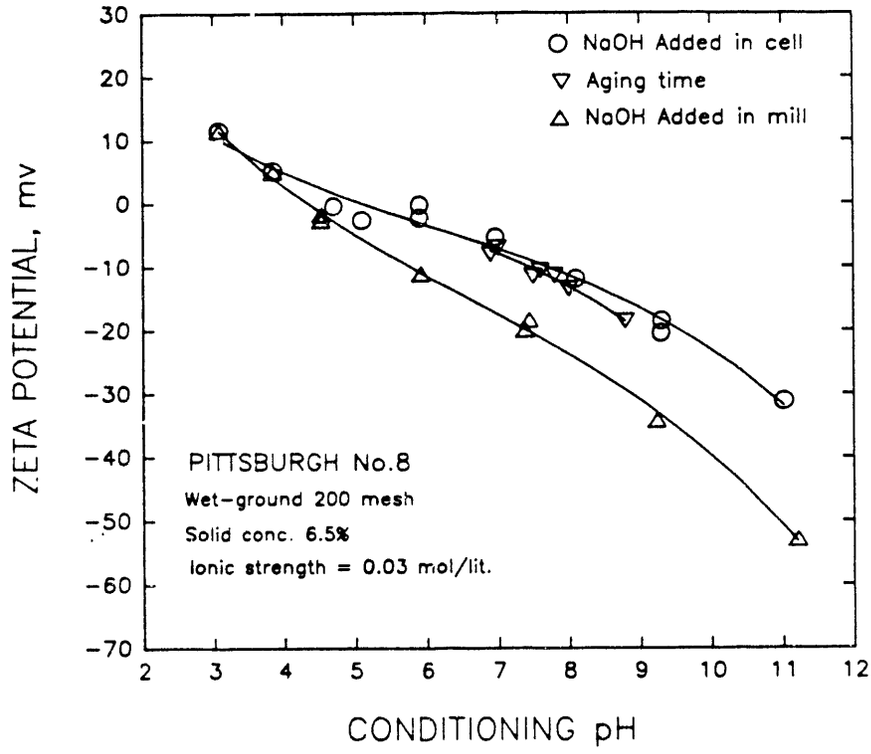

Figure 2.1 - Zeta potential versus pH curve for i) coal sample prepared under non-precipitation conditions (sodium hydroxide addition in the mill) and aged for different time intervals and ii) coal sample prepared under precipitation conditions (sodium hydroxide addition in the cell).

the observed difference in the ionic strengths cannot account for the difference in the magnitude of the zeta potentials.

To determine whether or not the shorter aging time was responsible for the difference in the zeta potentials of the coal samples, zeta potential measurements were made with samples that had been aged for different periods of time. Longer aging times resulted in lower pH's. The results, also presented in Figure 2.1, indicate that the zeta potential values are identical to those obtained for coal ground without pH modification. This suggests that aging time is not the reason for the less negative value obtained for the zeta potential of coal samples prepared under precipitation conditions compared to those prepared under non-precipitation conditions.

To determine the role of metal-hydroxide precipitates, the zeta potential behavior of precipitates formed by changing the pH of the supernatant of the coal slurry ground at natural

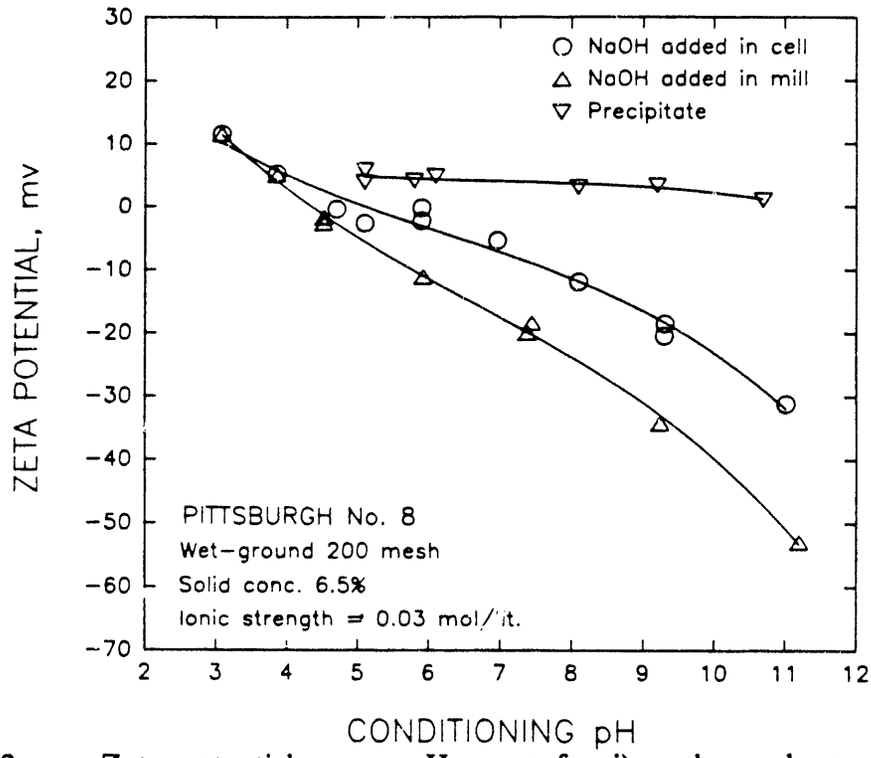

Figure 2.2 - Zeta potential versus pH curve for i) coal sample prepared under non-precipitation conditions (sodium hydroxide addition in the mill), ii) coal sample prepared under precipitation conditions (sodium hydroxide addition in the cell), and iii) precipitate formed from the supernatant of the coal slurry.

pH (~ 4), was studied. In Figure 2.2, the zeta potential curve of the precipitate is compared to those of the coal samples prepared under precipitation conditions and non-precipitation conditions. It can be seen that the zeta potential of the precipitate is slightly positive; if this positively charged precipitate coats the surface of coal it should reduce the magnitude of the negative zeta potential of coal. It appears, thus, that the precipitation of metal-hydroxide complexes on the coal surface is the most likely reason for the less negative zeta potential obtained for the coal prepared under precipitation conditions as compared to that prepared under non-precipitation conditions. This inference is also supported by the observed reduction in the floatability of coal under precipitation conditions (refer to Annual Report No. 2) as precipitation of metal-hydroxides on coal will render its surface hydrophilic.

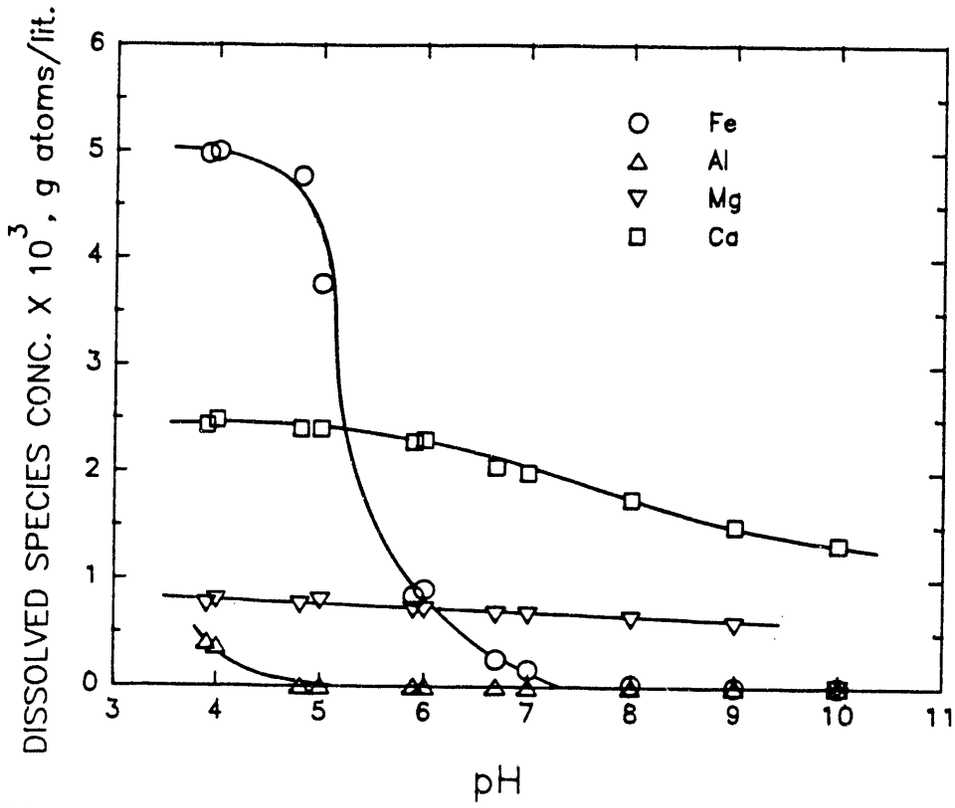

Figure 2.3 - Effect of pH on the concentration of dissolved inorganic species - supernatant of Pittsburgh No. 8 coal slurry prepared by grinding coal at natural pH.

An interesting observation that can be made from our results is that the zeta potential of the precipitates does not vary with pH. This is unusual since OH^- is a potential-determining ion for metal-hydroxides. One possible reason for the observed zeta potential behavior of the precipitates is the presence of four different species, namely Fe, Ca, Mg and Al, in the supernatant of the coal slurry (Figure 2.3). The precipitate formed from a solution consisting of different multivalent ions can have different characteristics from those formed from solutions containing only one type of ion since ionic composition of the medium will vary with pH due to differences in solubilities of various ions (as can be seen from the slope of the concentration curves in Figure 2.3). Thus the precipitate formed at different pH's can have different compositions.

To test the above two hypotheses, the zeta potential of precipitates formed from solutions of pure salts ($FeCl_2$ and $MgCl_2$) were compared with those formed from mixtures of salts of the

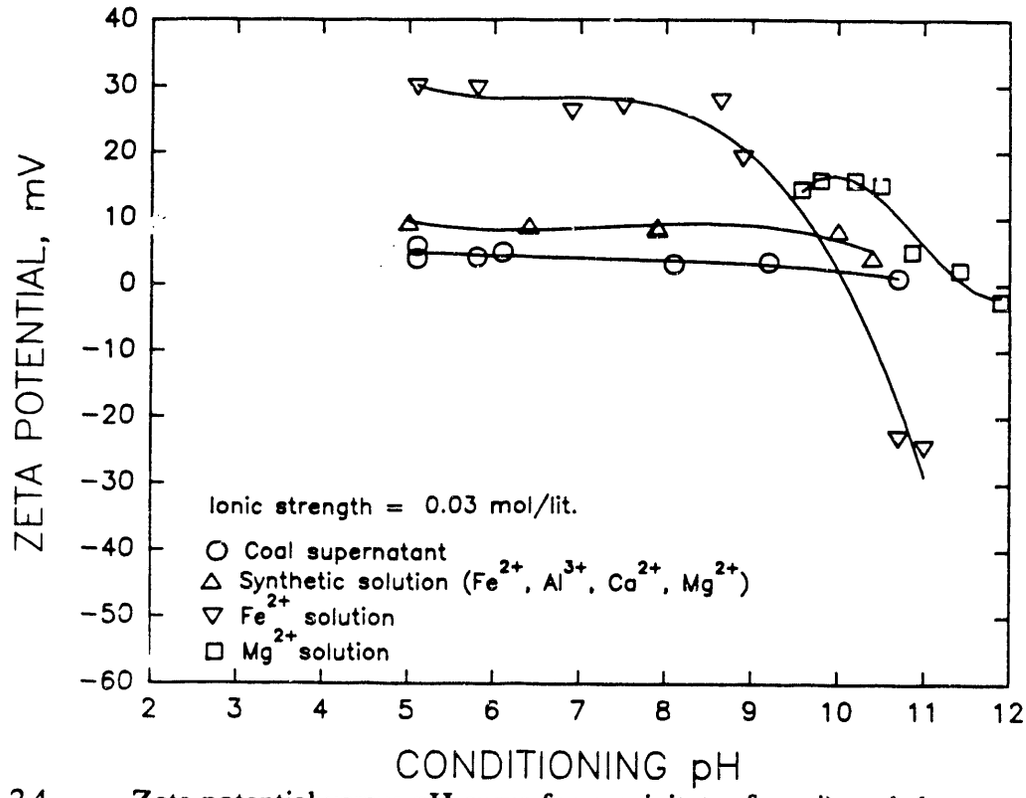

Figure 2.4 - Zeta potential versus pH curve for precipitates from i) coal slurry supernatant, ii) solution prepared using synthetic mixture of pure salts of different cationic species, and iii) $FeCl_2$ solution and iv) $MgCl_2$ solution.

four cationic species identified in the supernatant of the coal slurry* in Figure 2.4. It can be seen from these results that the zeta potential of precipitates formed from solutions containing only one salt does vary with pH, while that of the precipitate prepared from solutions containing all four salts does not vary with pH. The precipitate formed from the coal slurry supernatant alsodoes not show pH dependence. It can also be seen from Figure 2.4 that the magnitude of the zeta potential of the precipitate formed from solution of synthetic salt mixtures is about the same as that of the precipitate formed from the coal slurry supernatant.

Results of zeta potential measurements carried out during the current reporting period have shown that metal-hydroxide precipitates do coat the surface of coal and the composition of the precipitates probably varies with pH.

* The concentration of the different cationic species (Ca, Mg, Fe and Al), prepared from synthetic mixtures of pure salts, was maintained at the same value as in the supernatant of the coal slurry.

2.2 Flotation tests

Experiments carried out with 200 mesh wet-ground Pittsburgh No. 8 coal showed that the addition of sodium hydroxide to the flotation cell depressed the flotabilities of coal and pyrite. However, pyrite was relatively more depressed and this resulted in improved selectivity with sodium hydroxide addition (or increasing pH). Dissolved inorganic species analysis and zeta potential measurements carried out under flotation conditions indicated that the depression in flotabilities of coal and pyrite is due to the precipitation of metal hydroxide complexes on the surface. However, experiments carried out under the non-precipitation conditions (sodium hydroxide added to the mill) indicated that precipitation of metal hydroxide complexes is in fact non-selective and does not contribute to the improvement in selectivity resulting from increasing the pH.

In order to isolate the effect of pH from that of dissolved inorganic species, the coal sample was washed several times with distilled water to remove all the soluble species (until the supernatant showed no measurable level of inorganic species) and flotation tests were conducted with the washed coal. Flotation test results obtained with washed coal were compared with those obtained with unwashed coal in Figure 2.5. It can be seen from this figure that in the case of the unwashed coal, the increase of pH results in improved selectivity, whereas there is no effect of pH in the case of washed coal.

There are two possible reasons for the observed difference in the results obtained with washed and unwashed coals: i) there are no inorganic species present in the supernatant of washed coal and ii) the surface of pyrite may have changed due to washing. To test the first possibility, tests were conducted in which the flotation of washed coal was carried out in the supernatant of unwashed coal which contained inorganic species. The results of these tests are also shown in Figure 2.5 and show that pH had no effect on selectivity. Thus, it appears that only the surface of unwashed pyrite, and not washed pyrite, changes with pH and that the modified surface is relatively hydrophilic.

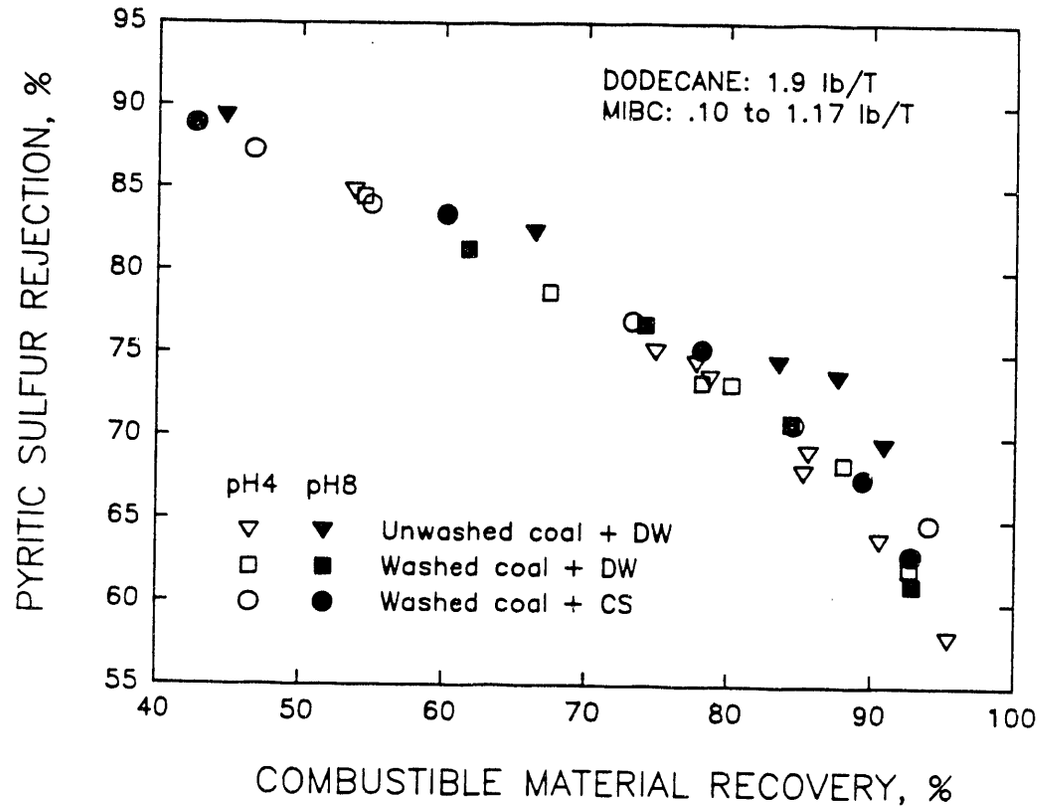

Figure 2.5 - Effects of washing and the presence of inorganic species on selectivity achieved during flotation of wet-ground 200 mesh Pittsburgh No. 8 coal.

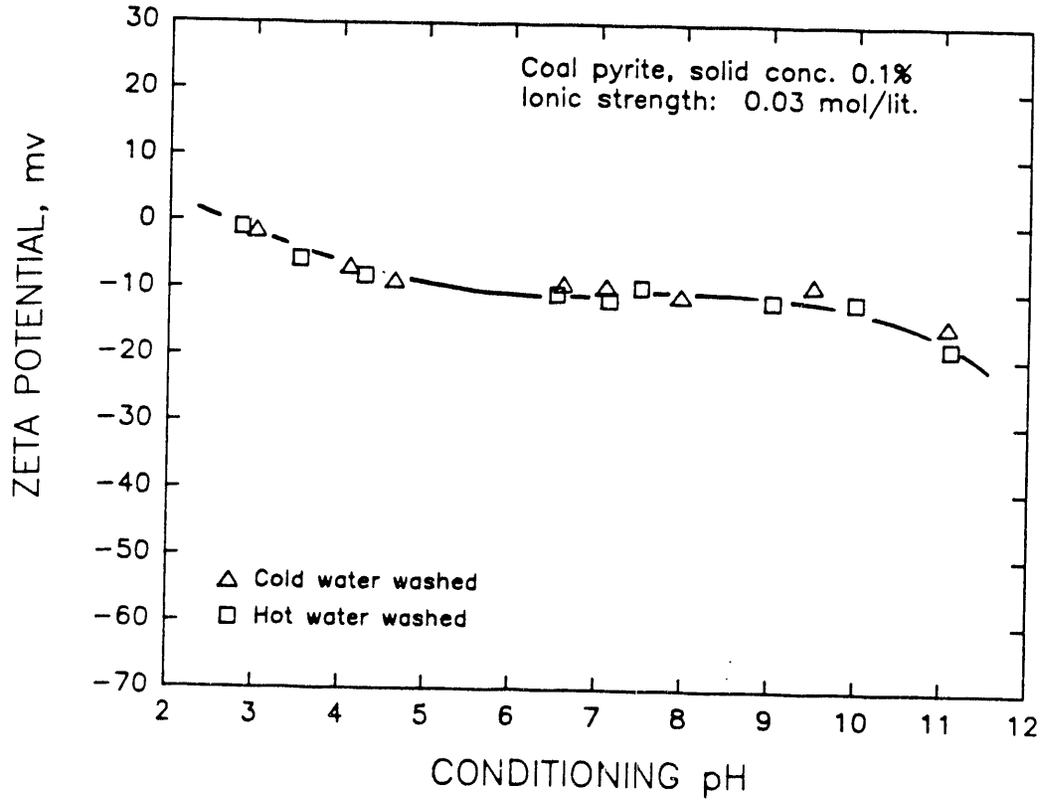

Figure 2.6 - Effect of washing on coal-pyrite zeta potential.

The flotation results discussed above indicated that the surface of unwashed pyrite does not undergo any change with pH in the range of 4 to 8. To test this hypothesis, zeta potential measurements were carried out using Pocohontas No. 3 coal pyrite which was washed with both cold and hot water. It can be seen from the results shown in Figure 2.6 that there is no significant change in the zeta potential of pyrite in the range of pH 4 to 8 suggesting that the surface of washed pyrite indeed does not undergo any noticeable change with pH increase.

3.0 SURFACE MODIFICATION

Surface modification to improve the flotation efficiency of coal can be accomplished by the addition of various types of reagents. The two basic approaches used in this program have been the enhancement of coal hydrophobiciby and the enhancement of pyrite hydrophilicity. Reverse flotation, depression of coal followed by pyrite flotation through surface modification, has also been investigated as part of this research effort.

3.1 Pyrite Depression

The flotation of pyrite, iron disulfide, commonly associated other base metal sulfides, is avoided in mineral processing plants most commonly by simply controlling the pulp pH. This prevents the formation of a hydrophobic surface on the pyrite when thiol-based collectors are added to the system. However, in coal flotation a high pH (>10) also results in low Btu recovery. Therefore, a reagent that adsorbs specifically on the pyrite surface and is hydrophilic should make an ideal pyrite depressant. This section discusses one attempt at decreasing the pyritic sulfur content of clean coal by the addition of one such reagent.

Haliimond tube flotation tests on pyrite have indicated that glycerol monothioglycolate (GMTG) could be an effective depressant for pyrite. However, when 1.0 lb/T of mono-thioglycolate was used for pyrite depression during flotation of the three coals at the 200-mesh grind, there was virtually no improvement in pyrite rejection. The apparent inability of GMTG to depress pyrite during coal flotation might be attributed to the consumption of the depressant by dissolved iron in the pulp due to high concentrations of iron which have been measured in the pulp after wet grinding the three coals to 200 mesh. To offset the possible consumption of GMTG by dissolved iron, which would render GMTG non-effective, a set of experiments involving two-stage grinding and flotation, with GMTG added during the grinding stage, was planned. The flowsheet of the experiment in shown in Figure 3.1 where the dashed lines indicate optional steps. Since the pH of the three coals are currently around 3.5, it was expected that a

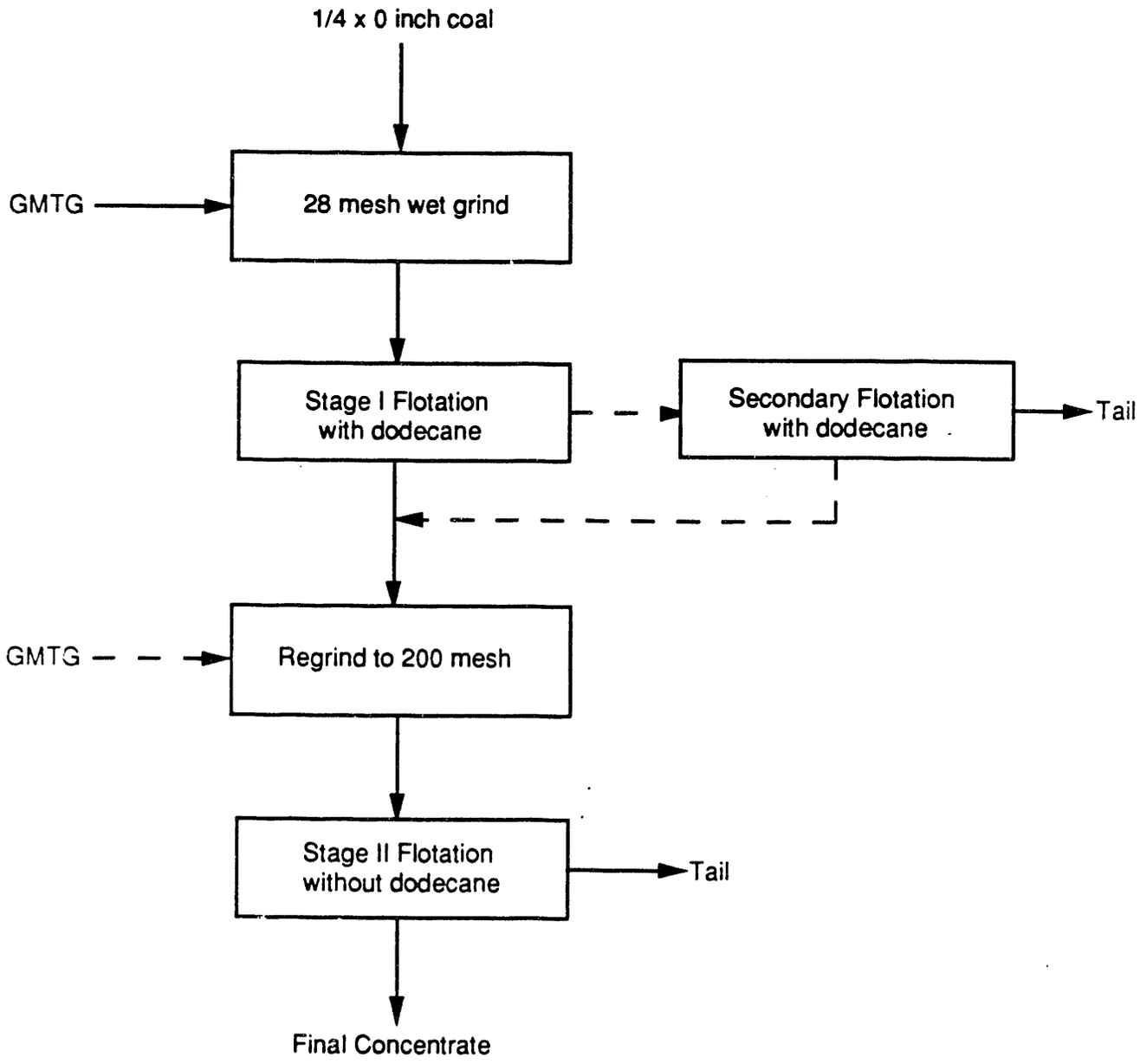

Figure 3.1-Flowsheet of the experiment.

first-stage grind to 28 mesh would minimize the amount of dissolved iron in the pulp. The addition of GMTG to the grinding stage should further facilitate GMTG - pyrite interaction. The concentrate from the flotation of 28 mesh coal was reground to minus 200 mesh and refloated. The standard dosage of collector was added only to the first stage of flotation while frother was added to both flotation stages. The flotation time in the first stage was two minutes for all three

Table 3.1 - Collector and frother dosages for the three coals.

	ILLINOIS NO. 6		PITTSBURGH NO. 8		UPPER FREEPORT PA	
	Collector	Frother	Collector	Frother	Collector	Frother
Stage	lb/T	lb/T	lb/T	lb/T	lb/T	lb/T
First	5.76	1.17	1.92	0.30	0.24	0.26
Second	1.17	0.30	0.26			

coals. An additional base-line flotation test was carried out with Illinois No. 6 coal ground to minus 200 mesh in one step with 1.0 lb/T GMTG. Table 3.1 gives the collector and frother dosages used for flotation of the three coals.

The flotation results are presented in Tables 3.2 to 3.9. For both Illinois No. 6 and Pittsburgh No. 8 coals, the addition of GMTG to the grinding stage gives about a five-percent increase in pyritic sulfur rejection for the same combustible material recovery. On the other hand, the addition of GMTG does not affect the flotation kinetics or combustible material recovery of Upper Freeport PA coal. In the case of Upper Freeport PA coal, the addition of GMTG apparently results in slightly lower combustible material recovery in both stages.

Figure 3.2 shows the effect of addition of GMTG to the grinding stage on pyritic sulfur and ash rejection for Illinois No. 6 coal for both single stage and two stage grinding. It is apparent from the results given in this figure that the increase in pyritic sulfur rejection due to addition of GMTG is similar for both the single and two-stage grinding. The two-stage process, however, results in a significant improvement in pyritic sulfur and ash rejection characteristics. The second stage is essentially a cleaning step. GMTG has virtually no effect on ash rejection.

Pyritic sulfur and ash rejection as a function of the combustible material recovery of Pittsburgh No. 8 coal for the two-stage process is given in Figure 3.3. Figure 3.4 presents the pyritic sulfur rejection characteristics of Upper Freeport PA coal. From these figures it appears that the effect of GMTG on pyritic sulfur rejection for Upper Freeport coal is at best marginal. This could be due to already high selectivity of the coal.

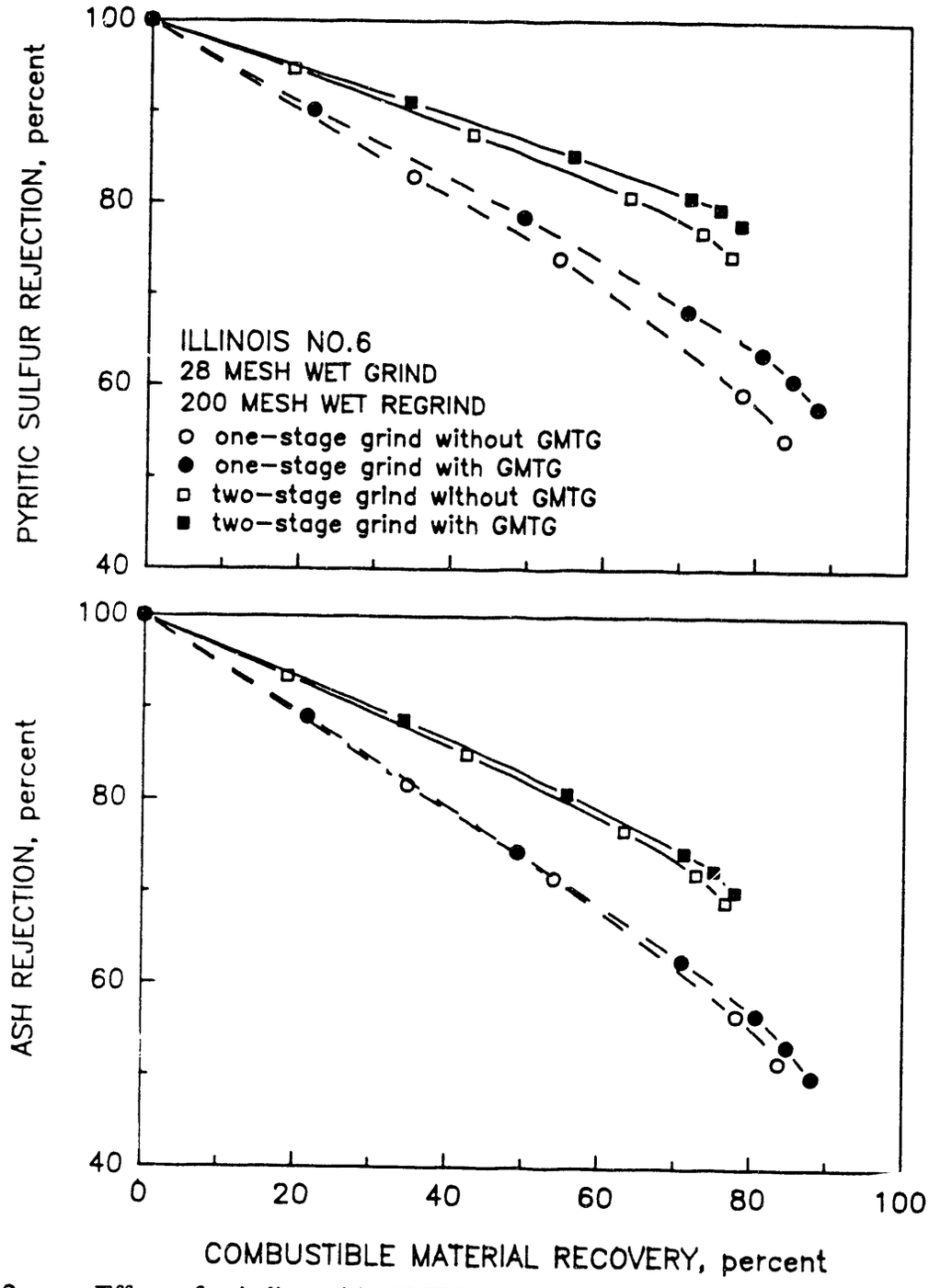

Figure 3.2 - Effect of grinding with GMTG on combustible matter recovery and ash and pyritic sulfur rejection in the flotation of Illinois No. 6 coal.

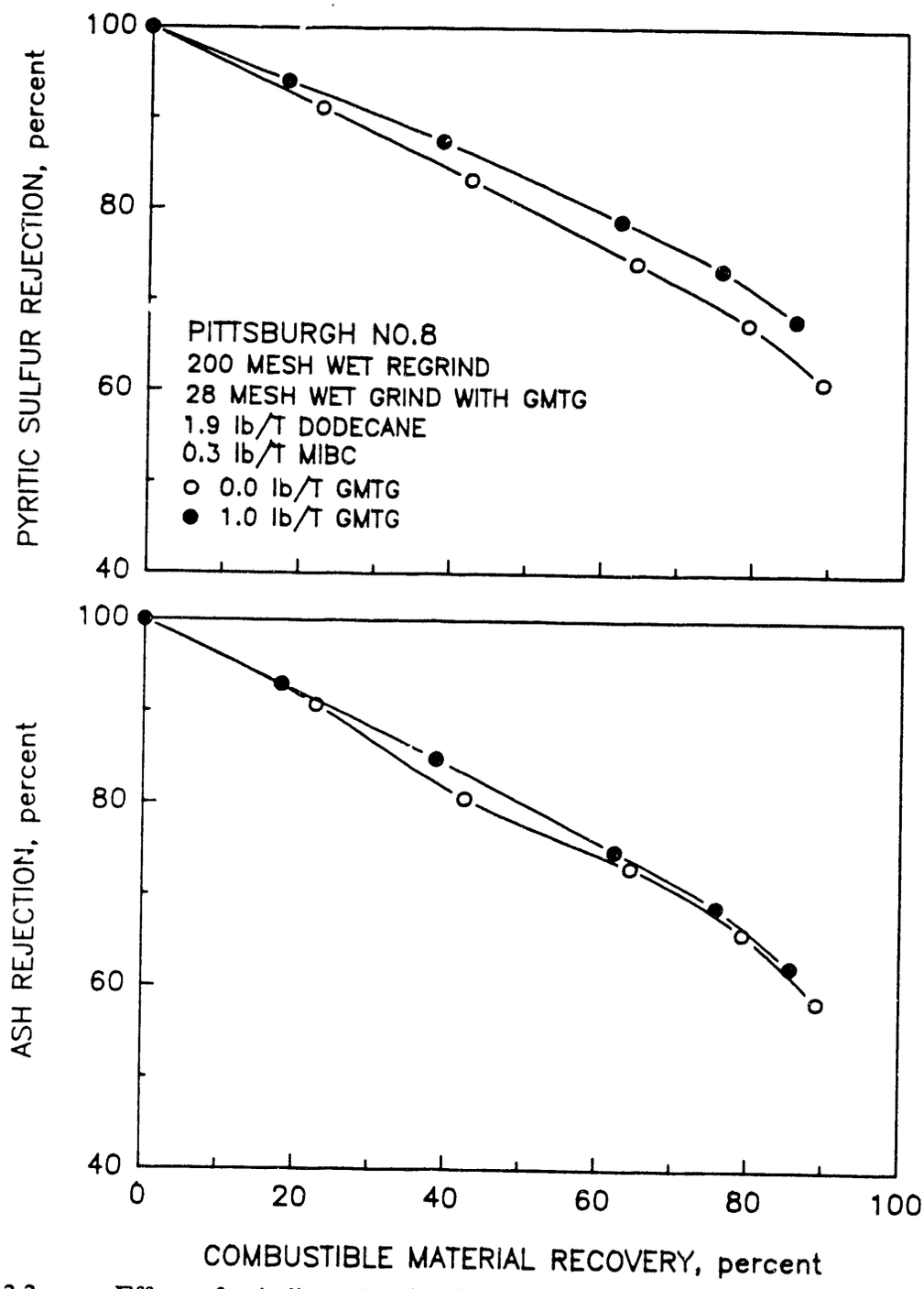

Figure 3.3 - Effect of grinding with GMTG on combustible matter recovery and ash and pyritic sulfur rejection in the flotation of Pittsburgh No. 8 coal.

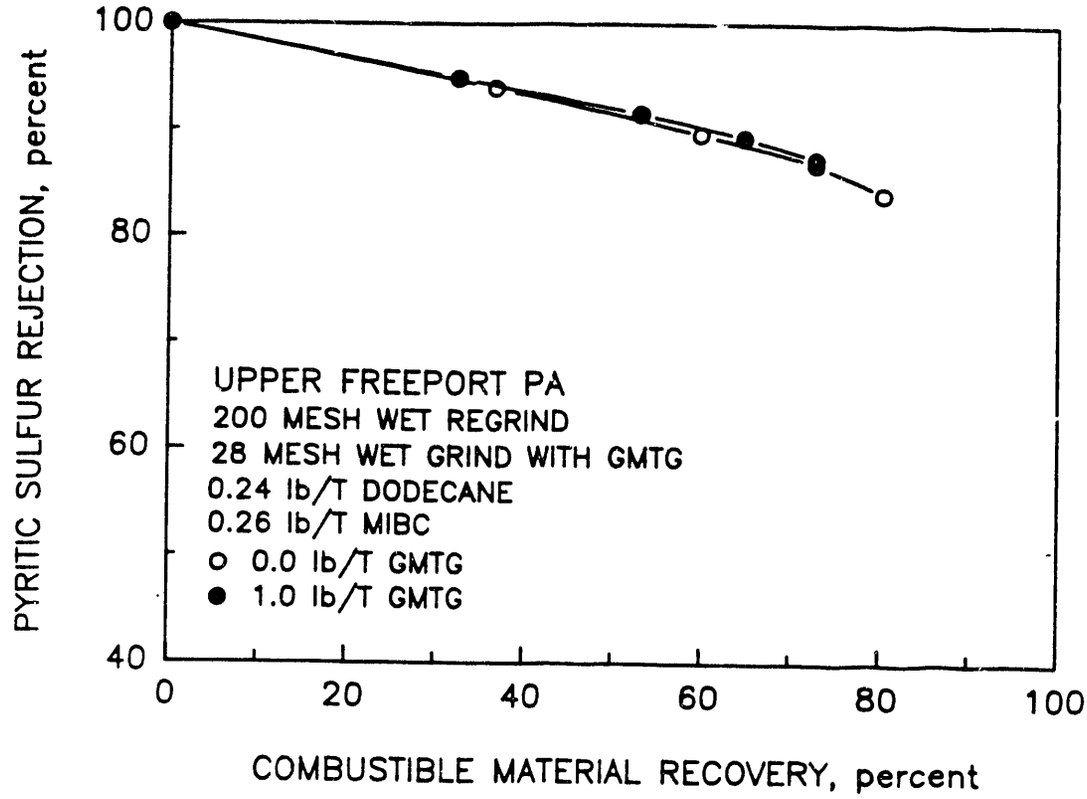

Figure 3.4 - Effect of grinding with GMTG on combustible matter recovery and ash and pyritic sulfur rejection in the flotation of Upper Freeport PA coal.

Table 3.2 - Two-stage flotation results for Illinois No. 6 coal with GMTG addition.

Stage	Flotation time minutes	CMR %	Ash Rej. %	Pyr. S Rej. %	EI_H
First (28 mesh)	2.0	81.8	54.8	66.0	47.7
Second (200 mesh)	0.25	41.8	74.9	73.7	15.4
	0.5	68.3	57.3	56.3	24.6
	1.0	87.1	43.3	43.3	30.5
	2.0	91.9	39.0	39.6	31.4
	5.0	95.3	34.0	34.6	29.9
Combined	0.25	34.2	88.7	94.7	28.9
	0.5	55.8	80.7	85.1	40.9
	1.0	71.2	74.4	80.7	51.9
	2.0	75.1	72.4	79.5	54.6
	5.0	77.9	70.2	77.8	55.7

Table 3.3 - Two-stage flotation results for Illinois No. 6 coal without GMTG addition.

Stage	Flotation time minutes	CMR %	Ash Rej. %	Pyr. S Rej. %	EI_H
First (28 mesh)	2.0	80.7	54.7	62.9	43.6
Second (200 mesh)	0.25	23.4	85.4	85.7	9.0
	0.5	52.6	66.8	66.3	18.9
	1.0	78.4	48.7	48.0	26.4
	2.0	90.2	38.3	37.6	27.8
	5.0	95.0	31.6	30.8	25.8
Combined	0.25	18.9	93.4	94.7	13.6
	0.5	42.5	85.0	87.5	30.0
	1.0	63.3	76.8	80.7	44.0
	2.0	72.8	72.1	76.9	49.7
	5.0	76.7	69.0	74.4	51.1

Table 3.4 - Single-stage flotation results for 200 mesh Illinois No. 6 with GMTG addition.

Stage	Flotation time minutes	CMR %	Ash Rej. %	Pyr. S Rej. %	EI_H
Single	0.25	21.5	89.0	90.2	10.5
	0.5	49.3	74.4	78.5	23.7
	1.0	71.0	62.6	68.3	33.6
	2.0	80.8	56.7	63.6	37.5
	3.0	84.9	53.4	60.8	38.3
	5.0	88.2	50.0	57.8	38.2

Table 3.5 - Two-stage flotation results for Pittsburgh No. 8 coal with GMTG addition.

Stage	Flotation time minutes	CMR %	Ash Rej. %	Pyr. S Rej. %	EI_H
First	2.0	92.0	48.3	35.6	27.6
Second	0.25	19.7	88.6	89.1	8.8
	0.5	42.1	75.7	76.5	18.6
	1.0	67.8	59.0	61.0	28.8
	2.0	82.4	48.6	51.5	33.9
	5.0	93.1	37.9	41.4	34.5
Combined	0.25	18.1	93.0	94.1	12.2
	0.5	38.7	84.9	87.4	26.1
	1.0	62.4	74.9	78.8	41.2
	2.0	73.1	68.8	73.4	46.5
	5.0	85.7	62.9	67.9	53.6

Table 3.6 - Two-stage flotation results for Pittsburgh No. 8 coal without GMTG addition.

Stage	Flotation time minutes	CMR %	Ash Rej. %	Pyr. S Rej. %	EI_H
First	2.0	95.0	39.4	29.8	24.9
Second	0.25	23.9	85.3	86.8	10.7
	0.5	44.7	72.3	75.1	19.8
	1.0	67.8	57.4	61.6	29.4
	2.0	83.5	46.3	51.4	34.9
	5.0	93.9	35.7	40.8	34.7
Combined	0.25	22.7	90.7	91.1	13.8
	0.5	42.5	80.6	83.2	25.7
	1.0	64.4	73.1	74.2	38.6
	2.0	79.4	65.9	67.4	46.8
	5.0	89.2	58.5	61.0	50.2

Table 3.7 - Single-stage flotation results for Illinois No. 6 coal without GMTG addition.

Stage	Flotation time minutes	CMR %	Ash Rej. %	Pyr. S Rej. %	EI_H
Single	0.5	34.7	81.6	82.9	16.3
	1.0	54.1	71.6	74.0	25.7
	2.0	78.2	56.7	59.3	34.9
	5.0	83.8	51.6	54.3	35.4

Table 3.8 - Two-stage flotation results for Upper Freeport PA coal with GMTG addition.

Stage	Flotation time minutes	CMR %	Ash Rej. %	Pyr. S Rej. %	EI_H
First	2.0	81.1	54.4	65.8	46.9
Second	0.5	40.1	77.7	84.8	24.9
	1.0	65.3	61.0	75.2	40.5
	2.0	79.8	49.8	68.7	48.5
	5.0	89.6	40.2	62.8	52.4
Combined	0.5	32.5	89.8	94.8	27.3
	1.0	53.0	82.2	91.5	44.5
	2.0	64.7	77.1	89.3	54.0
	5.0	72.7	72.7	87.3	60.0

Table 3.9 - Two-stage flotation results for Upper Freeport PA coal without GMTG addition.

Stage	Flotation time minutes	CMR %	Pyr. S Rej. %	EI_H
First	2.0	87.2	59.5	46.7
Second	0.5	42.0	85.0	27.0
	1.0	68.6	74.2	42.8
	2.0	83.4	67.3	50.7
	5.0	92.1	60.4	52.5
Combined	0.5	36.6	93.9	30.5
	1.0	59.8	89.6	49.4
	2.0	72.7	86.8	59.5
	5.0	80.3	84.0	64.3

In light of the results presented here and that from earlier experiments with GMTG, we conclude that GMTG has a depressant effect on the flotability of pyrite in coal. However, the soluble iron in the coal samples appears to have significant influence on the effectiveness of GMTG. In order to better assess the effect of soluble iron, additional flotation tests involving the washing of coal prior to grinding with GMTG are being planned for the three coals.

3.2 Reverse Flotation with Xanthate and Aerofloat 25 Promoter

The flotation of pyrite from coal is known as reverse flotation. For most hydrophobic coals, a suitable depressant must be added to keep the the coal from floating in order to produce a pyrite-rich refuse. Illinois No. 6 coal, however, is relatively hydrophilic and almost no material floats without the addition of an oily collector. Therefore, reverse flotation of Illinois No. 6 was attempted by adding pyrite-specific reagents with the aim of producing a hydrophobic coating on the pyrite surface.

In previous reports, the experimental results of Hallimond Tube flotation tests were presented for Arizona pyrite and oxidized Arizona pyrite. The objective of these tests was to study the effect of pH, metal ions such as copper, and chelate-forming reagents such as glycerol

Table 3.10 - Flotation of pyrite from Illinois No. 6 coal 200 mesh grind as a function of MIBC addition in the presence of 0.57 lb/Ton potassium ethyl xanthate (KEX) at pH 8 ± 0.5.

	FLOTATION PRODUCT ANALYSIS					RECOVERY			
MIBC lb/T	Yield %	1-Y %	CMR %	Ash %	Pyr. S %	Ash %	Pyr. S %	EI_H —	S —
0.0	11.3	88.7	11.5	12.7	1.51	10.28	9.61	1.9	1.2
0.39	9.9	90.1	10.0	12.7	1.53	8.69	7.83	2.2	1.3
0.78	14.0	86.0	14.6	10.2	0.96	10.33	8.00	6.6	1.8
1.17	29.9	70.1	31.1	10.4	0.89	22.83	17.83	13.3	1.8

monothioglycolate (GMTG) on pyrite flotation with sulfhydryl collectors. In addition, flotation tests in the standard Denver 2-liter cell were carried out with fresh-ground Arizona pyrite and with Illinois No. 6 coal samples in order to determine the best flotation conditions for pyrite in a reverse flotation scheme.

The preliminary flotation tests performed in the Denver 2-liter cell for Illinois No.6 coal indicate that the flotation of pyrite with 0.57 lb/T potassium amyl xanthate (KAX) is possible, although substantial amounts of the coal also float. Selective flotation of pyrite at high recovery from coal requires that the collector preferentially absorb on pyrite rather than on the coal. However, the hydrophobic chain of the collector will tend to adsorbs on the coal due to hydrophobic interaction. To reduce collector adsorption on the coal during pyrite flotation, a xanthate with a shorter hydrocarbon chain, such as potassium ethyl xanthate (KEX), was used instead of the 5-carbon amyl xanthate.

To further improve the selectivity of the flotation of pyrite from Illinois No. 6 coal, flotation tests were performed at pH 8. At this pH, the coal is expected to be slightly depressed, whereas the flotation of pyrite shows a maxima. The results of these tests, which are presented in Table 3.10, show that at pH 8 pyrite flotation was poor; furthermore, the recovery of coal increases with increasing MIBC addition. A possible explanation for the increase in coal recovery with added frother could be a result of frother adsorption by the coal during conditioning. In the

Table 3.11 - Flotation of pyrite from Illinois No. 6 coal 200 mesh grind as a function of MIBC addition in the presence of 0.57 lb/T potassium ethyl xanthate (KEX) at pH 4 ± 0.1. Frother conditioning time: 15 seconds.

	FLOTATION PRODUCT ANALYSIS					RECOVERY			
MIBC lb/T	Yield %	1-Y %	CMR %	Ash %	Pyr. S %	Ash %	Pyr. S %	EI_H —	Q —
0.0	12.1	87.9	12.3	13.2	1.93	11.0	10.1	2.2	1.2
0.39	16.7	83.3	17.2	12.5	1.60	14.0	12.4	4.8	1.4
0.78	31.0	69.0	32.6	10.1	1.50	21.4	21.1	11.5	1.5
1.17	58.2	41.8	60.8	10.5	1.55	41.1	39.3	21.5	1.5

case of pyrite, the poor flotation recovery (shown as pyritic sulfur recovery) could be related to the degree of oxidation of the pyrite surface in Illinois No. 6 coal, and the resulting presence of iron hydroxide complexes and organic products in solution, and to the adsorption of xanthate by the coal. Consequently, a higher collector dosage was required to float the pyrite from Illinois No. 6 coal. As can be seen from the flotation results given in Table 3.10, the efficiency index is low and Q (ratio of CMR to Pyritic Sulfur Recovery) is only slightly greater than unity.

Flotation tests of pyrite from Illinois No. 6 coal were also performed at pH 4, another pyrite flotation maximum, using the standard flotation conditions but with the addition of frother 15 seconds before flotation. The flotation results are presented in Table 3.11. As can be seen by comparing Tables 3.10 and 3.11 a reduction in pH from 8 to 4 increases the pyritic sulfur recovery. In the absence of frother, the pyritic sulfur recovery was 10%, at 0.39 lb/T MIBC added, the pyritic sulfur recovery increases to 12.4% at pH 4, an increase of 5%. At 0.78 lb/T MIBC, 21.1% of pyritic sulfur was recovered (13% increase) and at 1.17 lb/T MIBC addition, 39.3% the pyritic sulfur was recovered representing a 22% increase as compared to that at pH 8. However, the combustible material recovery (CMR) also increases with decreasing pH and increasing MIBC dosage. Even though MIBC was added just before flotation, it appears that the coal is still adsorbing the frother. The ratio between the CMR and the pyritic sulfur recovery (Q)

Table 3.12 - Step flotation of pyrite from Illinois No. 6 coal 200 mesh grind in the presence of potassium ethyl xanthate (KEX) and MIBC at pH 4 ± 0.1.

		FLOTATION PRODUCT ANALYSIS					RECOVERY			
MIBC	KEX	Yield	1-Y	CMR	Ash	Pyr. S	Ash	Pyr. S	EI_H	Q
lb/T	lb/T	%	%	%	%	%	%	%	—	—
0.24	1.42	16.1	83.9	16.3	12.9	2.26	14.4	13.4	2.9	1.2
0.24	2.85	17.4	82.6	17.7	12.7	1.85	15.9	18.2	-0.3	1.0
0.48	2.85	22.7	77.3	23.1	12.4	2.26	19.9	28.1	-5.0	0.8
0.79	5.70	67.1	32.9	69.6	10.5	3.18	51.2	83.2	-13.6	0.8
1.04	5.70	87.8	12.2	91.8	10.3	2.82	63.6	94.9	-3.9	1.0

decreases when the frother was added just before flotation and this ratio decreases with decreasing MIBC addition.

Based on these results, to reduce the effects of MIBC adsorption on the coal and to help avoid the adsorption of KEX on the coal at higher concentrations, a step flotation procedure was applied for the study of the effect of KEX dosage on pyrite recovery from Illinois No. 6 coal. In addition, a longer conditioning time was used to ensure the adsorption of the collector on pyrite. The procedure consisted of a 2-minute repulping and conditioning time, one minute for pH adjustment and twelve minutes of conditioning with xanthate. MIBC was added 15 seconds before the two-minute flotation stage. Xanthate was added three more times and conditioned for 5 minutes before flotation. The second and third flotation stages were of 2 minutes flotation time, and the final stage was for 5 minutes. The addition of the frother was distributed among the three first flotation steps.

Table 3.12 presents the composite results of the step flotation test for the removal of pyrite from Illinois No. 6 coal at 200-mesh as a function of KEX and MIBC additions at pH 4. As was expected, the pyritic sulfur recovery increases with increasing KEX addition at constant MIBC addition. Furthermore, as the KEX addition increases from 1.42 lb/ton to 2.85 lb/ton KEX, the ratio CMR/PSR (Q) decreases, suggesting that the collector preferentially adsorbs on pyrite. Nevertheless, the CMR increases with increasing KEX addition, showing that Illinois No. 6 coal also adsorbs xanthate.

Table 3.13 - Step flotation results for pyrite flotation from Illinois No. 6 coal at 200 mesh grind in the presence of potassium ethyl xanthate (KEX), hydrogen peroxide (H_2O_2), and 0.78 lb/T of MIBC.

		FLOTATION PRODUCT ANALYSIS					RECOVERY			
KEX lb/T	H_2O_2 %	Yield %	1-Y %	CMR %	Ash %	Pyr. S %	Ash %	Pyr. S %	EI_H —	Q —
0.57	--	31.0	69.0	32.6	9.3	1.29	21.4	21.1	11.5	1.5
0.57*	--	24.3	75.7	25.4	10.0	1.33	17.1	15.1	10.3	1.7
5.70	--	67.1	32.9	69.6	10.5	3.18	51.2	83.2	-13.6	0.8
5.70*	0.05	42.3	57.7	44.1	10.8	2.91	31.9	57.0	-12.9	0.8
5.70	0.10	31.3	68.7	32.0	12.2	3.52	27.3	43.3	-11.3	0.7

*sample was filtered after 3 minutes of conditioning.

Even though it was demonstrated that pyrite can be floated from coal with xanthate, the CMR also increased and the selectivity poor. As a consequence, work was performed to study the depression of coal with H_2O_2. Also, because the stability of xanthate is reduced at pH 4[2], other sulfhydryl collectors such as dithiophosphate reagents were also tested.

Flotation tests were performed using potassium ethyl xanthate (KEX) and Aerofloat 25 Promoter (dicresyldithiophosphoric acid and cresylic acid) as collectors and hydrogen peroxide (H_2O_2) as coal depressant. For some tests, the step flotation procedure described in the foregoing paragraphs was slightly modified with an additional step which incorporated filtration of the pulp to remove ferrous (or ferric) ions before the addition of the collector after the first 3 minutes of conditioning. Since hydrogen peroxide is a powerful oxidant, this reagent was added to oxidize the surface of the coal and, hence, to depress it. At the same time, the addition of hydrogen peroxide may also enhance the flotability of pyrite by slightly oxidizing its surface and/or by forming dixanthogen. Therefore, the modified flotation procedure was used to establish the effect of the hydroxy complexes formed in the bulk after the addition of the hydrogen peroxide on the flotation behavior of pyrite contained in Illinois No. 6 coal.

The results of the step flotation of pyrite from Illinois No. 6 coal using Aerofloat 25 Promoter (AF25P), hydrogen peroxide, and MIBC are given in Table 3.14. The amount of

Table 3.14 - Step flotation results for pyrite flotation from Illinois No. 6 coal at 200 mesh grind in the presence of Aerofloat 25 Promoter, hydrogen peroxide (H_2O_2), and MIBC.

		FLOTATION PRODUCT ANALYSIS						RECOVERY			
MIBC	A25P	H_2O_2	Yield	1-Y	CMR	Ash	Pyr. S	Ash	Pyr. S	EI_H	Q
lb/T	lb/T	%	%	%	%	%	%	%	—	—	—
0.39	2.85	--	18.5	81.5	19.1	10.8	1.36	14.2	12.2	6.9	1.6
0.39	5.70	--	95.8	4.2	98.0	12.1	2.13	82.5	94.9	3.1	1.0
1.04	5.70	--	96.8	3.2	99.2	12.3	2.74	82.5	99.2	0.0	1.0
0.39	5.70	0.20	17.3	82.7	17.6	13.7	1.59	15.6	15.1	2.5	1.2
0.39	5.70	0.10	17.2	82.8	17.6	13.1	1.61	14.6	14.9	2.7	1.2

Aerfloat 25 Promoter (5.70 lb/ton) was the same as that of KEX required for pyrite to float; however, the amount of frother used with Aerofloat 25 Promoter (0.39 lb/ton MIBC) is half of that required with KEX for an equivalent pyrite recovery. As can be seen from Table 3.14, the presence of 0.1% of H_2O_2 is enough to completely suppress the flotation of both coal and pyrite. Therefore, it seems that this reagent does not present any advantage over KEX as collector for the flotation of pyrite from Illinois No. 6 coal. Small differences in the flotation results can be attributed to changes in the natural pH of the samples.

3.3 Enhancement of Coal Hydrophobicity

Flotation tests of ethylene glycol (EG) and a series of polyethylene glycols (PEG) with different molecular weight were completed on wet-ground minus 200 mesh Upper Freeport PA coal. The flotation results obtained with these reagents are shown in Tables 3.15 through 3.19. As can be seen from Figure 3.5, which presents the separation efficiency of the flotation tests versus the dosage of EG and PEG-200, when the dosage of EG is increased from 2.0 to 16.0 lb/T, the separation efficiency increases from 29.1 to 43.8, whereas when the dosage of PEG-200 is increased from 1.0 to 2.5 lb/T, the separation efficiency increases from 45.3 to 66.5. These results indicate that PEG is a more effective flotation reagent than EG in coal flotation.

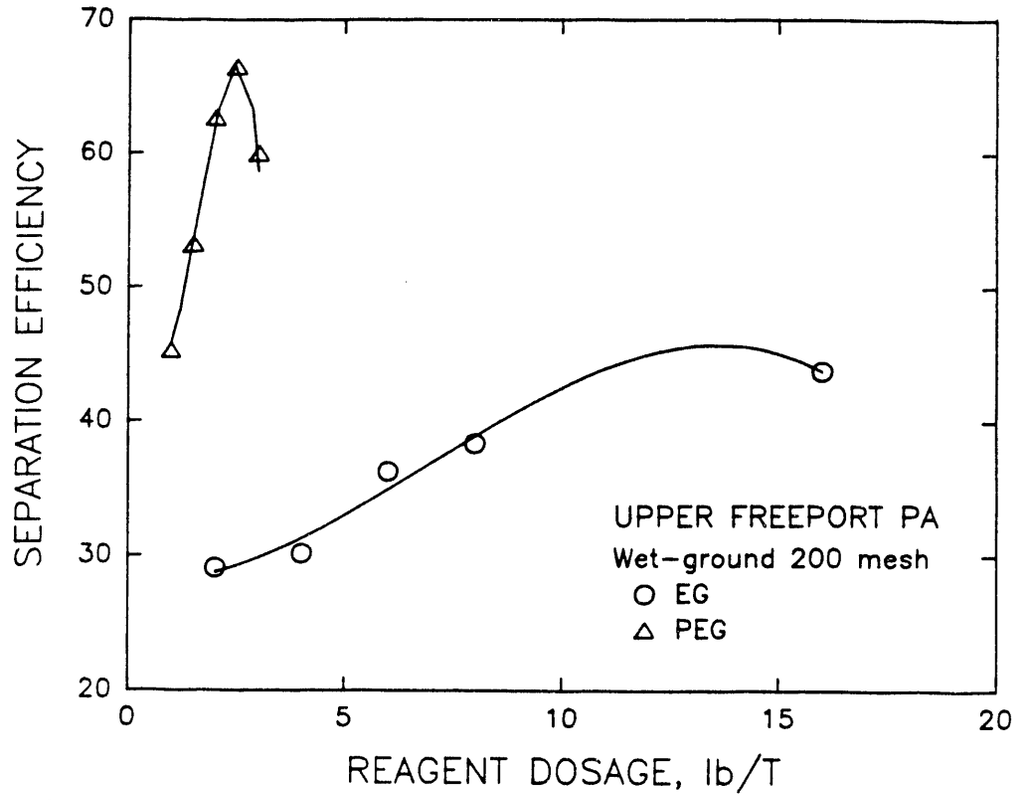

Figure 3.5 - Comparison of the effect of ethylene glycol (EG) and polyethylene glycol 200 (PEG-200) on the flotation of wet-ground minus 200 mesh Upper Freeport PA coal.

Table 3.15 - Flotation results of ethylene glycol (EG) for wet-ground minus 200-mesh Upper Freeport PA coal.

REAGENT DOSAGE	PRODUCT ANALYSIS				REJECTION		
Ethylene glycol lb/T	Yield %	CMR %	Ash %	Pyr S %	Ash %	Pyr S %	EI_H
2.0	34.6	37.3	5.59	0.37	84.3	91.8	29.1
4.0	35.5	38.2	5.45	0.35	84.2	92.0	30.2
6.0	41.5	44.8	5.43	0.32	81.8	91.5	36.3
8.0	45.9	49.3	5.79	0.37	78.3	89.1	38.4
16.0	54.8	58.6	6.30	0.42	72.0	85.2	43.8

Table 3.16 - Flotation results of polyethylene glycol 200 (PEG-200) for wet-ground minus 200-mesh Upper Freeport PA coal.

REAGENT DOSAGE	PRODUCT ANALYSIS				REJECTION		
PEG-200 lb/T	Yield %	CMR %	Ash %	Pyr S %	Ash %	Pyr S %	EI_H
1.0	51.1	55.8	5.00	0.32	79.1	89.5	45.3
1.5	62.8	67.3	5.44	0.35	70.9	85.9	53.2
2.0	74.7	79.9	5.95	0.36	63.3	82.8	62.7
2.5	91.5	95.8	7.90	0.50	40.0	70.7	66.5
3.0	93.3	97.1	8.21	0.62	35.0	62.9	60.0

Table 3.17 - Flotation test results with polyethylene glycol (PEG-400) on wet-ground minus 200-mesh Upper Freeport PA coal.

REAGENT DOSAGE	PRODUCT ANALYSIS				REJECTION		
PEG-400 lb/T	Yield %	CMR %	Ash %	Pyr S %	Ash %	Pyr S %	EI_H
0.5	33.6	36.1	5.53	0.34	84.6	92.7	28.8
1.0	63.4	68.2	5.61	0.31	70.3	87.4	55.6
1.3	89.5	94.0	7.68	0.52	43.1	70.2	64.2
1.5	92.7	96.4	8.47	0.68	34.4	59.6	56.0
2.0	95.4	98.2	9.21	0.71	25.7	56.6	54.8

Table 3.18 - Flotation test results with polyethylene glycol (PEG-1000) on wet-ground minus 200-mesh Upper Freeport PA coal.

REAGENT DOSAGE	PRODUCT ANALYSIS				REJECTION		
PEG-10 lb/T	Yield %	CMR %	Ash %	Pyr S %	Ash %	Pyr S %	EI_H
1.0	29.2	31.3	5.82	0.51	85.9	90.5	21.8
1.5	55.4	59.7	5.48	0.39	75.2	86.2	45.9
2.0	86.6	91.4	7.26	0.53	48.1	70.6	62.0
3.0	92.6	96.4	8.55	0.64	35.1	62.1	58.5

Table 3.19 - Flotation test results with polyethylene glycol (PEG-6000) on wet-ground minus 200-mesh Upper Freeport PA coal.

REAGENT DOSAGE	PRODUCT ANALYSIS				REJECTION		
PEG-6000 lb/T	Yield %	CMR %	Ash %	Pyr S %	Ash %	Pyr S %	EI_H
1.0	23.7	25.6	5.09	0.36	90.0	94.5	20.1
2.0	26.3	28.3	5.79	0.39	87.7	93.4	21.7
3.0	32.2	34.6	5.45	0.35	85.5	92.8	27.4
4.0	85.8	90.4	7.43	0.66	47.4	63.7	54.1

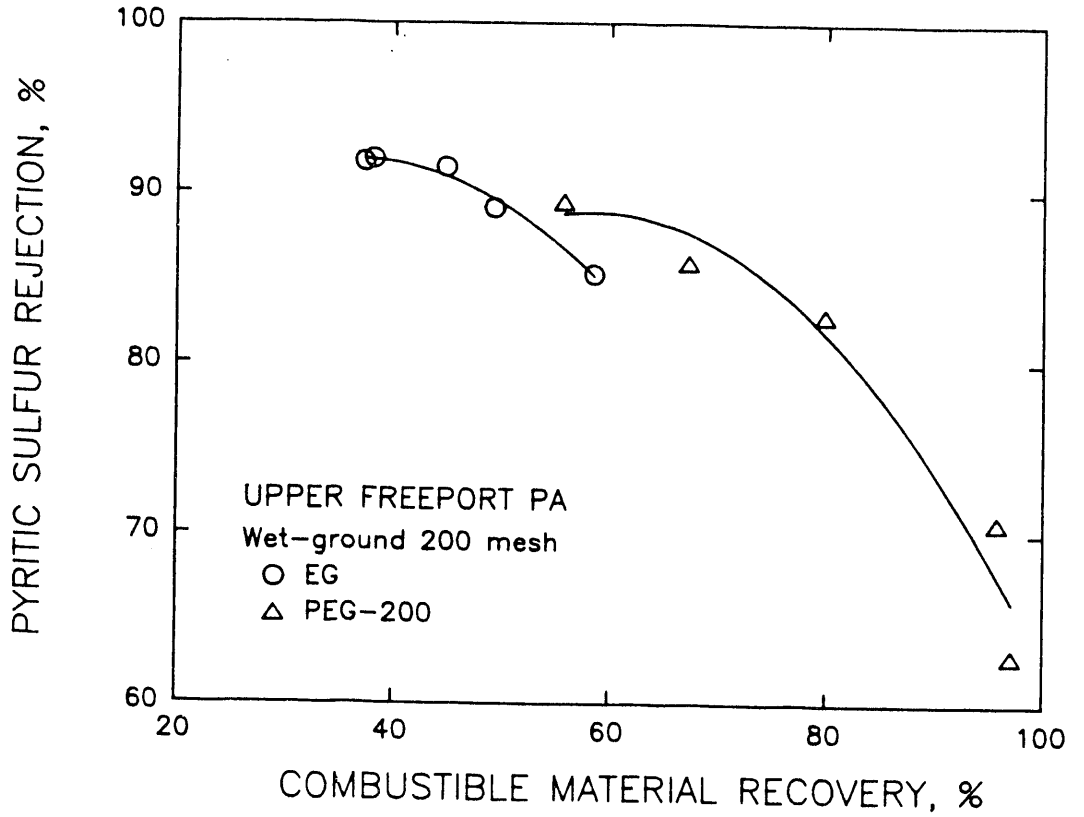

Figure 3.6 - Comparison of the effect of ethylene glycol and polyethylene glycol 200 (PEG-200) on the flotation of wet-ground minus 200 mesh Upper Freeport PA coal.

Figure 3.6 shows the comparison of the pyritic sulfur rejection and combustible material recovery of Upper Freeport PA coal with EG and PEG-200. It is clear that PEG-200 is also more selective than EG in terms of pyrite rejection.

The overall effects of the polyethylene glycol (PEG) series in flotation of Upper Freeport PA coal are shown in Table 3.16 (PEG-200), 3.17 (PEG-400), 3.18 (PEG-1000) and 3.19 (PEG-6000). To obtain the same flotation yield, PEG-400 requires the lowest dosage (from 0.5 to 2.0 lb/T). However, the highest separation efficiency (66.5) was achieved by using PEG-200. Based on the separation efficiency, the effectiveness of the PEG series decrease with increasing molecular weight: PEG-200>PEG-400>PEG-1000>PEG-6000.

Flotation tests with pentylether (PE), dipentylamine (DPA) and butylamine (BA), were completed on wet-ground minus 200-mesh Upper Freeport PA coal.

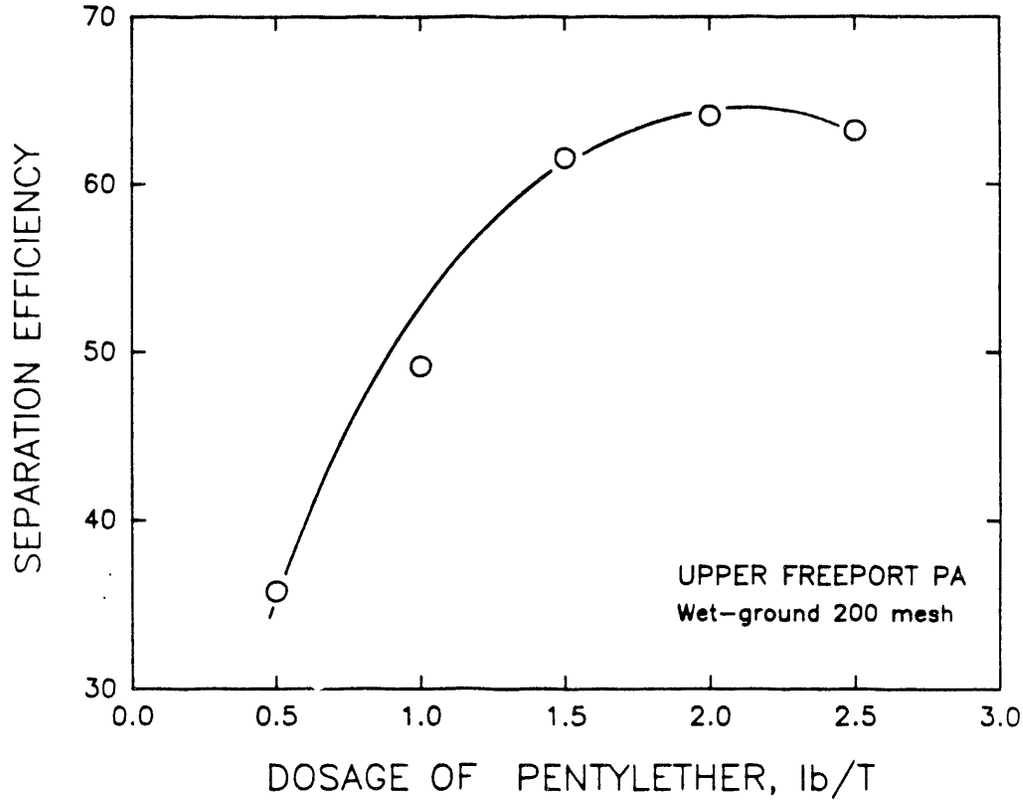

Figure 3.7 - Effect of pentylether on the flotation separation efficiency of wet-ground minus 200-mesh Upper Freeport PA coal.

Table 3.20 and Figure 3.7 show the test results using pentylether. It was found that as the dosage is increased from 0.5 to 2.0 lb/T, the separation efficiency increased from 35.8 to 64.1. Beyond 2.0 lb/T, the separation efficiency appears to level off.

Table 3.20 - Flotation test results of pentylether for wet-ground minus 200-mesh Upper Freeport PA coal.

REAGENT DOSAGE	PRODUCT ANALYSIS				REJECTION		
Pentylether lb/T	Yield %	CMR %	Ash %	Pyr S %	Ash %	Pyr S %	EI_H
0.5	43.4	46.6	5.71	0.39	79.7	89.2	35.8
1.0	61.5	65.8	6.04	0.42	69.6	83.4	49.2
1.5	79.6	84.6	6.73	0.46	56.1	76.5	61.6
2.0	82.8	87.5	7.30	0.44	50.9	76.6	64.1
2.5	87.8	92.5	6.96	0.52	47.8	70.7	63.2

Table 3.21 - Flotation results of dipentylamine for wet-ground minus 200 mesh Upper Freeport PA coal.

REAGENT DOSAGE	PRODUCT ANALYSIS				REJECTION		
Dipentylamine lb/T	Yield %	CMR %	Ash %	Pyr S %	Ash %	Pyr S %	EI_H
0.1	30.0	32.2	6.00	0.37	85.4	92.9	25.1
0.3	65.4	70.4	5.40	0.33	71.2	86.2	56.6
0.4	85.5	90.5	7.01	0.45	50.5	75.3	65.8
0.5	91.7	95.6	8.49	0.58	36.3	65.9	61.5
1.0	96.6	99.0	10.02	0.74	20.5	54.2	53.2

The flotation tests using dipentylamine are presented in Table 3.21. These results show that the dosage increases so does the yield (0.1 to 1.0 lb/T, resulting in a separation efficiency increase from 25.1 to 65.8).

Table 3.22 shows the flotation tests results with butylamine (BA). As the dosage is increased to 3.0 lb/T, the separation efficiency increases as well. Figure 3.8 shows that the effect of butylamine is better than the effect of dipentylamine at equivalent yields.

Flotation results using PE, DPA and BA are shown in Figure 3.10 amd show that all three reagents result in almost identical pyritic sulfur rejections for a given combustible material recovery.

Table 3.22 - Flotation results of butylamine for wet-ground minus 200-mesh Upper Freeport PA coal.

REAGENT DOSAGE	PRODUCT ANALYSIS				REJECTION		
Butylamine lb/T	Yield %	CMR %	Ash %	Pyr S %	Ash %	Pyr S %	EI_H
1.0	43.9	47.0	5.68	0.35	71.9	90.2	37.2
2.0	59.3	63.9	5.16	0.31	74.6	88.2	52.1
3.0	82.6	87.7	6.48	0.40	55.2	78.8	66.5
4.0	92.5	96.3	7.73	0.51	37.2	69.8	66.1

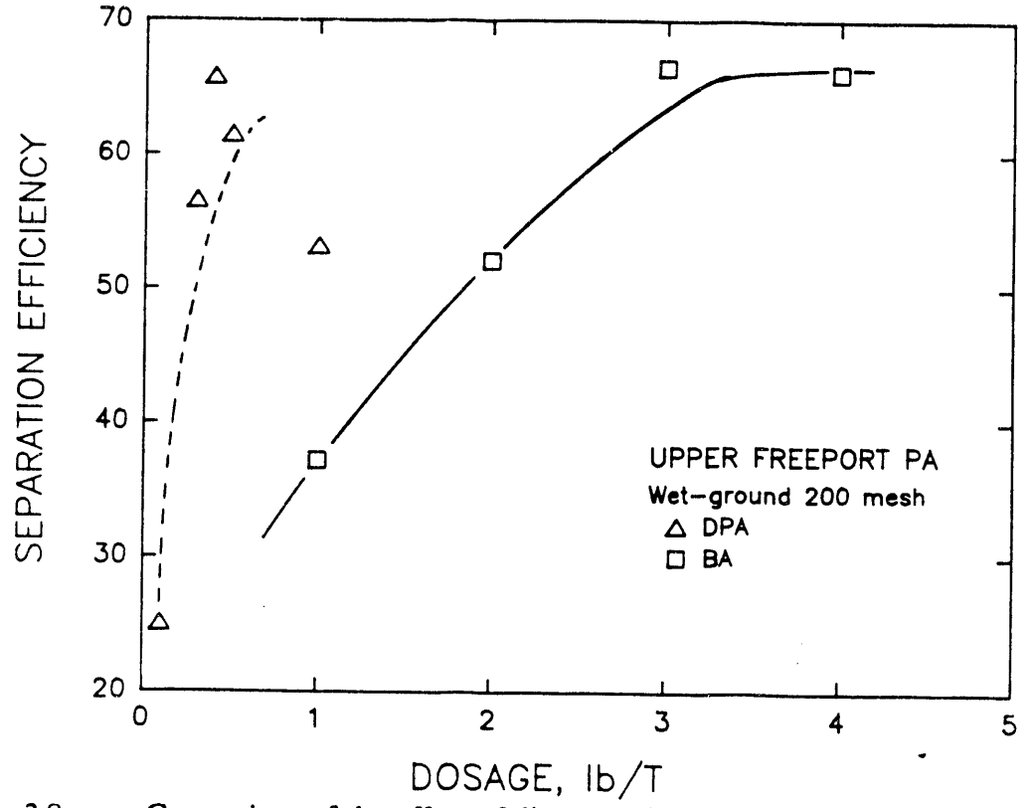

Figure 3.8 - Comparison of the effect of dipentyamine (DPA) and butylamine (BA) on the flotation of wet-ground minus 200-mesh Upper Freeport PA coal.

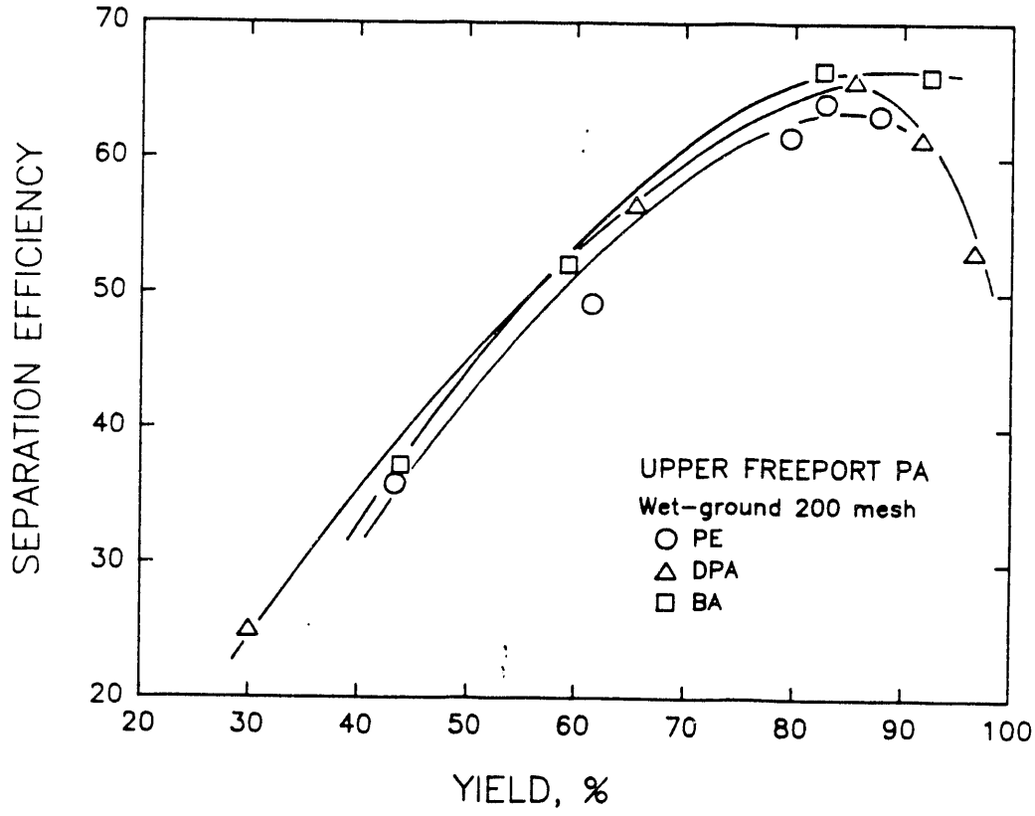

Figure 3.9 - Effect of pentylether (PE), dipentylamine (DPA) and butylamine (BA) on the flotation of wet-ground minus 200-mesh Upper Freeport PA coal.

4.0 COLUMN FLOTATION

In preliminary tests, it was found that the pyrite rejection obtained with a flotation column can match that obtained using two stages of flotation with a mechanically agitated cell. In order to enhance the performance obtained with the column, the effect of two different parameters, namely the bubble size and wash water, were tested. The effect of bubble size on the rejection of pyrite and non-pyritic minerals from 200-mesh wet ground (pH 8, sodium hydroxide added to mill) Pittsburgh No. 8 coal is illustrated in terms of selectivity curves in Figures 4.1 and 4.2. Washability curves are also shown in these figures for comparison purposes. In these tests the frother (MIBC) dosage was maintained at 0.78 lb/T and collector was not added. Various points of the selectivity curves were obtained by analyzing the samples withdrawn from different heights up the column.

Figure 4.1 shows that the pyritic sulfur rejection obtained using a coarse frit (40-60 microns) is higher than that obtained with a medium frit (10-15 microns). This observation can be explained in the following manner. Finer bubbles have larger specific surface area and hence will result in greater froth stability. This will cause decreased drainage of liquid, and hence greater hold-up of trapped solids (impurity). In the case of non-pyritic minerals, bubble size has no effect on selectivity (Figure 4.2). This is due to the fact that the selectivity curve obtained using the medium frit (finer bubbles) has already reached the limit of physical separation as it overlaps with the washability curve.

Figures 4.3 and 4.4 show the effect of wash water on pyrite rejection in the tests carried out using the coarse frit and medium frits. It can be seen from these figures that, in the range tested, there is no effect of wash water on selectivity. Tests at higher wash water rates are planned.

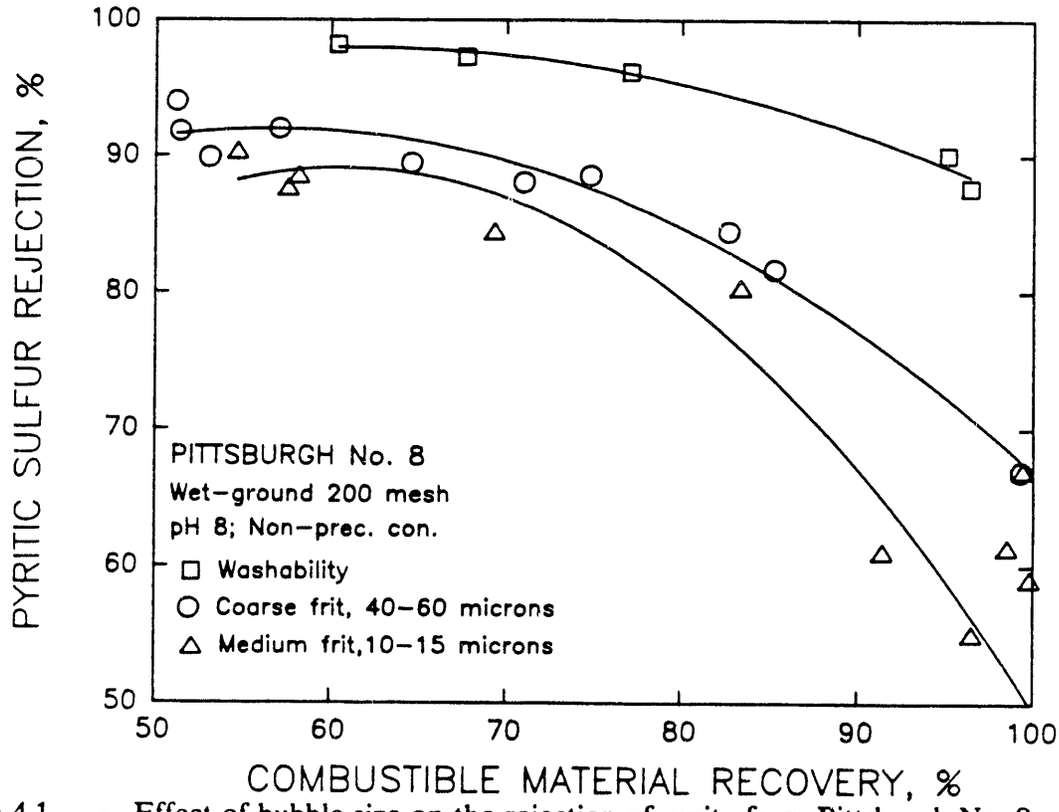

Figure 4.1 - Effect of bubble size on the rejection of pyrite from Pittsburgh No. 8 coal.

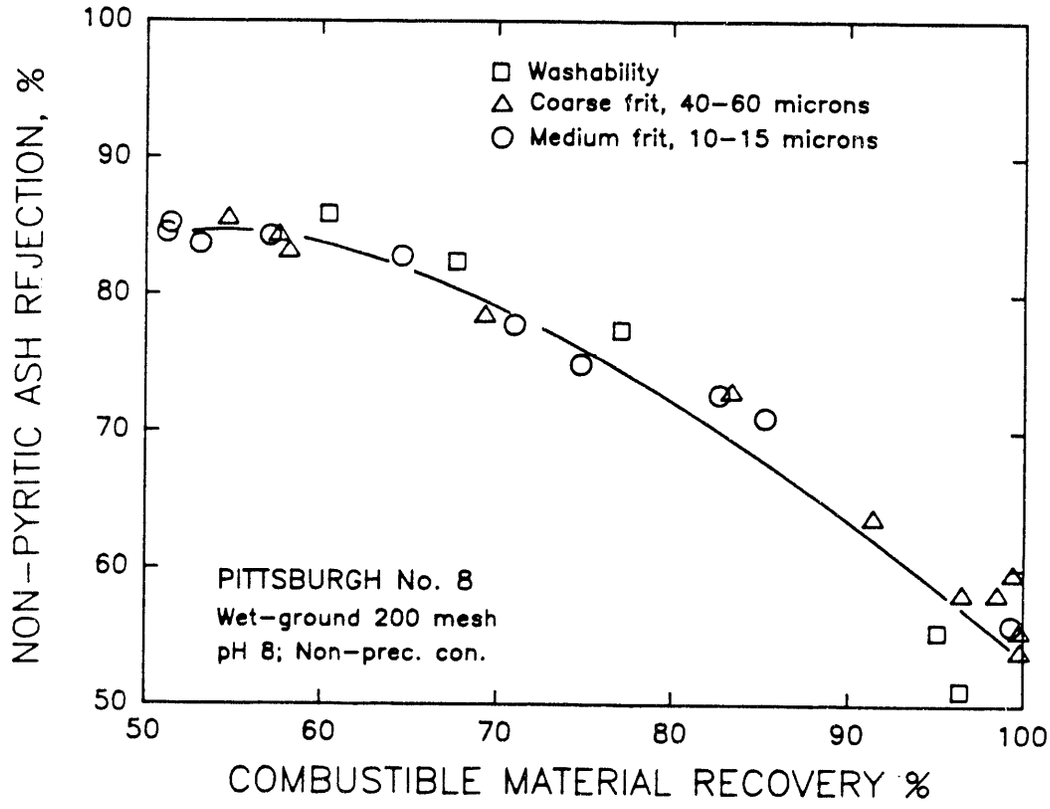

Figure 4.2 - Effect of bubble size on the rejection of non-pyritic minerals from Pittsburgh No. 8 coal.

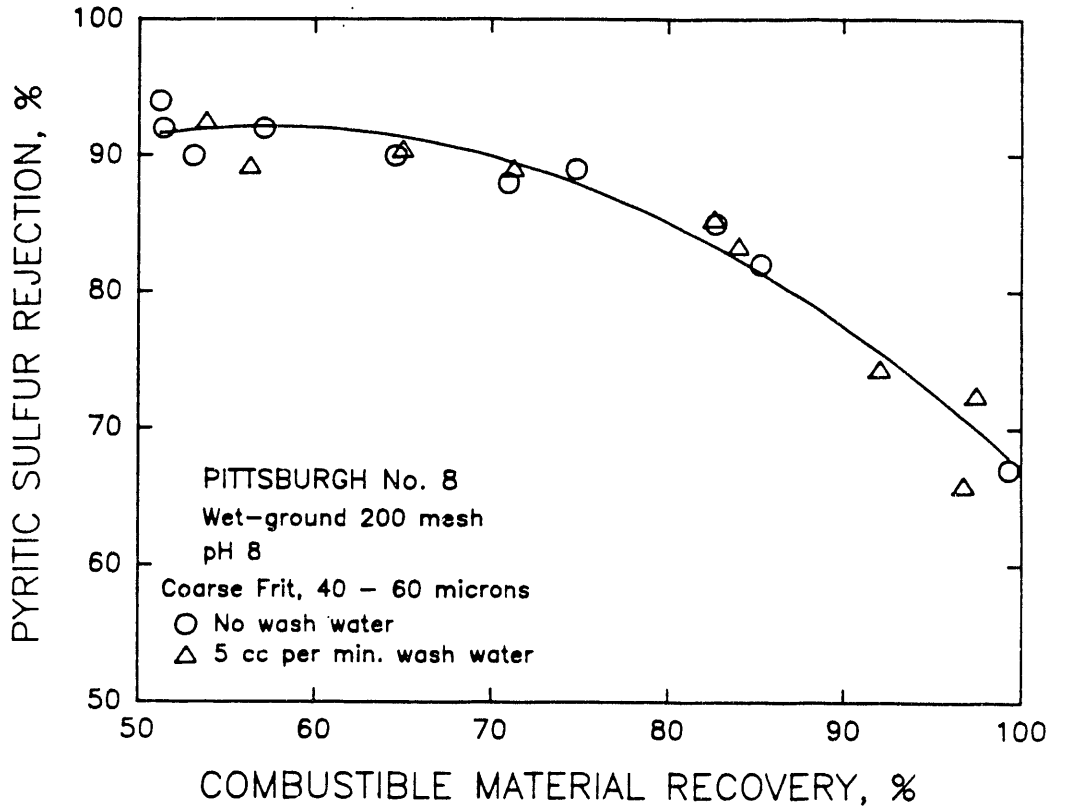

Figure 4.3 - Effect of wash water on the rejection of pyrite from Pittsburgh No. 8 coal - tests with coarse frit.

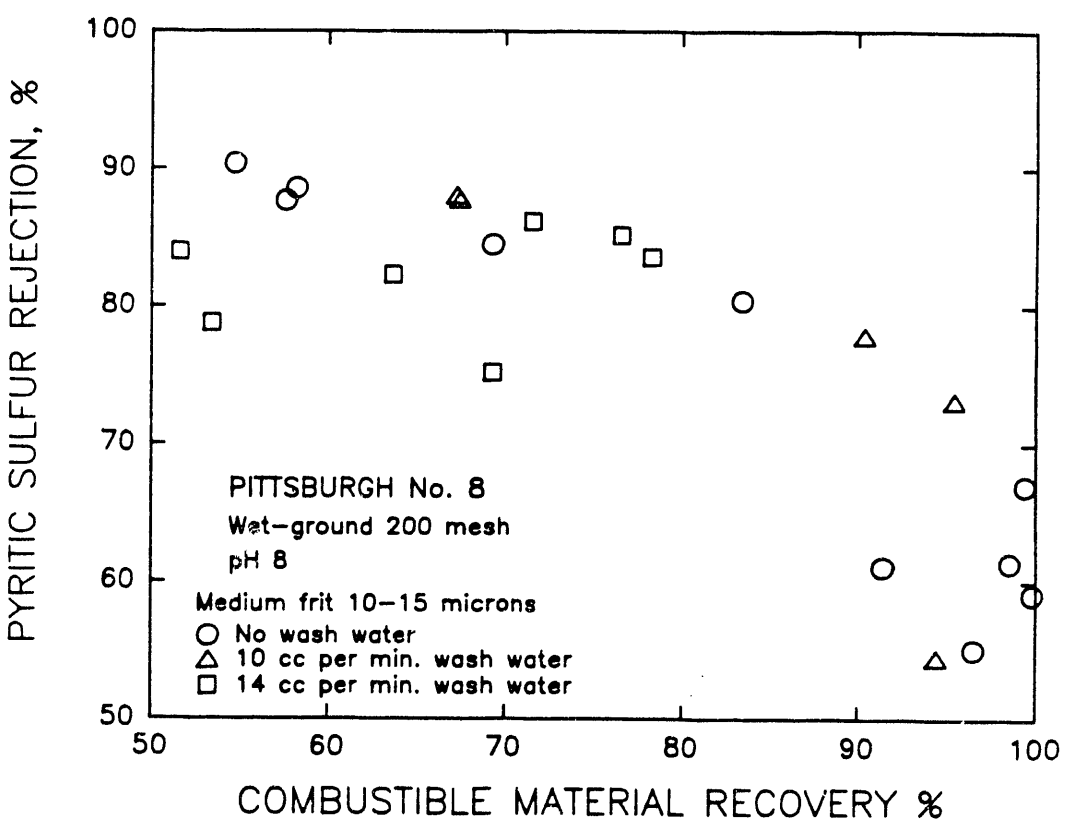

Figure 4.4 - Effect of wash water on the rejection of pyrite from Pittsburgh No. 8 coal - tests with medium frit.

5.0 FLOTATION KINETICS

5.1 Flotation Kinetics of 200-mesh Ground Coal

Results from flotation kinetic studies on minus 28 mesh coal, presented in Quarterly Report No. 9, showed that for all three coals the intermediate size fractions (48 x 100 and 100 x 200 mesh) have higher ultimate combustible materials recovery than both the larger (plus 48 mesh) and the smaller (minus 200 mesh) size fractions and that the effect of particle size on the ultimate recovery and the flotation rate constant depends on both the reagent dosage and the hydrophobicity of the coal. Results on minus 100 mesh coal, presented in Quarterly Report No. 10, showed that for all three coals the flotation rate constant of the coarser size fraction (plus 200 mesh) is higher than that of finer size fractions (200 x 400 and minus 400 mesh). However, the ultimate recovery of the combustible material (ultimate CMR) of the coarser material is lower than that of the finer size fractions. For the two finer size fractions, the 200 x 400-mesh size fraction has slightly higher flotation rate constant and slightly lower ultimate CMR than the minus 400-mesh size fraction.

In this report, results of the flotation kinetic study with minus 200-mesh samples of the three base coals are reported. To compare the flotation results of the minus 200-mesh coal with that of minus 28 and minus 100-mesh coal, all the flotation conditions and reagent dosages used in these tests were the same as those used in the flotation of the 28-mesh and 100-mesh grind samples. To obtain reliable results and collect enough concen- trates for various analyses, four flotation tests were conducted for each coal using samples split from a single ground sample. The flotation concentrate was collected at different time intervals; 0.25, 0.5, 1, 2 and 5 minutes. The corresponding flotation concentrates obtained from the four tests were then combined and wet sieved into two size fractions, plus 400 and minus 400-mesh. Each size fraction was dried, weighed and analyzed for ash and total sulfur content. The pyritic sulfur content of each size fraction was calculated from its ash and total sulfur content using the formula reported previously.

Table 5.1 - Combustible material recovery (CMR), ash and pyritic sulfur rejection, and separation efficiency of 200-mesh Illinois No. 6 coal (dodecane 4.92 lb/T and MIBC 0.98 lb/T at pH 4.0).

Particle Size mesh	Flotation Time, minutes	CMR %	Ash Rej., %	Pyr. S Rej., %	EI_H
+400	0.25	11.5	92.0	94.8	6.3
	0.5	22.1	85.2	90.3	12.4
	1.0	34.9	77.1	85.0	19.9
	2.0	45.1	70.5	81.3	26.4
	5.0	59.2	60.8	75.2	34.4
-400	0.25	15.6	91.9	92.6	8.2
	0.5	32.6	83.7	84.9	17.5
	1.0	53.4	73.6	75.6	29.0
	2.0	69.1	65.6	68.2	37.3
	5.0	84.7	55.0	57.1	41.7
Overall	0.25	14.1	91.9	93.2	7.3
	0.5	28.8	84.1	86.2	15.1
	1.0	46.6	74.4	78.0	24.6
	2.0	60.4	66.6	71.4	31.8
	5.0	75.4	56.3	61.6	37.0

Tables 5.1, 5.2 and 5.3 present the combustible material recovery (CMR), ash and pyritic sulfur rejection, and the separation efficiency of the two size fractions as well as their combined values at different flotation times for the three base coals. It can be seen from these tables that the combustible material recovery of the minus 400-mesh size fraction for all three coals is higher than that of the plus 400-mesh size fraction for all flotation times. However, pyritic sulfur rejections of the minus 400-mesh fraction for all three coals are lower than that of plus 400-mesh. The corresponding separation efficiency index of minus 400-mesh fractions for both Illinois No. 6 and Pittsburgh No. 8 coals is higher than that of the plus 400-mesh fraction. However, for Upper Freeport PA coal, the minus 400-mesh fraction has a lower EI than the plus 400-mesh fraction. The different behavior of EI for the two size fractions for the three coals might be due to both the particle size and the composition of the particles. Table 5.4 gives the yield, ash, total sulfur and pyritic sulfur content of the two size fractions of the three coals. These results indicate that

Table 5.2 - Combustible material recovery (CMR), ash and pyritic sulfur rejection, and separation efficiency of 200-mesh Pittsburgh No. 8 coal (dodecane 1.92 lb/T and MIBC 0.30 lb/T at pH 3.6).

Particle Size mesh	Flotation Time, minutes	CMR %	Ash Rej., %	Pyr. S Rej., %	EI_H
+400	0.25	5.6	96.2	96.6	2.2
	0.5	13.0	91.4	92.7	5.6
	1.0	27.1	82.8	85.2	12.3
	2.0	48.5	70.0	73.5	21.9
	5.0	68.0	57.8	61.8	29.7
-400	0.25	11.0	94.8	95.1	6.1
	0.5	25.1	88.7	89.3	14.5
	1.0	46.6	79.8	80.7	27.3
	2.0	70.3	70.4	70.6	40.9
	5.0	86.5	60.9	60.6	47.1
Overall	0.25	9.2	95.1	95.4	4.6
	0.5	21.0	89.3	90.1	11.1
	1.0	40.0	80.4	81.7	21.7
	2.0	62.9	70.3	71.3	34.2
	5.0	80.2	60.2	60.9	41.1

Table 5.3 - Combustible material recovery (CMR), ash and pyritic sulfur rejection, and separation efficiency of 200-mesh Upper Freeport PA coal (dodecane 0.24 lb/T and MIBC 0.26 lb/T at pH 3.4).

Particle Size mesh	Flotation Time, minutes	CMR %	Ash Rej., %	Pyr. S Rej., %	EI_H
+400	0.25	7.9	96.4	97.6	5.5
	0.5	17.7	92.1	94.8	12.5
	1.0	34.3	85.3	91.3	25.7
	2.0	56.9	75.5	86.6	43.5
	5.0	78.0	61.5	78.7	56.8
-400	0.25	13.0	94.1	95.6	13.4
	0.5	27.7	87.7	90.8	26.7
	1.0	49.0	78.4	84.7	41.6
	2.0	71.7	67.8	77.8	51.5
	5.0	88.1	56.3	69.4	51.9
Overall	0.25	11.7	94.6	95.9	7.6
	0.5	25.1	88.7	91.5	16.6
	1.0	45.1	80.1	85.9	31.0
	2.0	67.8	69.6	79.4	47.2
	5.0	85.5	57.5	71.1	56.6

Table 5.4 - Yield, ash, total sulfur and pyritic sulfur content of different size fractions of 200-mesh Illinois No. 6, Pittsburgh No. 8 and Upper Freeport PA coals.

Coal	Size, mesh	Yield, %	Ash, %	Tot. S, %	Pyr. S, %
Illinois No. 6	+400	34.4	9.06	4.07	1.48
	-400	65.6	16.53	4.83	2.32
	Overall		13.96	4.57	2.03
Piitsburgh No. 8	+400	32.7	6.74	3.14	1.66
	-400	67.3	11.93	4.19	2.80
	Overall		10.23	3.85	2.43
Upper Freeport PA	+400	26.0	11.26	1.86	1.09
	-400	74.0	12.88	2.54	1.75
	Overall		12.46	2.36	1.58

the size distribution of these three coals samples is similar and the pyritic sulfur content of minus 400-mesh fraction is higher than that of plus 400-mesh. For Illinois No. 6 and Pittsburgh No. 8 coals, the ash content of the minus 400-mesh fraction is significantly higher than that of the plus 400-mesh size fraction. However, for Upper Freeport PA coal, the ash content in the two size fractions is almost the same.

In general, higher ash and pyritic sulfur contents in the feed and fewer locked particles in the finer size fractions may result in an increase in both CMR and pyritic sulfur rejection and subsequently the separation efficiency index. On other hand, finer ash and pyrite particles are easily carried over by the froth and results in a decrease in the pyritic sulfur rejection and EI. Therefore, the change in the EI indicates the relative magnitude of the two effects. For Illinois No. 6 and Pittsburgh No. 8 coals, the effect of the higher ash and pyritic sulfur, and better liberation in the finer size fraction is predominate and therefore the value of EI for the minus 400-mesh size fraction is higher than that in the coarser size fraction. On other hand, for Upper Freeport PA coal, since the ash content of the two size fractions is similar and the ash and pyrite in this coal are liberated at a coarser size, the effect of carry over of fine ash and pyrite particles is predominate and, therefore the EI value for the minus 400-mesh size fraction is lower than that

for the plus 400-mesh fraction. The overall separation efficiency for the three coals given in Tables 5.1 through 5.3 shows that Upper Freeport PA is easier to clean (higher EI value) than Illinois No. 6 and Pittsburgh No. 8 coals.

Figures 5.1, 5.2 and 5.3 present the combustible material recovery of the plus 400 and the minus 400-mesh size fractions for the three base coals as a function of flotation time along with the fitting curves of the classical first-order kinetics and the two fitting parameters. It was found that for all three coals both the ultimate CMR and the flotation rate constant of the minus 400-mesh fraction is higher than that of the plus 400-mesh fraction. The difference in ultimate CMR of minus 400-mesh size fraction and the plus 400-mesh size fraction for the three coals decreases in the following order: Illinois No. 6 > Pittsburgh No. 8 > Upper Freeport PA coal. This is the same order as the hydrophilicity of the three coals as well as the difference in ash content of the two size fractions. This might suggest that higher ultimate CMR of the minus 400-mesh size fraction is due partially to the higher ash content in the finer size fraction. However, for Upper Freeport PA coal, the smaller difference (1.6%) in ash content between the two size fractions cannot explain the significant difference between the ultimate CMR of the two size fractions. These figures show that the difference between the ultimate CMR of the minus 400-mesh size fraction for the three coals is much smaller than that of plus 400-mesh size fraction. The magnitude of the ultimate CMR of the minus 400-mesh fraction does not correlate with the hydrophobicity of the three coals, whereas the ultimate CMR value of the plus 400-mesh fraction does. This suggests that a different flotation mechanism is involved in the flotation of the two different size fractions. In the collector starvation situation, the minus 400-mesh fraction is floated predominately by carryover in the froth, which is not controlled by the hydrophobicity of the coals. On other hand, the plus 400-mesh fraction is floated by true flotation, which is controlled by the hydrophobicity of the coals. Therefore, the higher ultimate CMR and flotation

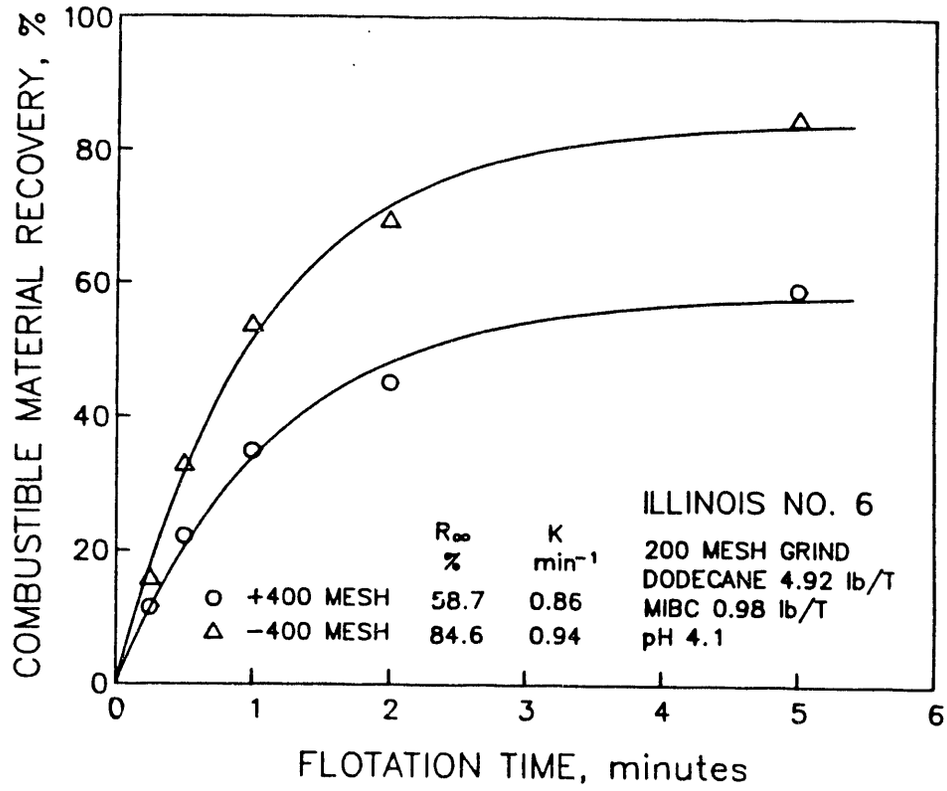

Figure 5.1 - The combustible material recovery of plus 400 and minus 400-mesh size fractions of minus 200-mesh Illinois No. 6 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics.

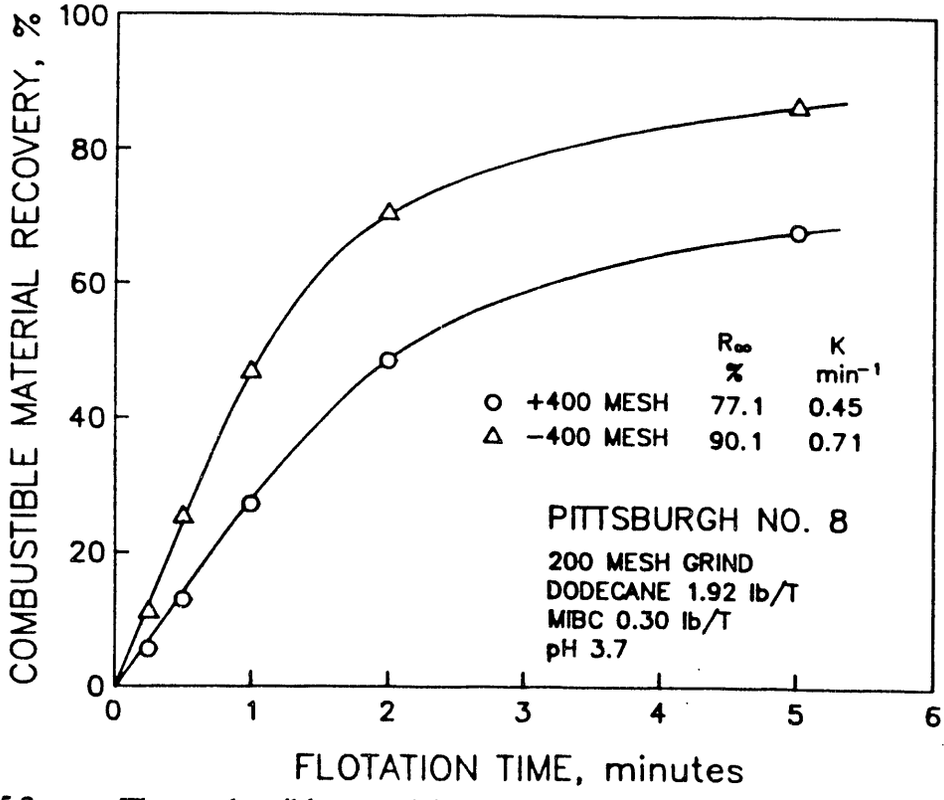

Figure 5.2 - The combustible material recovery of plus 400 and minus 400-mesh size fractions of minus 200-mesh Pittsburgh No. 8 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics.

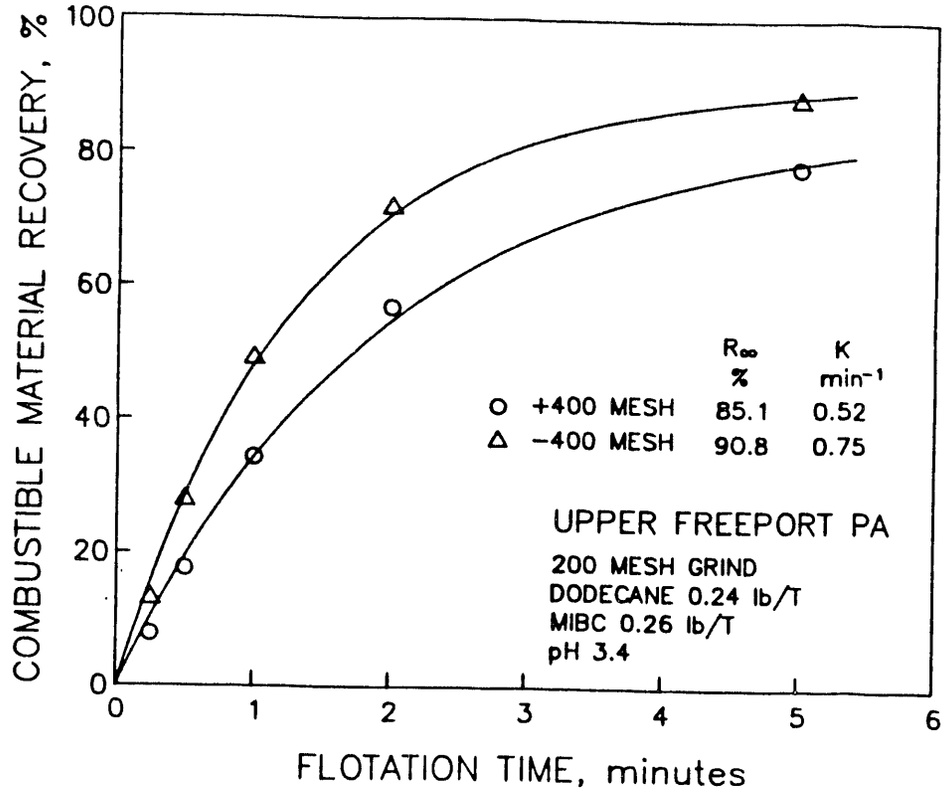

Figure 5.3 - The combustible material recovery of plus 400 and minus 400-mesh size fractions of minus 200-mesh Upper Freeport PA coal as a function of flotation time along with the fitting curves of the classical first-order kinetics.

rate constant of the minus 400-mesh fraction than that of the plus 400-mesh fraction are due to froth carry over and the formation of agglomerates of the finer coal particles.

Figures 5.4, 5.5 and 5.6 show the overall flotation recoveries of combustible materials, ash and pyritic sulfur of the three base coals as a function of flotation time along with the fitting curves of the classical first-order kinetics and the two fitting parameters. It can be seen from these figures that for all three coals, the ultimate combustible material recovery is significantly higher than that of ash and pyritic sulfur, whereas the flotation rate constants of the three different components are almost the same. This may indicate that the float portion of ash and pyrite may be either locked with coal or carried over by coal particles during flotation. Another important observation from Figures 5.4, 5.5 and 5.6 is that the recoveries of ash and pyrite for Illinois No. 6 and Pittsburgh No. 8 coals are very close at all flotation times, whereas the pyritic sulfur recovery of Upper Freeport PA coal is significantly lower than its ash recovery. This may

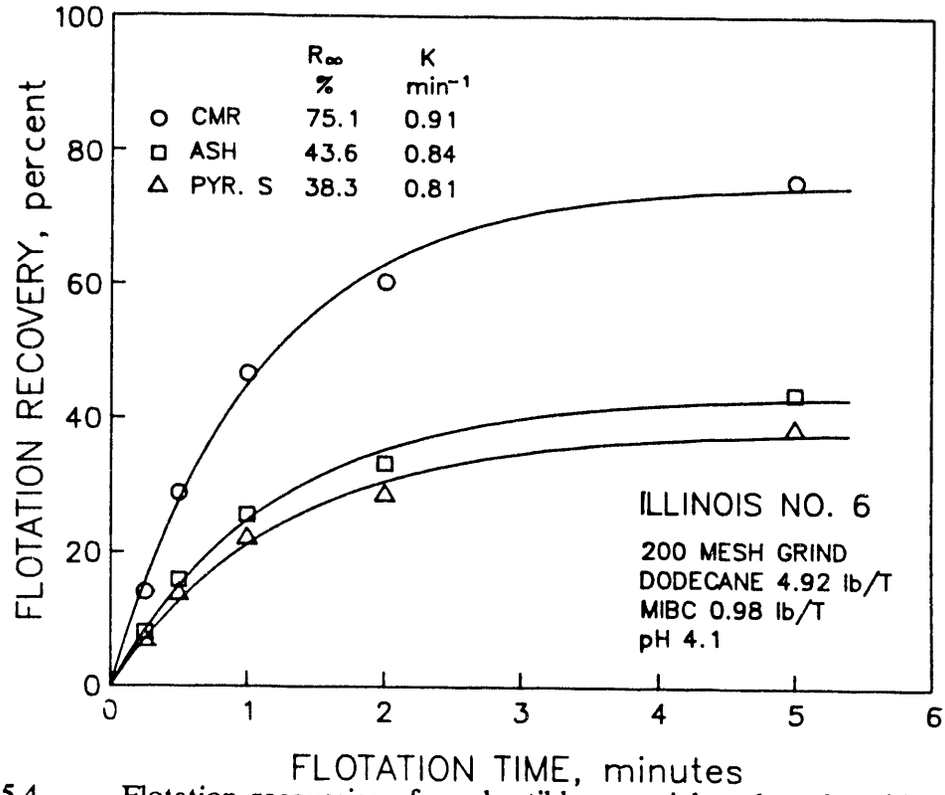

Figure 5.4 - Flotation recoveries of combustible materials, ash and pyritic sulfur of minus 200-mesh Illinois No. 6 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics.

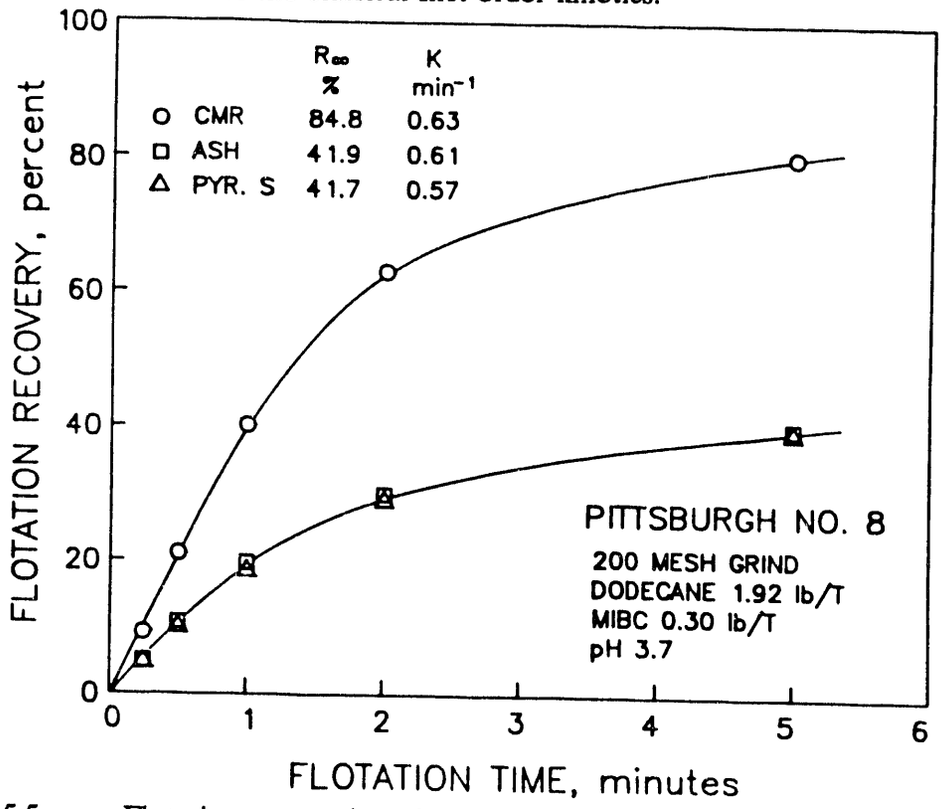

Figure 5.5 - Flotation recoveries of combustible materials, ash and pyritic sulfur of minus 200-mesh Pittsburgh No. 8 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics.

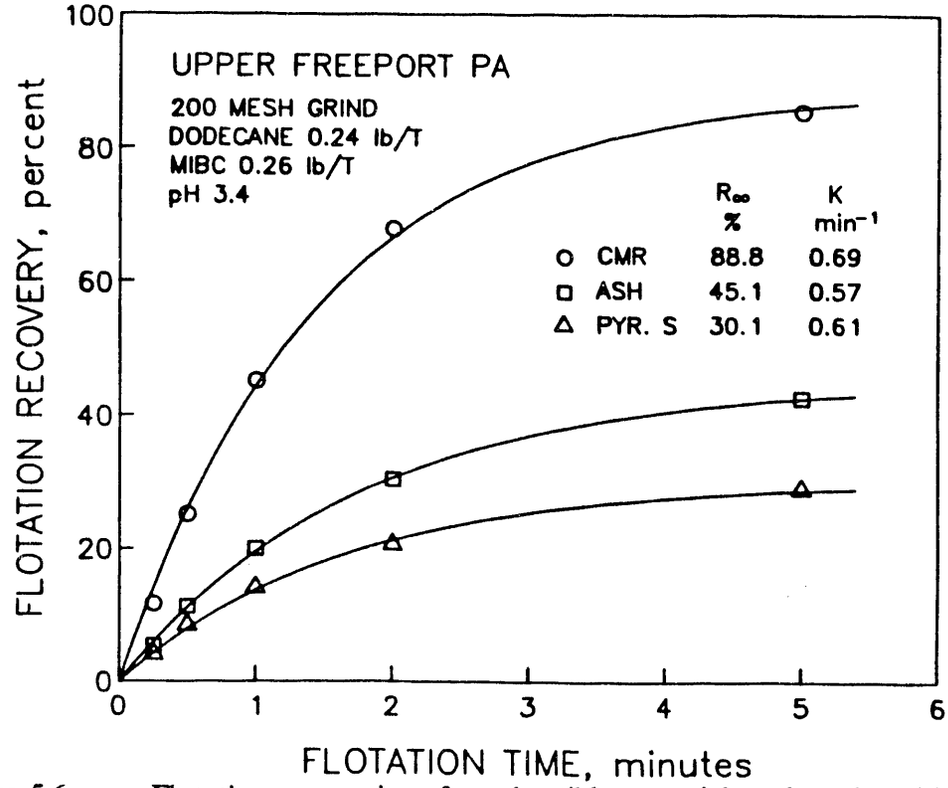

Figure 5.6 - Flotation recoveries of combustible materials, ash and pyritic sulfur of minus 200-mesh Upper Freeport PA coal as a function of flotation time along with the fitting curves of the classical first-order kinetics.

indicate the higher percentage of liberated pyrite in Upper Freeport PA coal and/or lower hydrophobicity of the pyrite particles.

5.2 Effect of particle topsize of the feed on separation efficiency and flotation kinetics.

In order to delineate the effect of grind size on the flotation performance of the three coals, the CMR, ash and pyritic sulfur rejection and separation efficiency of the three coals at 28, 100 and 200-mesh topsize were compiled and are presented in Tables 5.5 through 5.7. It can be seen from these tables that for all three coals the CMR decreases while the ash and pyritic sulfur rejections increase with decreasing feed size. Because the same amount of dodecane and MIBC was used in the different grinds for each coal and the sample with finer feed size has larger total surface area per unit weight, the collector coverage on the coal surface decreases with decreasing grind size, and therefore, the CMR is expected to decrease as well. On the other hand, the

Table 5.5 - Combustible material recovery (CMR), ash and pyritic sulfur rejection, and separation efficiency of Illinois No. 6 coal for different grind sizes (dodecane 4.92 lb/T and MIBC 0.98 lb/T at pH about 4.5).

Grind Size, mesh	Flotation Time, minutes	CMR %	Ash Rej., %	Pyr. S Rej., %	EI_H
28	0.25	60.2	66.6	65.0	25.2
	0.5	84.1	51.7	48.1	32.3
	1.0	92.1	46.1	43.0	35.1
100	0.25	35.1	81.2	80.1	15.2
	0.5	60.9	67.5	65.9	26.8
	1.0	76.0	58.8	57.7	33.7
	2.0	82.3	52.9	54.6	37.0
	5.0	85.8	47.7	51.2	37.0
200	0.25	14.1	91.9	93.2	7.3
	0.5	28.8	84.1	86.2	15.1
	1.0	46.6	74.4	78.0	24.6
	2.0	60.4	66.6	71.4	31.8
	5.0	75.4	56.3	61.6	37.0

Table 5.6 - Combustible material recovery (CMR), ash and pyritic sulfur rejection, and separation efficiency of Pittsburgh No. 8 coal for different grind sizes (dodecane 1.92 lb/T and MIBC 0.30 lb/T at pH about 3.4).

Grind Size, mesh	Flotation Time, minutes	CMR %	Ash Rej., %	Pyr. S Rej., %	EI_H
28	0.25	72.1	56.3	47.8	19.8
	0.5	85.4	47.0	37.1	22.6
	1.0	94.2	41.5	30.7	24.9
100	0.25	30.0	84.1	82.8	12.7
	0.5	53.2	72.3	70.2	23.4
	1.0	69.7	64.2	61.6	31.3
	2.0	77.6	59.4	56.9	34.6
	5.0	83.1	54.0	51.9	35.0
200	0.25	9.2	95.1	95.4	4.6
	0.5	21.0	89.3	90.1	11.1
	1.0	40.0	80.4	81.7	21.7
	2.0	62.9	70.3	71.3	34.2
	5.0	80.2	60.2	60.9	41.1

Table 5.7 - Combustible material recovery (CMR), ash and pyritic sulfur rejection, and separation efficiency of Upper Freeport PA coal for different grind sizes (dodecane 0.24 lb/T and MIBC 0.26 lb/T at pH about 3.4).

Grind Size, mesh	Flotation Time, minutes	CMR %	Ash Rej., %	Pyr. S Rej., %	EI_H
28	0.25	58.6	68.7	70.9	29.5
	0.5	70.2	61.8	64.5	34.7
	1.0	83.9	53.8	56.8	40.7
100	0.25	23.4	89.7	92.0	15.4
	0.5	45.5	79.9	84.5	30.0
	1.0	66.5	69.9	77.7	44.2
	2.0	81.0	61.1	71.2	52.3
	5.0	89.5	51.8	62.89	52.4
200	0.25	11.7	94.6	95.9	7.6
	0.5	25.1	88.7	91.5	16.6
	1.0	45.1	80.1	85.9	31.0
	2.0	67.8	69.6	79.4	47.2
	5.0	85.5	57.5	71.1	56.6

increase in ash and pyritic sulfur rejection with decreasing grind size is due to both the lower CMR and better liberation at finer sizes. However, the change in EI for Illinois No. 6 coal is insignificant with decreasing grind size, which indicates that the decrease in CMR almost match the increase in the pyritic sulfur rejection. For Pittsburgh No. 8 and Upper Freeport PA coals, the value of EI increases with decreasing grind size, indicating that the decrease in CMR is smaller than the increase in pyritic sulfur rejection.

Figures 5.7, through 5.9 present the combustible material recovery of 28, 100 and 200-mesh grinds for the three coals as a function of flotation time along with the fitting curves of the classical first-order kinetics and the two fitting parameters. The results given in these figures show clearly that the flotation rate constant for all three coals decreases significantly as the grind size decreases. The lower collector coverage on the coal surface for the finer size is considered to be the main reason for the decrease in flotation rate constant rather than the effect of particle size because for 28-mesh grind, the flotation rate constant of the plus 48-mesh size fraction is not significant higher than that of the minus 200-mesh size fraction for all three coals.

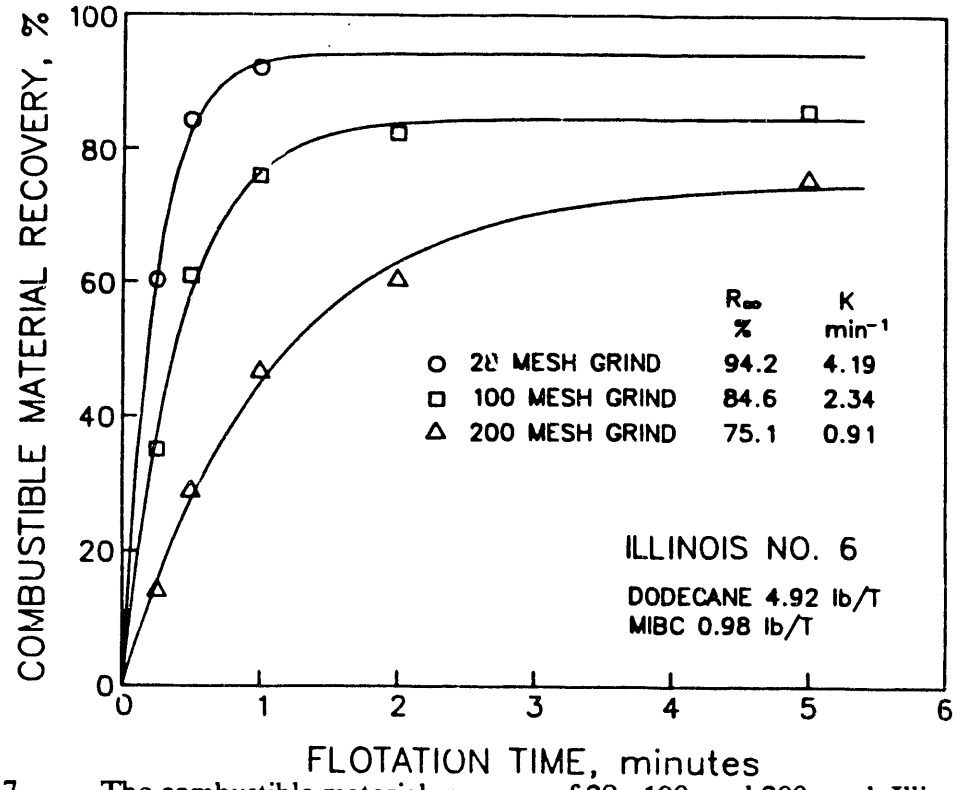

Figure 5.7 - The combustible material recovery of 28-, 100- and 200-mesh Illinois No. 6 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics.

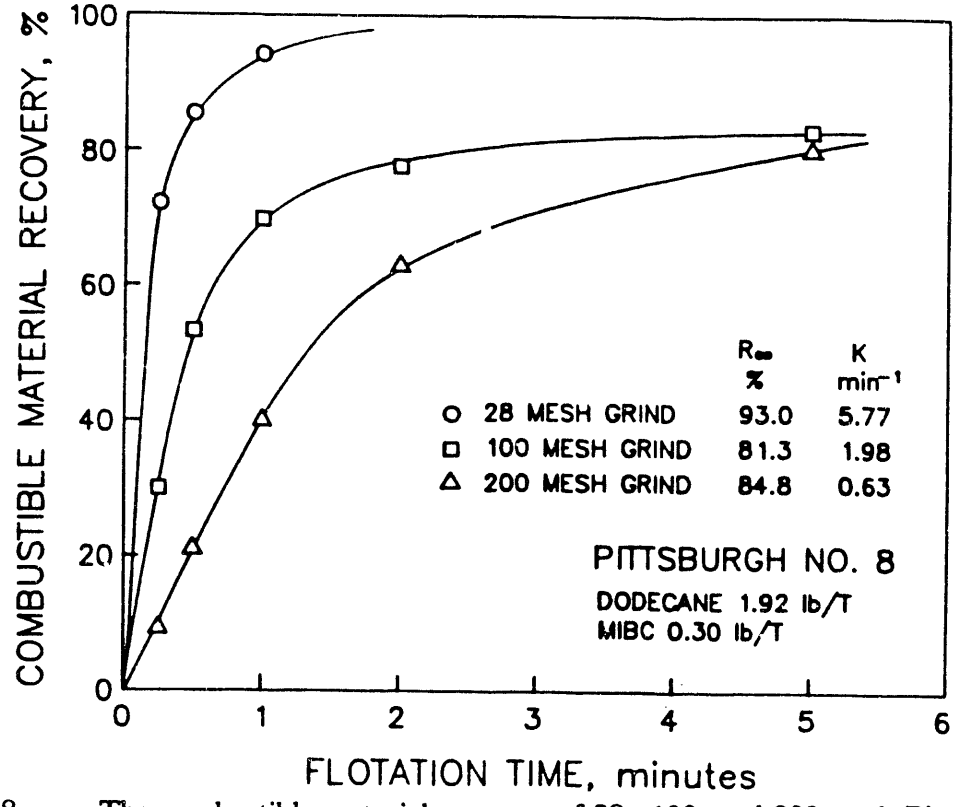

Figure 5.8 - The combustible material recovery of 28-, 100- and 200-mesh Pittsburgh No. 8 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics.

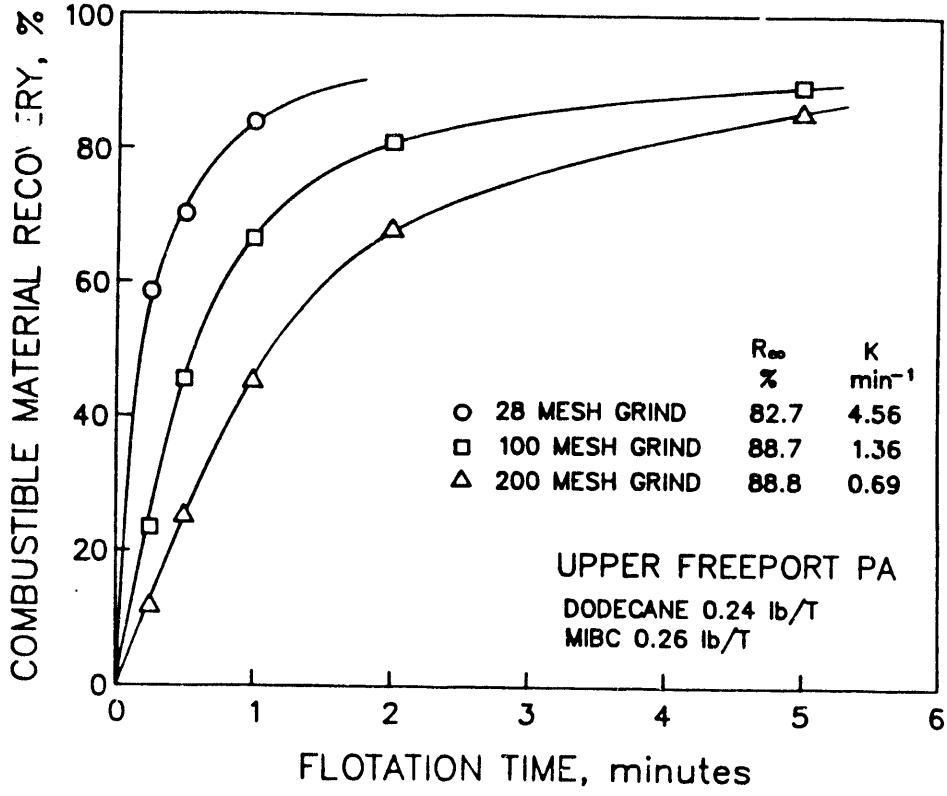

Figure 5.9 - The combustible material recovery of 28-, 100- and 200-mesh Upper Freeport PA coal as a function of flotation time along with the fitting curves of the classical first-order kinetics.

APPENDIX

DATA FOR FIGURES

Figure 2.1 Zeta potential-pH curve for i) coal sample prepared under non-precipitation conditions (sodium hydroxide addition in the mill) and aged for different intervals and ii) coal sample prepared under precipitation conditions (sodium hydroxide addition in the cell).

NaOH IN MILL		NaOH IN CELL		AGING TIME	
Cond. pH	Zeta pot. mV	Cond. pH	Zeta pot. mV	Cond. pH	Zeta pot. mV
3.08	11.54	3.08	11.54	8.8	-18.47
3.86	5.01	3.86	5.19	8.0	-13.35
4.52	-2.62	4.7	-0.37	7.8	-11.22
4.52	-1.72	5.1	-2.59	7.6	-10.48
5.92	-11.01	5.9	-2.19	7.5	-11.39
7.38	-19.89	5.9	-0.17	6.89	-7.93
7.44	-18.34	6.96	-5.33	7.0	-6.9
9.24	-34.18	8.1	-11.82		
11.2	-52.9	9.3	-20.38		
		9.31	-18.41		
		11.02	-31.13		

Figure 2.2 Zeta potential-pH curve for i) coal sample prepared under non-precipitation conditions (sodium hydroxide addition in the mill), ii) coal sample prepared under precipitation condition (sodium hydroxide addition in the cell), and iii) precipitate formed from the supernatant of the coal slurry.

NAOH ADDED IN CELL		NAOH ADDED IN MILL		PRECIPITATE	
Cond. pH	Zeta pot. mV	Cond. pH	Zeta pot. mV	Cond. pH	Zeta pot. mV
3.08	11.54	3.08	11.54	5.1	5.82
3.86	5.01	3.86	5.19	5.1	3.88
4.52	-2.62	4.7	-0.37	5.8	4.15
4.52	-1.72	5.1	-2.59	6.1	4.9
5.92	-11.01	5.9	-2.19	8.1	3.15
7.38	-19.89	5.9	-0.17	10.7	1.1
7.44	-18.34	6.96	-5.33	9.2	3.45
9.24	-34.18	8.1	-11.82		
11.2	-52.9	9.3	-20.38		
		9.31	-18.41		
		11.02	-31.13		

Figure 2.3 Effect of pH on the concentration of dissolved inorganic species-supernatant of Pittsburgh No. 8 coal slurry prepared by grinding coal at natural pH.

	DISSOLVED SPECIES CONC. X 10^3, G ATOMS/LIT.			
pH	Fe	Al	Mg	Ca
3.9	4.98	0.41	0.75	2.43
4.0	5.0	0.37	0.79	2.48
4.8	4.77	0.0	0.75	2.4
5.0	3.76	0.0	0.79	2.4
5.9	0.84	0.0	0.71	2.28
6.0	0.9	0.0	0.71	2.3
6.7	0.25	0.0	0.67	2.05
7.0	0.16	0.0	0.67	2.0
8.0	0.02	0.0	0.63	1.75
9.0	0.0	0.0	0.58	1.5
10.0	0.0	0.0	0.0	1.33

Figure 2.4 Zeta potential-pH curve for precipitates from i) coal slurry supernatant, ii) solution prepared using synthetic mixture of pure salts of different cationic species, iii) FeCl2 solution and iv) $MgCl_2$ solution.

COAL SUPERNATANT		SYNTHETIC SOLUTION		Fe^{2+}		Mg^{2+}	
Cond. pH	Zeta pot. mV	Cond. pH	Zeta pot. mV	Cond. pH	Zeta pot. mV	Cond. pH	Zeta pot. mV
5.1	5.82	5.0	9.35	5.1	29.87	9.58	14.41
5.1	3.88	6.4	8.9	5.8	29.61	9.8	15.81
5.8	4.15	7.9	8.8	6.9	26.14	10.2	15.81
6.1	4.9	7.91	8.47	7.5	27.01	10.5	15.07
8.1	3.15	10.0	8.25	8.64	27.72	10.86	5.07
9.2	3.45	10.4	4.21	8.9	19.18	11.42	2.28
10.7	1.1	10.7	-23.0	11.9	-2.43		
				11.0	-24.49		

Figure 2.5 Effects of washing and the presence of inorganic species on selectivity achieved during flotation of wet-ground 200 mesh Pittsburgh No. 8 coal.

pH 8 UNWASHED COAL + DW		pH 8 WASHED COAL + CS		pH 4 UNWASHED COAL + DW	
CMR %	PSR %	CMR %	PSR %	CMR %	PSR %
46.7	87.3	42.6	88.9	53.7	84.8
54.9	84.0	60.2	83.4	74.9	75.2
73.3	77.0	78.1	75.3	77.7	74.5
84.6	70.8	89.4	67.5	78.7	73.6
94.0	64.8	92.8	62.9	85.3	67.9
				85.6	69.1
				90.6	63.8
				95.4	57.9

pH 4 WASHED COAL + CS		pH 4 WASHED COAL + DW		pH 8 WASHED COAL + DW	
CMR %	PSR %	CMR %	PSR %	CMR %	PSR %
44.7	89.3	54.4	84.5	84.4	70.9
66.4	82.3	67.5	78.7	61.8	81.3
83.5	74.5	78.1	73.3	92.9	61.1
87.6	73.6	80.2	73.2	74.2	76.8
90.9	69.5	88.5	67.3		
		92.7	62.1		

Figure 2.6 Effect of washing on coal-pyrite zeta potential.

COLD WATER WASHED		HOT WATER WASHED	
Cond. pH	Zeta pot. mV	Cond. pH	Zeta pot. mV
3.01	-1.3	2.84	-0.9
4.1	-6.64	3.52	-5.61
4.62	-8.71	4.28	-8.02
6.59	-9.04	6.52	-10.63
7.08	-9.41	7.12	-11.49
7.96	-10.75	7.5	-9.57
9.5	-8.94	9.02	-11.53
11.06	-14.88	9.99	-11.52
		11.1	-18.38

Figure 3.2 Effect of grinding with GMTG on combustible matter recovery ash and pyritic sulfur rejection in the flotation of Illinois No. 6 coal.

ONE-STAGE GRIND WITHOUT GMTG			ONE-STAGE GRIND WITH GMTG		
CMR %	AR %	PSR %	CMR %	AR %	PSR %
0.0	100.0	100.0	0.0	100.0	100.0
34.7	81.63	82.87	21.5	89.0	90.2
54.08	71.55	73.98	49.3	74.4	78.5
78.22	56.67	59.27	71.0	62.6	68.3
83.77	51.56	54.28	80.8	56.7	63.6
			84.9	53.4	60.8
			88.2	50.0	57.8

Figure 3.3 Effect of grinding with GMTG on combustible matter recovery and ash and pyritic sulfur rejection in the flotation of Pittsburgh No. 8 coal.

0.0 LB/T GMTG			1.0 LB/T GMTG		
CMR %	AR %	PSR %	CMR %	AR %	PSR %
0.0	100.0	100.0	0.0	100.0	100.0
23.35	89.22	91.68	18.7	93.53	94.21
43.72	80.44	84.21	40.03	85.19	87.93
66.31	70.64	75.4	64.42	75.29	79.62
81.72	63.65	68.74	78.15	68.48	74.66
91.78	56.96	62.31	88.21	61.88	69.43

Figure 3.4 Effect of grinding with GMT on combustible matter recovery, ash and pyritic sulfur rejection in the flotation of Upper Freeport PA coal.

0.0 LB/T		1.0 LB/T GMTG	
CMR %	PSR %	CMR %	PSR %
0.0	100.0	0.0	100.0
36.6	90.74	32.5	92.98
59.8	80.57	53.0	84.87
72.7	73.05	64.7	74.89
80.3	65.9	72.7	68.78

Figure 3.5 Comparison of the effect of ethylene glycol (EG) and polyethylene glycol 200 (PEG-200) on the flotation of wet-ground minus 200 mesh Upper Freeport PA coal.

EG		PEG-200	
Dos. lb/T	EI_H	Dos. lb/T	EI_H
2.0	29.1	1.0	45.3
4.0	30.2	1.5	53.2
6.0	36.3	2.0	62.7
8.0	38.4	2.5	66.5
16.0	43.8	3.0	60.0

Figure 3.6 Comparison of the effect of ethylene glycol and polyethylene (PEG-200) on the flotation of wet-ground minus 200 mesh Upper Freeport PA coal.

EG		PEG-200	
CMR %	PSR %	CMR %	PSR %
37.3	91.8	55.8	89.5
38.2	92.0	67.3	85.9
44.8	91.5	79.9	82.8
49.3	89.1	95.8	70.7
58.6	85.2	97.1	62.9

Figure 3.7 Effect of pentylether on the flotation separation efficiency of wet-ground minus 200-mesh Upper Freeport PA coal.

Dosage lb/T	EI_H
0.5	35.8
1.0	49.2
1.5	61.6
2.0	64.1
2.5	63.2

Figure 3.8 Comparison of the effect of dipentyamine (DPA) and butylamine on the flotation of wet-ground minus 200-mesh Upper Freeport PA coal.

DPA		BA	
Dosage lb/T	EIH	Dosage lb/T	EIH
0.1	25.1	1.0	37.2
0.3	56.6	2.0	52.1
0.4	65.8	3.0	66.5
0.5	61.5	4.0	66.1
1.0	53.2		

Figure 3.9 Comparison of effect of pentylether (PE), dipentylamine (DPA) and butylamine (BA) on the flotation of wet-ground minus 200 Upper Freeport PA coal.

PE		DPA		BA	
Yield %	EI_H	Yield %	EI_H	Yield %	EI_H
43.4	35.8	30.0	25.1	43.9	37.2
61.5	49.2	65.4	56.6	59.3	52.1
79.6	61.6	85.5	65.8	82.6	66.5
82.8	64.1	91.7	61.5	92.5	66.1
87.8	63.2	96.6	53.2		

Figure 4.1 Effect of bubble size on the rejection of pyrite from Pittsburgh No. 8 coal.

WASHABILITY		COARSE FRIT		MEDIUM FRIT	
CMR %	PSR %	CMR %	PSR %	CMR %	PSR %
53.1	89.9	99.4	42.1	60.4	98.2
57.1	92.0	96.5	55.1	67.7	97.3
82.7	84.5	99.8	44.7	77.1	96.2
51.2	94.0	99.9	32.4	95.1	90.1
74.8	88.6	99.4	67.0	96.4	87.7
51.4	91.8	99.8	59.1		
71.0	88.1	57.6	87.7		
99.3	66.9	98.5	61.4		
64.6	89.5	91.4	61.1		
85.3	81.7	69.3	84.5		
		54.7	90.4		
		83.4	80.4		
		58.2	88.6		

Figure 4.2 Effect of bubble size on the rejection of non-pyritic minerals from Pittsburgh No. 8 coal.

WASHABILITY		COARSE FRIT		MEDIUM FRIT	
CMR %	Non Pyr. Ash Rej. %	CMR %	Non Pyr. Ash Rej. %	CMR %	Non Pyr. Ash Rej. %
53.1	83.7	99.4	46.7	60.4	85.9
57.1	84.3	96.5	58.3	67.7	82.4
82.7	72.7	99.8	54.1	77.1	77.4
51.2	84.5	99.9	28.4	95.1	55.4
74.8	74.9	99.4	59.8	96.4	51.1
51.4	85.2	99.8	55.6		
71.0	77.8	57.6	84.5		
99.3	55.9	98.5	58.3		
64.6	82.8	91.4	63.8		
85.3	71.0	69.3	78.6		
		54.7	85.7		
		83.4	73.0		
		58.2	83.3		

Figure 4.3 Effect of wash water on the rejection of pyrite from Pittsburgh No. 8 coal - tests with coarse frit.

NO WASH WATER		5 CC PER MIN. WASH WATER	
CMR %	PSR %	CMR %	PSR %
53.1	90.0	53.8	92.6
57.1	92.0	84.0	83.4
82.7	85.0	65.0	90.5
51.2	94.0	71.3	89.1
74.8	89.0	82.6	85.4
51.4	92.0	96.7	65.9
71.0	88.0	97.4	72.5
99.3	67.0	56.3	89.3
64.6	90.0	92.0	74.4
85.3	82.0		

Figure 4.4 Effect of wash water on the rejection of pyrite from Pittsburgh No. 8 coal - tests with medium frit.

NO WASH WATER		10 CC PER MIN. WASH WATER		14 CC PER MIN. WAS	
CMR %	PSR %	CMR %	PSR %	CMR %	PSR %
99.4	42.1	67.3	88.1	76.6	85.2
96.5	55.1	95.4	73.2	53.4	78.8
99.8	44.7	67.5	87.8	69.3	75.2
99.9	32.4	90.4	77.9	51.6	84.0
99.4	67.0	94.4	54.5	63.7	82.3
99.8	59.1			78.3	83.6
57.6	87.7			71.6	86.2
98.5	61.4				
91.4	61.1				
69.3	84.5				
54.7	90.4				
83.4	80.4				
58.2	88.6				

Figure 5.1 The combustible material recovery of plus 400 mesh and minus 400-mesh size fractions of minus 200-mesh Illinois No. 6 coal function of flotation time along with the fitting curves of classical first-order kinetics.

Flotation time, min.	+400 MESH CMR %	-400 MESH CMR %
0.25	11.5	15.6
0.5	22.1	32.6
1.0	34.9	53.4
2.0	45.1	69.1
5.0	59.2	84.7

Figure 5.2 The combustible material recovery of plus 400 and minus 400-size fractions of minus 200-mesh Pittsburgh No. 8 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics.

Flotation time, min	+400 MESH CMR %	-400 MESH CMR %
0.25	5.6	11.0
0.5	13.0	25.1
1.0	27.1	46.6
2.0	48.5	70.3
5.0	68.0	86.5

Figure 5.3 The combustible material recovery of plus 400 and minus 400-mesh size fractions of minus 200-mesh Upper Freeport PA coal as a of flotation time along with the fitting curves of the class first-order kinetics.

Flot. time min.	+400 MESH CMR %	-400 MESH CMR %
0.25	7.9	13.0
0.5	17.7	27.7
1.0	34.3	49.0
2.0	56.9	71.7
5.0	78.0	88.1

Figure 5.4 Flotation recoveries of combustible materials, ash and pyritic sulfur of minus 200-mesh Illinois No. 6 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics.

Flot. time min.	CMR Flot. rec.	ASH Flot. rec.	PYR. S Flot. rec.
0.25	85.9	8.1	6.8
0.5	71.2	15.9	13.8
1.0	53.4	25.6	22.0
2.0	39.6	33.4	28.6
5.0	24.6	33.7	38.4

Figure 5.5 Flotation recoveries of combustible materials, ash and pyritic sulfur of minus 200-mesh Pittsburgh No. 8 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics.

Flot. time, min.	CMR Flot. rec.	ASH Flot. rec.	PYR. S Flot. rec.
0.25	90.8	4.9	4.6
0.5	79.0	10.7	9.9
1.0	60.0	19.6	18.3
2.0	37.1	29.7	28.7
5.0	19.8	39.8	39.1

Figure 5.6 Flotation recoveries of combustible materials, ash and pyritic sulfur of minus 200-mesh Upper Freeport PA coal as a function of flotation time along with the fitting curves of the classical first-order kinetics.

Flot. time, min.	CMR Flot. rec.	ASH Flot. rec.	PYR. S Flot. rec.
0.25	88.3	5.4	4.1
0.5	74.9	11.3	8.5
1.0	54.9	19.9	14.1
2.0	32.2	30.4	20.6
5.0	14.5	42.5	28.9

Figure 5.7 The combustible material recovery of 28-, 100- and 200-mesh Illinois No. 6 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics.

Flot. time, min.	COMBUSTIBLE MATERIAL RECOVERIES 28 mesh	100 mesh	200 mesh
0.25	60.2	35.1	14.1
0.5	84.1	60.9	28.8
1	92.1	76.0	46.6
2		82.3	60.4
5		85.8	75.4

Figure 5.8 The combustible material recovery of 28-, 100- and 200-mesh Pittsburgh No. 8 coal as a function of flotation time along with the fitting curves of the classical first-order kinetics.

Flot. time, min.	COMBUSTIBLE MATERIAL RECOVERIES 28 mesh	100 mesh	200 mesh
0.25	72.1	30.0	9.2
0.5	85.4	53.2	21.0
1.0	94.2	69.7	40.0
2.0		77.6	62.9
5.0		83.1	80.2

Figure 5.9 The combustible material recovery of 28-, 100- and 200-mesh Upper Freeport PA coal as a function of flotation time along curves of the classical first-order kinetics.

Flot. time, min.	COMBUSTIBLE MATERIAL RECOVERIES 28 mesh	100 mesh	200 mesh
0.25	58.6	23.4	11.7
0.5	70.2	45.5	25.1
1.0	83.9	66.5	45.1
2.0		81.0	67.8
5.0		89.5	85.5

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