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MODIFICATION OF THE FLOATABILITY OF COAL PYRITES

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ABSTRACT. The effect of various flotation depressants and surface treatments on the floatability of coal derived pyrites in the presence of MIBC was investigated with a modified Hallimond tube microflotation cell. The floatability of pyrite particles which had been cleaned with hot dilute (5%) hydrochloric acid was relatively large. However, the floatability of such particles was reduced greatly by the addition of specific depressants such as calcium hydroxide and also by treating the pyrite with an aerated warm alkaline solution. Although this treatment and these depressants also had some effect on the floatability of coal particles, the effect was much less than on the pyrite particles.

INTRODUCTION

Although the cleaning and recovery of fine-size coal by froth flotation has been practiced commercially for many years, the technique has not been perfected to the degree where it can be counted on to remove consistently a large percentage of the iron pyrites which contaminate most coal (1,2). Finely disseminated microcrystallites of pyrite are particularly troublesome. The problem of separation seems due partly to the similarity in surface properties of unweathered bituminous coal and freshly exposed (unoxidized) pyrite (3,4). Both materials tend to be naturally water repellant or hydrophobic and both tend to float readily in an aerated water suspension using only a frothing agent or an agent such as methyl isobutyl carbinol (MIBC) which is reputed to have both frothing and collecting properties (4-7). Sometimes nonspecific collectors such as kerosene or fuel oil are used to enhance the recovery of less floatable coals. Unfortunately oily collectors also increase the recovery of pyrites (2). Apparently there are no known collectors which are specific for coal (8).

A method of improving the separation of coal and pyrites which has received consideration is that of utilizing specific pyrite depressants which suppress the flotation of pyrite while not affecting the recovery of coal. While pyrite depression is a well-developed commercial technique in the case of metalliferous ore flotation, it has not achieved similar status in the case of coal flotation (2). However, several previous studies have laid the groundwork. Many years ago Yancey and Taylor (9) showed by means of flotation tests conducted with pine oil as a frother that in a pH range of 4.5 to 6.9 iron sulfates were powerful depressants for pyrites which had been isolated from coal. But these agents were less effective when applied to mixtures of coal and pyrites. As a result of a subsequent study, Baker and Miller (10) attributed the depression of pyrite by a ferric salt to the formation of a positively charged colloidal ferric hydroxide precipitate. These investigators found too that the colloidal hydroxides of aluminum, chromium and copper were also effective depressants for pyrite in coal flotation using MIBC as a frother. In another study Miller (11) showed that lime or a mixture of potassium permanganate and sodium sulfite also tended to depress pyrite in coal flotation with MIBC. On the other hand, Min (12), Le (13), and Laros (14) tested several of these potential depressants for pyrite and met with only limited success in treating Iowa bituminous coal containing finely disseminated pyrites.

An alternate approach to pyrite depression is through wet oxidation of the pyrite surface by a warm alkaline solution containing dissolved air or oxygen. The effectiveness of this treatment in reducing the floatability of pyrite in coal flotation was demonstrated by Min (12), Le (13), and Patterson (15). According to Glembotskii et al.(4), wet oxidation of pyrite leads to the formation of a highly hydrated film of ferric hydroxide on the pyrite surface, and this film greatly reduces the floatability of the pyrite. Moreover, wet oxidation is more active in an alkaline solution.

In the experimental investigation described below, various potential methods of depressing pyrite were applied to coal-derived pyrites and beneficiated coal fines, and the relative floatability of the materials was measured with a modified Hallimond tube microflotation cell to determine the effectiveness of the method. Raw pyrites and pyrites which had been cleaned by different procedures to remove possible oxidation products were included in the study.

EXPERIMENTAL METHODS AND MATERIALS

The relative floatability of pyrite and/or coal particles was measured with a modified Hallimond tube microflotation cell (Figure 1) which was similar in design to one described by Fuerstenau et al. (16). A suspension consisting of 1 g. particles, 100 ml. solution, and a measured amount of MIBC was placed in the cell and aerated with 35 ml./min. nitrogen gas. Particles which became attached to gas bubbles were buoyed to the surface, and as the bubbles burst the particles were deposited in the concentrate collecting stem. The percentage of solids by weight which floated and collected in the stem during a 4-min. period was reported as the relative recovery and a measure of floatability.

In some instances the coal or pyrite was wet oxidized before measuring its floatability. This step involved treating 4 g. of particles suspended in 500 ml. of solution with air in an agitated, 1-liter, three-neck Pyrex flask. The oxidative treatment was applied for 15 min. at 80°C. After treatment the suspension was cooled and filtered to recover the solids. The filtrate was saved and used as the solution for the subsequent floatability measurement. The filter cake was washed with water and air dried for 10 min. Portions of the solids were weighed out and used for the floatability determination. Prolonged exposure of the freshly treated solids to the atmosphere was avoided.

Pyrite used in this study was recovered in the form of nodules from the refuse produced in cleaning coal from the Childers site adjacent to the Iowa State University Demonstration Mine in Mahaska County, Iowa. The nodules were cleaned and then in the dry state they were crushed, pulverized, and screened to provide the 124 μm X 104 μm (115 mesh X 150 mesh) particles for the floatability measurements.

The composition of the raw sized pyrite is shown in Table 1; the data indicate that the material contained about 74% FeS_2 based on the pyritic sulfur content of the sample as determined by the standard ASTM procedure for determining pyritic sulfur in coal. In addition to pyrite or marcasite, the material contained significant amounts of other iron, sulfur, and calcium compounds.

Run-of-mine high volatile C bituminous coal from the Childers site was also used in this study. The coal was prepared in the laboratory by crushing and screening to produce a 9.53 mm X 4.76 mm (3/8 in. X 4 mesh) size fraction which was then cleaned by gravity separation with a magnetite suspension having a specific gravity of 1.29. The wet float coal was further crushed, ground, and wet screened to provide the 177 μm X 149 μm (80 mesh X 100 mesh) particles for the floatability measurements. The average composition of the prepared coal is shown in Table 2. This material was stored under water until needed in order to minimize surface oxidation.

FLOATABILITY OF PYRITE AND COAL

As noted above, the materials used in this investigation were impure. The raw pyrites contained 4.8% calcium, and calcium is regarded as a depressant for pyrite (2,4-7). Moreover, the surface of pyrite is reputed to oxidize fairly rapidly on exposure to the atmosphere or to water containing dissolved oxygen (4,9). As a result, the surface becomes contaminated with iron oxides and sulfates which affect the floatability of the material. In order to determine the consequences of these contaminants, various portions of sized raw pyrites were subjected to different cleaning procedures before testing.

Effect of Surface Cleaning

The first method of cleaning involved washing the raw sized pyrite with deionized water in an agitated flask for 1 hr. followed by filtration and further washing of the filter cake. This method was designed to remove soluble sulfates which Yancey and Taylor (9) had found to depress pyrite. The second method of cleaning involved soaking the raw sized pyrites in 5% hydrochloric acid at room temperature for 8 hr. with occasional stirring of the mixture followed by filtering and water rinsing. This method was designed to remove calcium carbonate and some forms of iron oxide as well as the soluble sulfates. The third method of cleaning involved washing the raw sized pyrite with 5% hydrochloric acid heated to the boiling point for 2 hr. in an agitated flask followed by cooling, filtering, and water rinsing. This method was designed to remove the less soluble iron oxides in addition to the more soluble oxides, sulfates, and carbonates. After cleaning, the materials were stored under water to minimize contact with the air. The composition of the acid cleaned materials is given in Table 1 along with the composition of the raw material. It can be seen from the data that acid cleaning increased the pyrite (FeS_2) content of the material from 74% to either 87 or 88% depending on whether cold or hot acid was used. Also acid cleaning removed most of the calcium. On the other hand, the data do not reveal any major differences between the pyrites cleaned with cold acid or hot acid.

The floatability of the raw pyrites and of the pyrites cleaned by the various procedures described above was measured with the Hallimond cell for different amounts of MIBC. The results presented in Table 3 show that with no addition of frother (MIBC) the recovery of pyrite was uniformly low (1-3%) regardless of surface preparation. The recovery of pyrite was only slightly larger when 1 μl MIBC was added, except in the case of the hot acid cleaned pyrite where the recovery was 7.2%. However, the recovery increased considerably, especially for the acid cleaned materials, when 10 μl MIBC was used. Thus for the largest amount of MIBC the recovery of hot acid cleaned pyrites was 53.1% and of cold acid cleaned pyrites 21.5%. Consequently the removal of calcium and other acid soluble impurities from the pyrite surface did increase the floatability of the material substantially. Also the hot acid treatment was much more effective than the cold acid treatment, and the difference must have been due mainly to the removal of oxides or other impurities from the surface since the bulk composition of the material was not noticeably different. On the other hand, water washing alone did not increase the floatability of the pyrites, which was counter to the experience of Yancey and Taylor (9).

Each value of the relative recovery listed in Table 3 is an average of two or more determinations. The results were fairly reproducible inasmuch as the standard deviation of the measurements ranged from about 0.3% for the smaller values of the relative recovery to 7.6% for the highest value.

In the experiments which follow 10 μl MIBC was used for most of the floatability measurements for two reasons. First, this amount provided a relatively high recovery of acid cleaned pyrites when no depressant was applied, and second, this amount also provided a high recovery of the Iowa coal which was used. Therefore it was possible to observe a large change in pyrite floatability upon the application of an effective depressant. On the other hand, it should be noted that this amount of MIBC is 20-30 times greater than would be used in commercial practice.

Potential Pyrite Depressants

The effect of various inorganic chemical reagents on the floatability of hot acid cleaned pyrites and/or washed coal was also studied with the Hallimond cell. For each floatability determination, one of the chemically pure reagents was added to a suspension of coal or pyrites in the cell along with 10 μl MIBC. The reagent concentration ranged from 0.5 to 4.0 wt.% in most cases.

The results presented in Figure 2 show how the relative recovery of coal or pyrites was affected by reagent concentration. Each plotted point represents an average of two or more floatability measurements. In general, the relative recovery of either material decreased upon the addition of almost any of the reagents. Also a reagent concentration of 0.5 wt.% in many cases and 1.0 wt.% in others was as effective as much higher concentrations. In other words, the floatability of the materials seemed to be independent of concentration once some threshold concentration was exceeded. Therefore it seemed appropriate to average the values of relative recovery obtained with any given reagent over the range of concentration where the results seemed essentially independent of concentration. Subsequent calculation of the mean relative recovery of coal or pyrites and the standard deviation about the mean in the case of each reagent provided the values reported in Table 4.

From Table 4 it can be seen that calcium hydroxide was the most effective depressant for pyrites and sodium chloride the least effective among the reagents tested. Moreover the concentration of calcium hydroxide was much lower than that of the other reagents because of the limited solubility of this base. Next to calcium hydroxide, the most effective depressant was sodium hydroxide, but calcium chloride in higher concentrations was as effective as sodium hydroxide (Figure 2).

Interestingly enough, the effectiveness of the four sodium compounds in depressing pyrite increased in proportion to the basicity of these compounds, that is, in the following order: NaCl, $NaHCO_3$, Na_2CO_3 and NaOH. This trend supports the suggestion of Glembotskii et al. (4) that the flotation of pyrite is depressed by the adsorption of hydroxyl ions which are furnished by most of these compounds in an aqueous solution. However, the depressing action of sodium chloride which is neither acidic nor basic requires another explanation. Perhaps the explanation lies in the adsorption of sodium ions. Gaudin and Charles (17) showed that pyrite adsorbs sodium ions over a wide range of pH with the surface concentration of sodium being proportional to both the pH and the liquid phase concentration of sodium ions. These investigators also reported that pyrite adsorbs calcium ions more strongly than sodium ions, and this may explain the depressing action of calcium chloride. The strongly depressing action of calcium hydroxide is probably due to the adsorption of both calcium ions and hydroxyl ions as Glembotskii et al.(4) suggested. These authors also indicated that calcium combines with various pyrite oxidation products forming hydrated films of calcium sulfate and/or carbonate on the pyrite surface. In this regard, Gaudin and Charles (17) observed that calcium is adsorbed by pyrite more strongly from solutions containing oxygen. The action of ferric chloride seems to lie in the hydrolysis of the ferric ions and precipitation of colloidal ferric hydroxide which is adsorbed by the pyrite as suggested by Baker and Miller (10).

None of these inorganic reagents depressed the floatability of coal as much as that of pyrite (Figure 2 and Table 4). Even the strongest depressants for coal (ferric chloride and sodium hydroxide) did not reduce the relative recovery much below 80%, while magnesium chloride and sodium chloride hardly reduced the recovery at all. Since calcium hydroxide had about as much effect as sodium hydroxide on the recovery of coal, it appears that the depressing action of these compounds was due mainly to the hydroxyl ions rather than the cations. The importance of the hydroxyl ions was further indicated by the ranking of the four sodium compounds as coal depressants in the same order as their basicity. Furthermore, calcium chloride had much less effect on the recovery of coal than on the recovery of pyrite which seems to indicate that calcium ions are not as strongly adsorbed by coal as by pyrite.

Wet Oxidation

Wet oxidation was also investigated as a means of depressing the floatability of pyrites. Raw, unwashed pyrites or pyrites which had been cleaned with hydrochloric acid were treated with a warm aerated solution to oxidize the surface of the material. Following this treatment, the material was transferred to the Hallimond cell and the floatability of the material determined in the usual manner with 10 μl MIBC. Except for the presence of oxygen, the same solution was employed for both the oxidative treatment and the floatability measurement. The treatments were carried out both with and without an alkali present as well as with different alkalis and alkali concentrations. Wet oxidation was also applied to precleaned and sized coal to see whether it would affect the floatability of the coal.

The floatability of coal or pyrites which had been wet oxidized as well as the floatability of coal or pyrites which had not been wet oxidized is shown in Figures 3-6 for the different alkalis employed in this study. Again, each point plotted in these diagrams represents an average of two or more floatability measurements. Since there was little variation in the relative recovery of these materials due to alkali concentration as long as the concentration was larger than some threshold value, the recovery was averaged over the appropriate range of concentration for any given alkali; the results are presented in Table 5.

The results achieved when sodium hydroxide was used (Figure 3 and Table 5) show that the oxidative treatment significantly reduced the floatability of either unwashed pyrites or hot acid cleaned pyrites. More importantly, the oxidative treatment was more effective than sodium hydroxide alone in depressing the pyrites while not exerting any greater effect than the alkali on the coal. Also the effect of the oxidative treatment was more pronounced when it was applied to clean pyrites than to unwashed pyrites. On the other hand, the floatability of the pyrites oxidized in an alkaline solution was about the same (5-7% recovery) regardless of previous preparation or alkali concentration. In other words, it seemed to make little difference whether the pyrites had been precleaned with acid or not. But when the oxidative treatment was applied without alkali present, the previous preparation made considerable difference as can be seen by comparing the recovery of hot acid cleaned pyrites (45%), cold acid cleaned pyrites (17%) and unwashed pyrites (5%). The floatability of unwashed pyrites seemed completely insensitive to the concentration of alkali used in the oxidative treatment.

The floatability of unwashed pyrites which had not been wet oxidized was always lower than that of the hot acid cleaned but unoxidized pyrites, and it was not affected by sodium hydroxide nearly as much (Figure 3). Whereas the recovery of acid cleaned pyrites dropped from 52 to 18% in going from an alkali concentration of 0 to 0.2 wt.%, the recovery of unwashed pyrites dropped from 8.5 to 6.5%. Moreover with sodium hydroxide concentrations of 0.5 to 4.0 wt.%, the recovery of unwashed pyrites was slightly larger than when no alkali was present. Therefore larger alkali concentrations which seemed to depress acid cleaned pyrites did not do much for unwashed pyrites.

The results obtained with sodium carbonate (Figure 4 and Table 5) were similar to those obtained with sodium hydroxide (Figure 3 and Table 5). Again, the oxidative treatment was a more effective depressant for either unwashed pyrites or acid cleaned pyrites than the alkali alone while not exerting any greater effect on the coal. However, the floatability of pyrites, which was somewhat higher in sodium carbonate solutions than in sodium hydroxide solutions, was not reduced to quite as low a level when the oxidative treatment was applied with the sodium carbonate solutions as with the more basic solutions. Furthermore, the oxidative treatment in the milder alkali did not reduce the floatability of the acid cleaned pyrites to the same level that it did the unwashed pyrites. Consequently, the relative recovery of wet oxidized pyrites in sodium carbonate solutions was about 10% for the acid cleaned pyrites and 7% for the unwashed pyrites as compared to 5-7% for any of these materials treated by wet oxidation in sodium hydroxide solutions.

Considering only the effect of sodium carbonate solutions on the floatability of unwashed pyrites and acid cleaned pyrites, neither of which had been wet oxidized, it is apparent from Figure 4 that a sodium carbonate concentration of 0.5 wt.% or more appreciably reduced the floatability of hot acid washed pyrites but only slightly reduced the floatability of cold acid washed pyrites and reduced the floatability of unwashed pyrites even less. The floatability of unwashed pyrites seemed to be a minimum with 1.0 wt.% sodium carbonate, while concentrations of 2.0 wt.% or more did not seem to affect the floatability of this material.

When sodium bicarbonate was used in the wet oxidation of pyrites, the results (Figure 5 and Table 5) were generally similar to those noted above for the other alkalis. However, the depressing action of the oxidative treatment in a sodium bicarbonate solution to that of a sodium bicarbonate solution alone was even greater than noted above for the other alkalis. Consequently the floatability of wet oxidized pyrites was about the same regardless of whether sodium bicarbonate of sodium carbonate solutions were used, even though by itself sodium bicarbonate was not as strong a depressant for acid cleaned pyrites as sodium carbonate. Sodium bicarbonate also had the advantage that it did not reduce the recovery of coal as much as the stronger alkalis reduced it.

The results achieved with calcium hydroxide are presented in Figure 6 (and Table 5). In Figure 6 the concentration of this material is shown as a percent of the saturated solution concentration at room temperature (25°C). A saturated solution was found to contain 0.15 wt.% calcium hydroxide at 25°C which agrees well with the previously reported value of 0.155 wt.% (18).

Because of the strongly depressing action of calcium hydroxide on pyrites, it is not surprising that further treatment by wet oxidation had little additional effect on the floatability of pyrites. Thus the relative recovery of 5% following the oxidative treatment of acid cleaned pyrites in lime water was only slightly less than the 8% recovery realized without the treatment. Furthermore with unwashed pyrites the difference in the floatability of the material which had been wet oxidized compared to that which had not was too small to be significant.

Effect of MIBC Concentration

Since most of the floatability determinations reported here were made with an MIBC concentration which was much larger than would be used in commercial or industrial practice, several determinations were made with a smaller concentration to see how the change would affect the results. These determinations were limited to precleaned coal and sized unwashed pyrites in either sodium hydroxide or sodium carbonate solutions of various concentrations.

The results of changing the MIBC concentration on the floatability of coal or pyrites in sodium hydroxide solutions are shown in Figure 7. It is apparent that noticeably less pyrite was floated with 1 μl MIBC than with 10 μl MIBC and this was the case for either the untreated raw pyrites or the wet oxidized pyrites. While the recovery of coal was not reduced significantly by changing to the lower MIBC concentration at higher alkali concentrations, it was reduced noticeably at lower alkali concentrations. Thus with an alkali concentration of 0.5 wt.%, the recovery of coal was 72% with 1 μl MIBC compared to 81% with 10 μl MIBC.

The effects of changing the MIBC concentration were more pronounced when sodium carbonate (Figure 8) was used instead of sodium hydroxide (Figure 7). Thus when the MIBC concentration was reduced, the recovery of both coal and pyrite decreased more in the presence of sodium carbonate solutions than in the presence of sodium hydroxide solutions. Consequently with 1 μl MIBC the recovery of coal was essentially the same with either alkali as long as the alkali concentration was over 1 wt.%. Also with 1 μl MIBC the recovery of wet oxidized pyrites was virtually the same with either alkali. Therefore the use of the larger MIBC concentration did tend to increase the sensitivity of the floatability of either material to the nature of the alkali used.

DISCUSSION AND CONCLUSIONS

The preceding results indicate that both bituminous coal and clean unoxidized pyrites are floated readily by aeration of a suspension containing MIBC. While the raw impure pyrites used in this study did not float readily until cleaned with hot acid, other forms of pyrite in coal may be purer and naturally more floatable. The numerous single microcrystals and framboids of pyrite observed by Greer (19) in various bituminous coals give the appearance of greater purity than the massive polycrystalline nodules used here as a source of pyrite. Also in unweathered coal the surface of these microcrystallites should be in a reduced state as long as the pyrite is imbedded in the coal and kept from contact with oxygen. Therefore in freshly ground coal before surface oxidation has taken place there may well be pyrite particles which float readily. Consequently the natural floatability of both pyrite and coal may be the principal reason why coal is so difficult to separate from pyrite by froth flotation.

The tests of various depressants showed that chemical reagents which contribute either calcium ions or hydroxyl ions are the most effective in depressing the flotation of clean unoxidized pyrites. Consequently calcium hydroxide which contributes both types of ions was found to be the most effective of all. While it was also observed that strong bases tend to depress coal, the effect is less than that on pyrites. In addition it was noted that calcium ions in themselves are not a strong depressant for coal. Therefore calcium hydroxide is probably a better depressant than sodium hydroxide because it exerts relatively more effect on pyrites than on coal.

It was demonstrated that treatment of clean pyrites with a warm alkaline solution containing dissolved air is a very effective method of reducing the floatability of pyrites. Furthermore even though the treatment exerts a greater depressing effect on pyrites than an alkaline solution by itself, it does not exert any greater effect on coal than the alkaline solution.

While these results are interesting and provide an indication of how pyrites may be depressed in coal flotation, they do not represent a complete practical demonstration. Therefore further work is being undertaken to apply these results on a larger scale and to the actual separation of coal and pyrites as they occur in different coals. This work will include both batch flotation tests with laboratory cells and continuous flotation tests with a battery of four cells, each having a volume of 0.14 m^3.

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Table 1. Composition of the Raw Sized Pyrites and Acid Cleaned Pyrites

Component	Raw pyrites	Acid cleaned pyrites	
		cold HCl	hot HCl
Pyritic sulfur, wt.%	39.7	46.6	47.0
Total sulfur, wt.%	40.2	47.2	47.9
Iron, wt.%	38.3	43.6	43.9
Calcium, wt.%	4.8	0.2	0.2
Iron pyrites, wt.%	74.3	87.2	87.9
Sulfur : iron ratio	1.81	1.86	1.86

Table 2. Average Composition of Precleaned Coal

Component		wt.%
Ash		3.46
Sulfur		
Pyritic	0.62	
Sulfate	0.09	
Organic	4.58	
Total	5.29	5.29
Calcium		0.08
Iron		0.73

Table 3. Floatability of Pyrites Cleaned by Different Procedures and Effect of Different Concentrations of MIBC

Cleaning procedure	Relative recovery, %			Standard deviation, %		
	0 μl	1 μl	10 μl	0 μl	1 μl	10 μl
None	2.6	3.8	11.4	0.18	0.13	2.25
Water washed	1.2	3.2	11.3	0.35	0.62	1.35
Cold acid cleaned	2.4	3.5	21.5	0.53	0.06	0.94
Hot acid cleaned	2.2	7.2	53.1	0.13	0.48	7.56

Table 4. Relative Recovery of Precleaned Coal and Hot Acid Washed Pyrites in the Presence of Various Reagents and 10 μl MIBC

Material	Reagent	Concentration wt.%	Relative recovery, % mean	std. dev.
Pyrites	none	------	53.1	7.56
Pyrites	NaCl	0.5 - 4	30.2	1.95
Pyrites	$NaHCO_3$	1 - 4	26.6	3.11
Pyrites	$MgCl_2$	0.5 - 4	23.8	2.68
Pyrites	Na_2CO_3	0.5 - 4	22.2	2.37
Pyrites	$FeCl_3$	0.5 - 4	16.8	2.43
Pyrites	$CaCl_2$	1 - 4	15.7	2.60
Pyrites	NaOH	0.5 - 4	14.0	1.48
Pyrites	$Ca(OH)_2$	0.03 - 0.15	8.1	1.51
Coal	none	------	92.1	2.10
Coal	$MgCl_2$	0.5 - 4	91.3	1.21
Coal	NaCl	0.5 - 4	90.0	1.74
Coal	$NaHCO_3$	1 - 4	86.9	1.56
Coal	$CaCl_2$	0.5 - 4	85.9	2.29
Coal	Na_2CO_3	1 - 4	85.4	3.37
Coal	$Ca(OH)_2$	0.03 - 0.15	80.9	1.36
Coal	NaOH	0.5 - 4	80.0	0.95
Coal	$FeCl_3$	1 - 4	79.3	3.75

Table 5. Relative Recovery of Coal and Pyrites in the Presence of Various Alkalis and 10 µl MIBC.

Material	Treatment	Alkali	Conc. wt.%	Relative recovery, %	
				mean	std. dev.
Pyrites					
unwashed	none	NaOH	0.5 - 4	9.5	1.60
unwashed	wet oxid.	NaOH	0.5 - 4	7.4	1.42
cold acid washed	wet oxid.	NaOH	0.5 - 4	4.9	0.57
hot acid washed	none	NaOH	0.5 - 4	14.0	1.48
hot acid washed	wet oxid.	NaOH	0.5 - 4	7.6	2.78
unwashed	none	Na_2CO_3	0.5 - 4	12.7	2.37
unwashed	wet oxid.	Na_2CO_3	0.5 - 4	7.4	1.42
cold acid washed	none	Na_2CO_3	0.5 - 4	14.7	1.38
cold acid washed	wet oxid.	Na_2CO_3	0.5 - 4	10.0	1.09
hot acid washed	none	Na_2CO_3	0.5 - 4	22.2	2.37
hot acid washed	wet oxid.	Na_2CO_3	0.5 - 4	11.3	1.69
unwashed	none	$NaHCO_3$	0.5 - 4	10.8	1.26
cold acid washed	none	$NaHCO_3$	0.5 - 4	18.0	1.73
cold acid washed	wet oxid.	$NaHCO_3$	0.5 - 4	7.6	1.00
hot acid washed	none	$NaHCO_3$	0.5 - 4	28.0	4.09
hot acid washed	wet oxid.	$NaHCO_3$	0.5 - 4	12.4	1.59
unwashed	none	$Ca(OH)_2$	0.03 - 0.15	5.3	0.65
unwashed	wet oxid.	$Ca(OH)_2$	0.03 - 0.15	5.7	1.29
hot acid washed	none	$Ca(OH)_2$	0.03 - 0.15	8.1	1.51
hot acid washed	wet oxid.	$Ca(OH)_2$	0.03 - 0.15	5.0	1.15
Precleaned coal					
unwashed	none	NaOH	0.5 - 4	80.0	1.52
unwashed	wet oxid.	NaOH	0.5 - 4	81.5	1.51
unwashed	none	Na_2CO_3	0.5 - 4	84.3	2.31
unwashed	wet oxid.	Na_2CO_3	0.5 - 4	82.9	2.47
cold acid washed	none	Na_2CO_3	0.5 - 4	82.6	0.75
cold acid washed	wet oxid.	Na_2CO_3	0.5 - 4	84.4	1.98
unwashed	none	$NaHCO_3$	0.5 - 4	86.9	1.56
unwashed	none	$Ca(OH)_2$	0.03 - 0.15	80.9	1.36
unwashed	wet oxid.	$Ca(OH)_2$	0.03 - 0.15	81.5	2.62

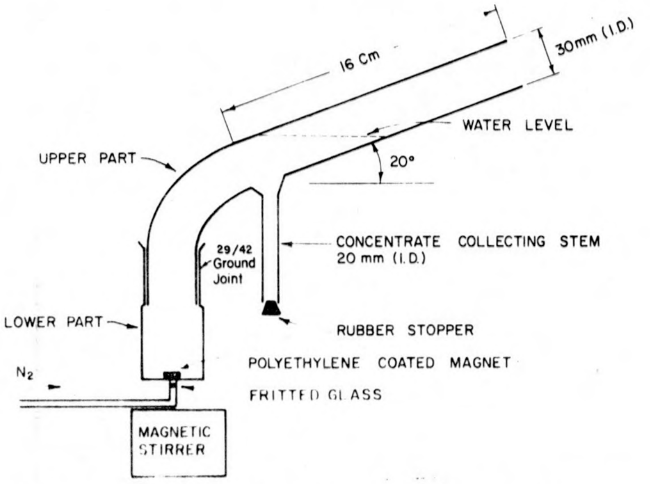

Figure 1. Modified Hallimond tube microflotation cell.

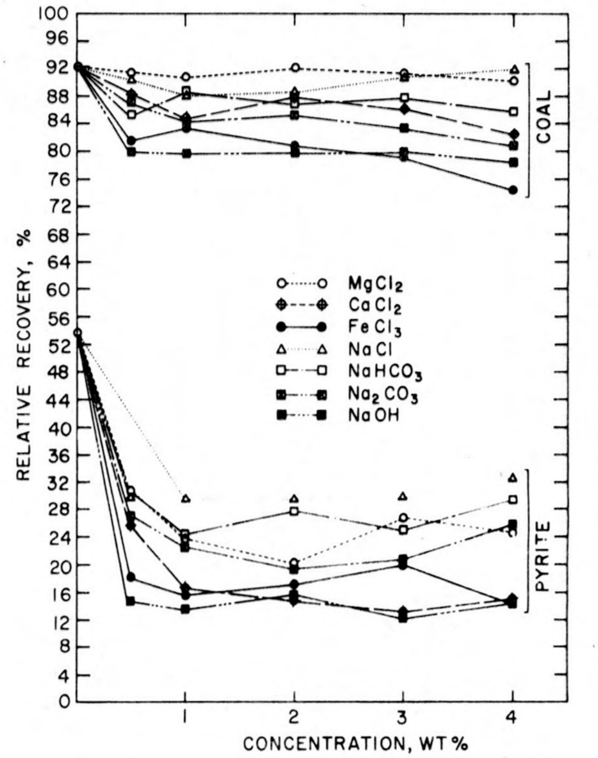

Figure 2. Effect of different chemical reagents on the floatability of coal or pyrites.

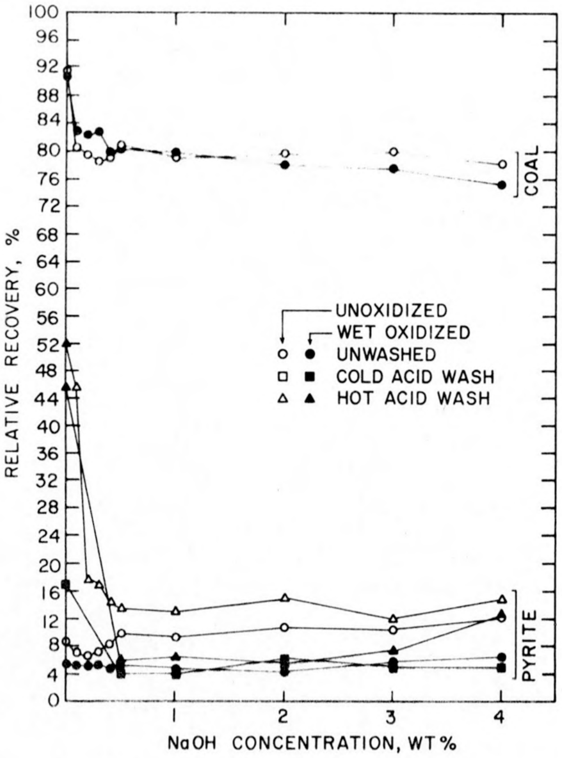

Figure 3. Effect of wet oxidation in NaOH solutions on the floatability of coal or pyrites.

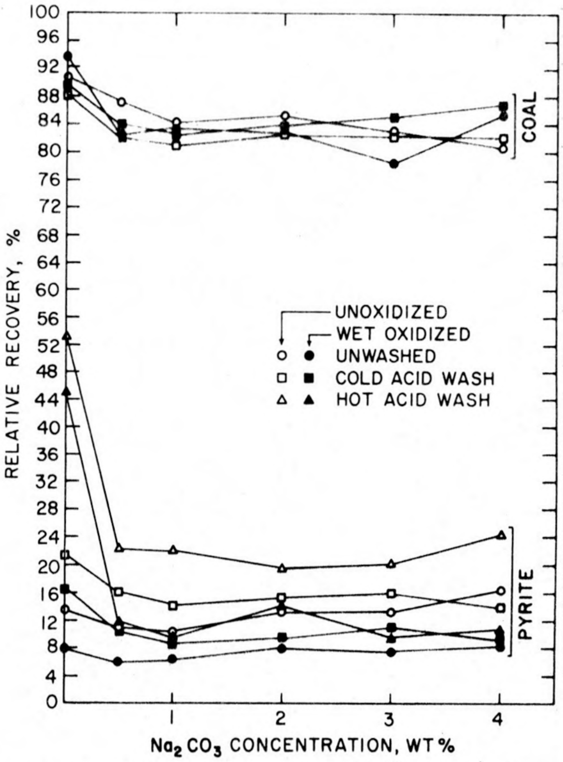

Figure 4. Effect of wet oxidation in Na_2CO_3 solutions on the floatability of coal or pyrites.

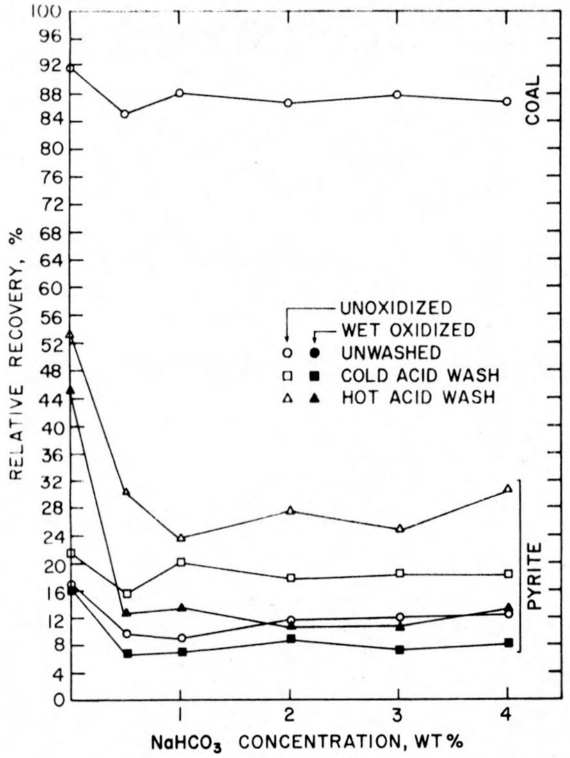

Figure 5. Effect of wet oxidation in $NaHCO_3$ solutions on the floatability of coal or pyrites.

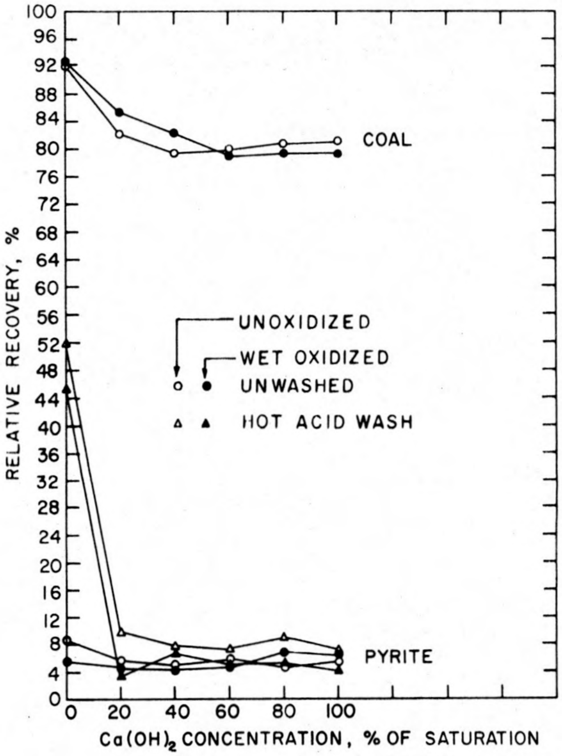

Figure 6. Effect of wet oxidation in $Ca(OH)_2$ solutions on the floatability of coal or pyrites.

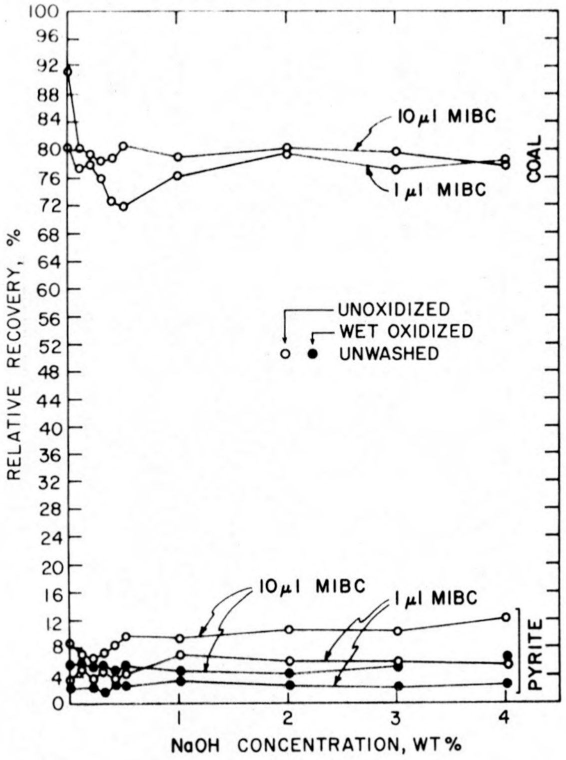

Figure 7. Effect of MIBC concentration on the floatability of coal or pyrites in NaOH solutions.

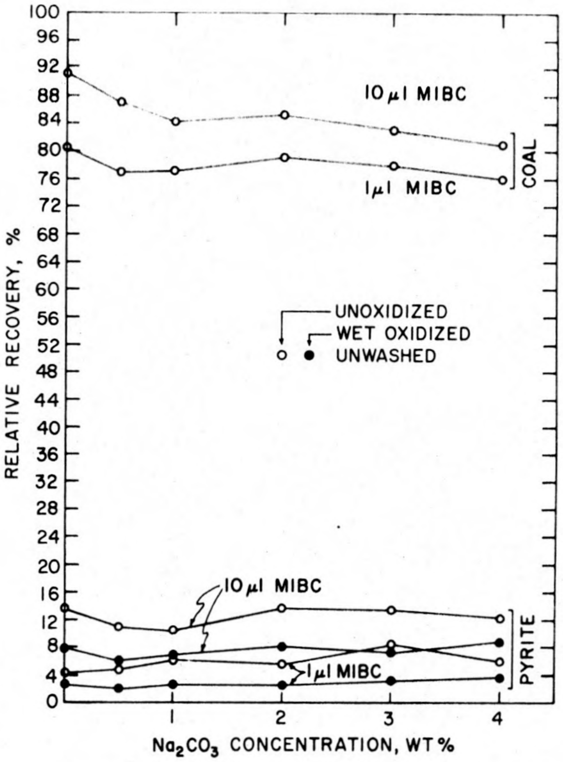

Figure 8. Effect of MIBC concentration on the floatability of coal or pyrites in Na_2CO_3 solutions.