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THE EFFECT OF ULTRASONIC CONDITIONING ON THE FROTH FLOTATION OF PITTSBURGH NO. 8 COAL

by

Louis Schlesinger and R. B. Muter

ABSTRACT

A laboratory study has been conducted to determine the effects of conditioning an ultrafine coal slurry with ultrasonic energy prior to froth flotation. Pittsburgh No. 8 coal, containing approximately 14% ash and 3.0% total sulfur (1.8% pyritic), was floated using a frother only. Ultrasound was applied using a constant frequency (20 khz) variable power supply, transducer, gain booster, and horn. The amplitude of the mechanical load ranged from 0.42 to 4.2 kw, while wave intensities varied from 210 to 2100 kw/m^2. The ultrasonic wave promoted cavitation in the coal slurry. This sharpened the separation through two mechanisms: 1) liberation of surface and pore-bound ash and pyrite from the coarsest coal particles and 2) surface polishing of minus 200 mesh clay and pyrite particles to increase their hydrophilicity. A typical flotation at 10% solids and 1500 rpm resulted in a coal product containing 0.7% less ash (4.7% compared to 5.5%) and 0.20% less sulfur (1.70% compared to 1.90%).

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I. INTRODUCTION

A. The Problem of Cleaning Ultrafine Coal

The cleaning of ultrafine coal ($\leq$ 0.5 mm) into a saleable product is one of the difficult tasks facing coal operators. Coal preparation plants which clean ultrafine coal use the froth flotation process, which exploits differences in the surface characteristics of the coal and unwanted mineral. Coal flotation feed is wet-classified out of the overall preparation plant feed and pumped into a series of tanks with impellers (Zimmerman 1979). With most flotation machines, the impeller's action draws air through a standpipe into the bottom of the tank, forming millions of tiny bubbles about 1 mm in diameter. The hydrophobic coal particles will preferentially cling to the air bubbles, which become laden with coal and rise to the surface to be mechanically removed as froth. The hydrophilic mineral particles will be wetted and will not rise to the surface (Sun 1979).

The process works well with many coals; however, many operators elect not to clean ultrafines by flotation due to (Aplan 1976): 1) inability to remove sufficient sulfur to market the coal, 2) the cost of dewatering, and 3) inability to clean ultrafine coal with a high clay content. This practice is undesirable because it wastes potentially valuable fuel and greatly increases the size of mine waste impoundments.

There are three factors which undermine the selectivity of flotation. First, coal particles have surfaced-exposed pores which can contain inclusions of ash mineral. Such particles will float, albeit more slowly than purer coal particles. Second, fine clay particles often adhere to the coal's surface due to electrostatic forces. Much of this is often recovered with the froth. Third, the economics of coal flotation require that at least 75-80% of the flotation feed be removed as froth. This mass must rise countercurrently past descending mineral particles; consequently, mineral matter can become entrapped in the froth product.

B. Application of Ultrasound

Ultrasound is the term used to describe a vibratory wave that has a frequency above the detection limit of the human ear, about 16 KHz. It has proven useful in areas as diverse as the pharmaceutical, aerospace, food, and medical industries (Cracknell 1980). Use of ultrasound in mineral or coal processing goes back to 1967; however, it has yet to be applied to coal flotation. For a complete literature review, the reader is referred elsewhere (Schlesinger 1989).

At sufficiently high intensities (i.e., threshold intensity), an ultrasonic wave will cause water to cavitate during its expansion cycle, creating millions of small low pressure bubbles. Two main types of cavitation bubbles are formed: 1) bubbles of visible size (≈1 mm in diameter) which contain air that has previously been dissolved and 2) smaller bubbles (≈0.1 mm in diameter) of water vapor (Crawford 1955). At a frequency of 20 Khz, the threshold intensities for aerated and degassed water are 10 and 1 Kw/m^2, respectively (Cracknell).

During the subsequent compression cycle of the wave, the bubbles collapse with great force and energy. Lord Rayleigh developed a simplified equation for calculating the forces developed by the collapse of a spherical bubble (Cracknell):

$$P = P_0 \ (4)^{-4/3} \ (r_0/r)^3$$

where: P = pressure developed in the liquid
P_0 = initial hydrostatic pressure
r_0 = starting radius of the bubble
r = radius at some point of collapse

At atmospheric pressure in water, the collapse of a bubble to one twentieth of its radius will generate a pressure of over 1000 atmospheres.

In addition, the presence of solid particles, coupled with crevices, pores, and irregularities on the solid surface, further promote cavitation at the liquid-solid interface. The destructive action of the bubbles at the interface, known as cavitation erosion, is the principle behind ultrasonic cleaning. This investigation centered on the effects of using this process to condition an ultrafine coal slurry prior to froth flotation.

II. EXPERIMENTAL

A. Equipment

All batch flotation tests utilized a Denver Equipment Company Laboratory Model Flotation Machine with a 2.5 liter stainless steel cell. Conditioning prior to flotation was also performed with the Denver cell; however, prewetting of the coal prior to conditioning was performed using a motor-driven single-shaft impeller with three blades.

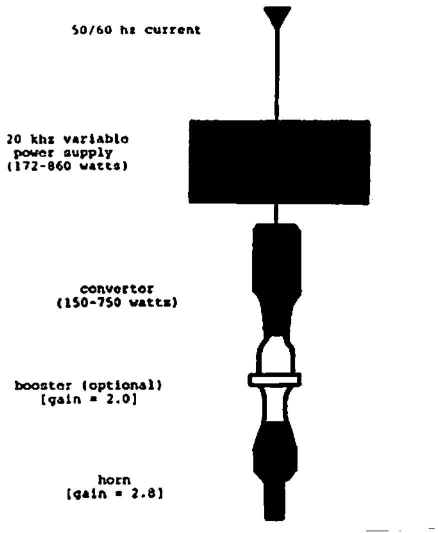
Ultrasonic power was applied using equipment designed for the ultrasonic welding of plastics by the Branson Sonic Power Company of Danbury, Connecticut. The configuration (Figure 1) consisted of four elements:

1. <u>Power Supply</u> (Model No. 184V) - A variable power supply with a 20 khz output frequency. The supply is scaled from 20-100% of full power, which is 860 electrical watts to the converter. The model utilized a line voltage of 117 volts (single phase) and draws 9.7 amps.

2. <u>Converter</u> (No. 102) - An electromechanical transducer which converts the 20 khz electrical signal (maximum 860 watts) to a mechanical vibration (maximum 750 watts).

3. <u>Booster</u> (EDP No. 101-149-013) - A ½ wavelength long resonant metal section mounted between the converter and horn for increasing (or decreasing) the amplitude of the wave at the face of the horn. Use of the booster is optional. The part used was aluminum and has a gain of 2.0. Boosters having gains varying from 0.4 to 4.0 are available in titanium as well as aluminum.

FIG. 1
ULTRASONIC EQUIPMENT



4. <u>Horn</u> (EDP No. 316-017-020) - A ½ wavelength long resonant metal section, which transfers energy to the work. This horn had circular high-gain geometry, a 2-in. diameter cross-section, and an amplitude gain of 2.8. Horns having gains varying from 0.8 to 6.7 are available in a variety of geometries and cross-sectional areas.

The combination of equipment selected afforded an amplitude range of 0.42 to 4.2 kw. The intensity of the ultrasonic wave could be varied from 210 to 2100 kw/m^2.

<u>B. Test Coal</u>

Pittsburgh No. 8 coal was selected as the test coal for three reasons: 1) it is one of the chief commercially-important coals in West Virginia and Pennsylvania, 2) is relatively low in ash (typically 12-18%) and floats fairly well; consequently, any improvement from ultrasonic conditioning would be meaningful and 3) it is generally high in pyritic sulfur and has fragile market conditions as a steam coal.

A sample of 3/8-in. x 0 coal was obtained from Consolidation Coal Company's Preparation Plant in Granville, West Virginia, which serves the Arkwright No. 1 and Osage No. 3 mines. The coal was screened using a U.S. No. 30 (0.5 mm) sieve. The undersize was mixed and split into representative samples for flotation tests. Table 1 shows the results of the coal's chemical analysis on a moisture-free basis.

TABLE 1. CHEMICAL ANALYSES OF THE TEST COAL (Moisture-Free Basis)

Percent Ash	Percent Sulfur			
	Total	Pyritic	Organic	Sulfate
14.3	3.03	1.91	1.01	0.11

C. Experimental Design and Procedure

A first experiment was conducted to determine: 1) how the amplitude of the ultrasonic wave affects flotation performance, 2) the effect of the total ultrasonic energy applied, and 3) whether ultrasound affects flotation performance in the same way at different flotation impeller speeds. (Flotation becomes slower and inherently more selective as the impeller speed is reduced; consequently, any improvement due to ultrasound might disappear.) A three-factor design was employed, using the following procedure:

- Prewet the coal at 10% solids (15 min. @ 660 rpm)
- Add 0.36 lbs. of surfactant per ton of coal (to promote frothing)
- Condition (2 min. @ appropriate machine speed)
- Float coal ½ min.
- Float coal 1½ min.
- Stage add 0.14 lbs. surfactant per ton of coal
- Condition (½ min. @ appropriate machine speed)
- Float coal 6 min.

Ultrasonic power was applied for varying amounts of time during the end of the 15-minute prewetting period at a constant amplitude of 1.4 kw. Varying amplitudes of power were applied during the ensuing 2-minute surfactant conditioning period. The pulp temperature was measured and recorded before and after the application of ultrasound. All combinations of ultrasonic conditioning were run at both 1000 and 1500 rpm. No collector was used in order to discern the effect of ultrasound on the coal's natural floatability. Methylisobutylcarbonil (MIBC) was the surfactant used. Deionized and demineralized water was employed to ensure constant water quality. Clean coal concentrate samples were removed after ½, 2, and 8 minutes of elapsed flotation time.

All concentrate and tailing samples were air dried, weighed, and pulverized to minus 60 mesh in preparation for chemical analysis. Samples were analyzed for moisture, ash, and total sulfur according to the appropriate ASTM Standard. All analyses were reported on a moisture-free basis. In calculating the result of a single flotation test, the air-dried sample weights were corrected for moisture. From these, the cumulative clean coal yields after ½, 2, and 8 minutes were calculated. Then, the individual moisture-free analyses for ash, total sulfur, and pyritic sulfur (where applicable) were used to compute the cumulative percentages of these constituents in the clean coal after ½, 2, and 8 minutes.

After evaluating the results of this experiment, a single condition for applying ultrasound was selected for use in the second experiment designed to determine the effect of ultrasound upon the coal's particle size distribution. The criteria used for selection were: 1) improvement in ash and pyrite rejection and 2) roughly equal flotation rate. Application of a 2.8 kw amplitude wave for 2 minutes during MIBC conditioning matched the criteria best. Coal samples were floated with and without ultrasound at 1500 rpm. Timed samples were taken as was the case with the preceding experiment; however, in this case, the samples were sized before weighing and chemical analysis. These size-fractionated concentrates and tails were analyzed for pyritic sulfur as well as total sulfur and ash.

The size and chemical analyses of the clean coal and tail samples were used to calculate the distributions of ash, sulfur, and combustibles according to size fraction. This enabled the separation indices (SI) for ash, total sulfur, and pyritic sulfur to be computed for each size range. Coal separation index is defined by Yoon (1984) as:

$$SI = C.D. - I.D.$$

where: SI = Separation Index

C.D. = Percentage of Combustibles Reporting to the Clean Coal

I.D. = Percentage of Ash (or Sulfur) Reporting to the Clean Coal

SI combines yield and grade into a single number between 0 and 100. (Example: If 95% of the combustibles were recovered during flotation, and 45% of the ash floated with the clean coal, the SI would be 50). This offered a simple means of comparing the flotation selectivities of the different size fractions.

III. RESULTS AND DISCUSSION

A. Effect of Varying the Level of Ultrasonic Energy

Figure 2 shows that the temperature of the coal slurry depended upon the total quantity of ultrasonic energy applied. An increase of roughly 5° C resulted from each increase of 0.10 kw-hr of energy. Figure 3 depicts the general effect of total ultrasonic energy upon clean coal yield. In general, yield increased slightly as the energy was increased to 0.094 kw-hr. Beyond this level,

FIG. 2
EFFECT OF ULTRASONIC ENERGY
UPON COAL SLURRY TEMPERATURE

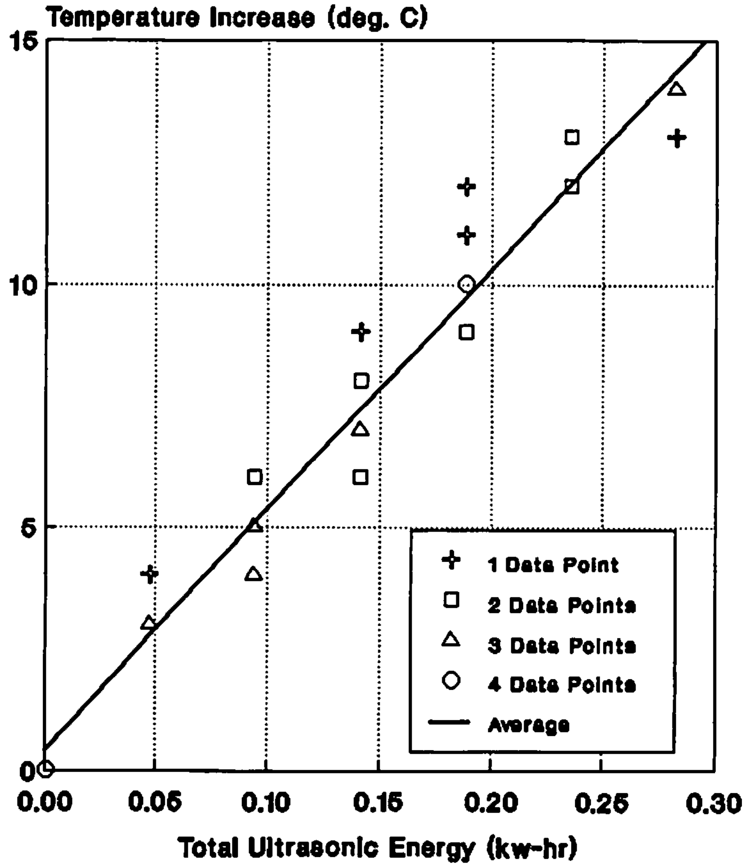
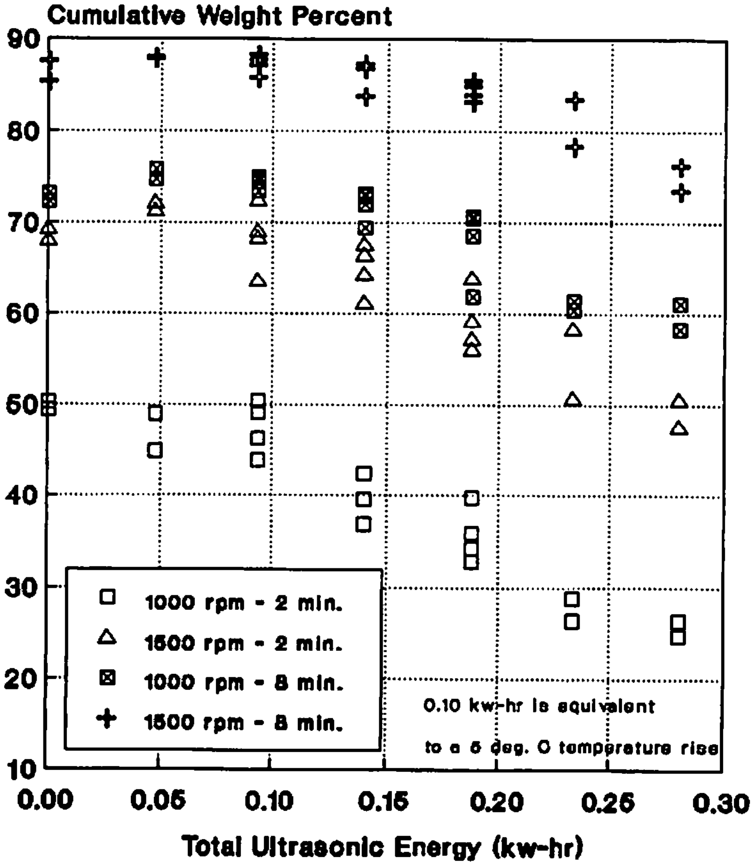


FIG. 3
EFFECT OF ULTRASONIC ENERGY
UPON CLEAN COAL YIELD



hereafter referred to as "threshold energy" (TE), the froth became progressively drier and less stable as the energy was increased. This was reflected by corresponding decreases in clean coal yield, which occurred at both the high and low impeller speeds.

Figures 4 and 5 show the general effect of total ultrasonic energy upon the percentages of ash and total sulfur in the clean coal, respectively. These decreased steadily as the energy was increased from zero, regardless of the impeller speed.

Figure 6 shows the effect of ultrasound on the ash content of the clean coal. Here, ultrasound was applied at a constant amplitude of 1.4 kw for various times during prewetting, and flotation was at 1500 rpm. Each curve is a plot of cumulative ash percent versus yield, with respect to elapsed flotation times of 30 seconds, 2 minutes, and 8 minutes. Ultrasound had the effect of translating the baseline (i.e. no ultrasound applied) ash versus yield curve to the left. As the ultrasonic conditioning time was increased, the leftward translation also increased. Figure 7 shows an identical result for the set of curves for total sulfur. Comparison of these curves for 4 and 8 minutes of ultrasonic conditioning reveals that the initial flotation rate decreased sharply as the conditioning time was increased. This can be seen after both 30 seconds and 2 minutes of flotation time. The level of energy at 4 minutes corresponds to TE.

Figures 8 and 9 illustrate a similar result when ultrasound was applied for a constant 2 minute time at various amplitudes during the surfactant conditioning stage. As the amplitude was increased, a leftward translation of the curves resulted. One difference, as compared to the cases of Figures 6 and 7, was the increase in flotation rate that occurred until the 2.8 kw amplitude (TE) was exceeded.

Figures 10 and 11 show the interaction between ultrasound and impeller speed. As expected, the flotation rates were faster and the yields higher at the higher speed. At 1500 rpm, the flotation

FIG. 4
EFFECT OF ULTRASONIC ENERGY UPON PERCENT ASH IN CLEAN COAL

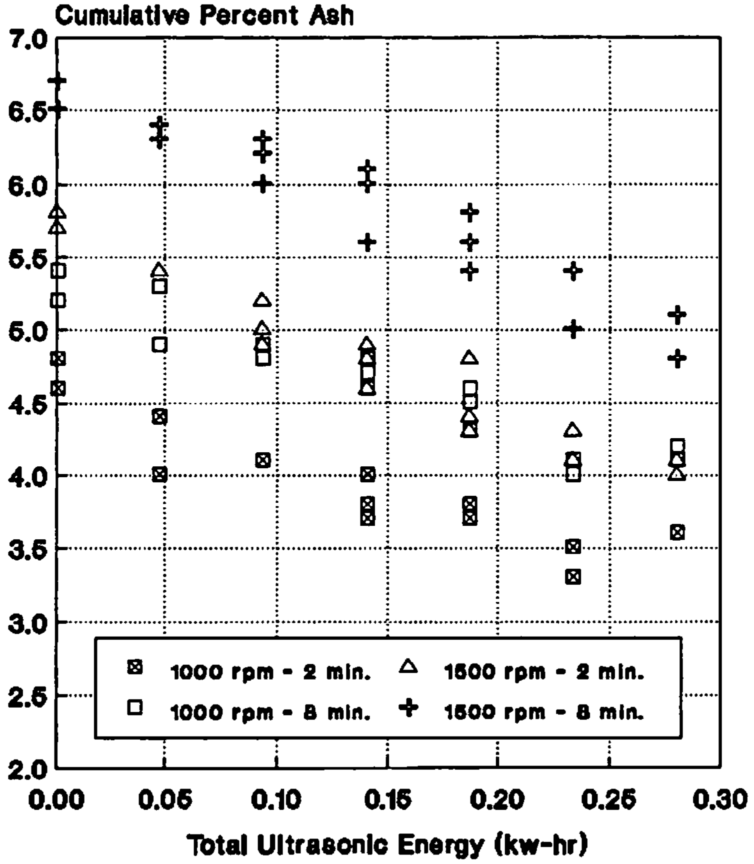


FIG. 5
EFFECT OF ULTRASONIC ENERGY UPON PERCENT SULFUR IN CLEAN COAL

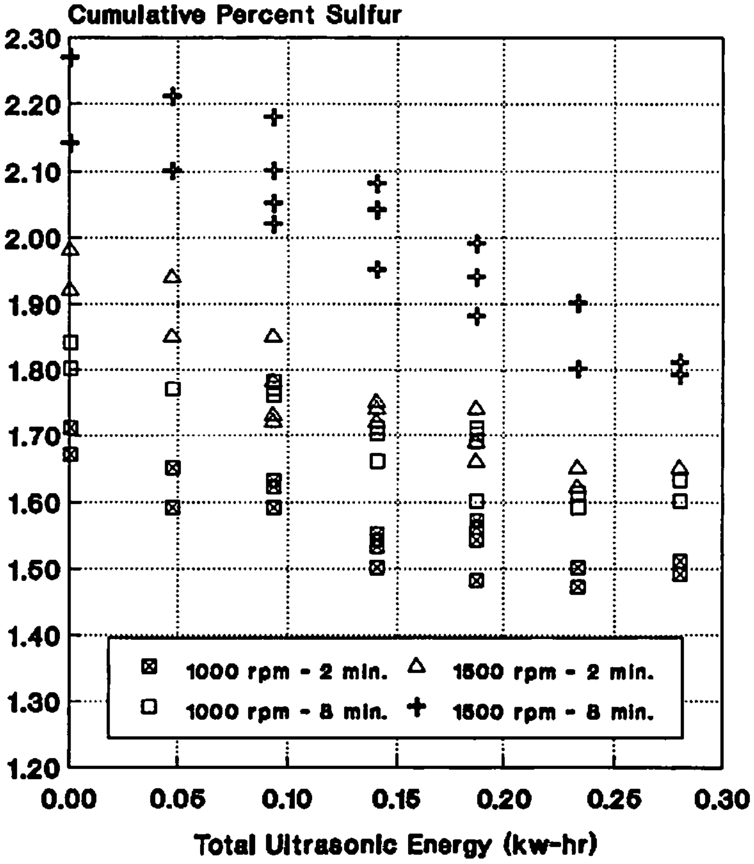


FIG. 6
EFFECT OF ULTRASONIC PREWETTING TIME
UPON COAL YIELD AND ASH CONTENT

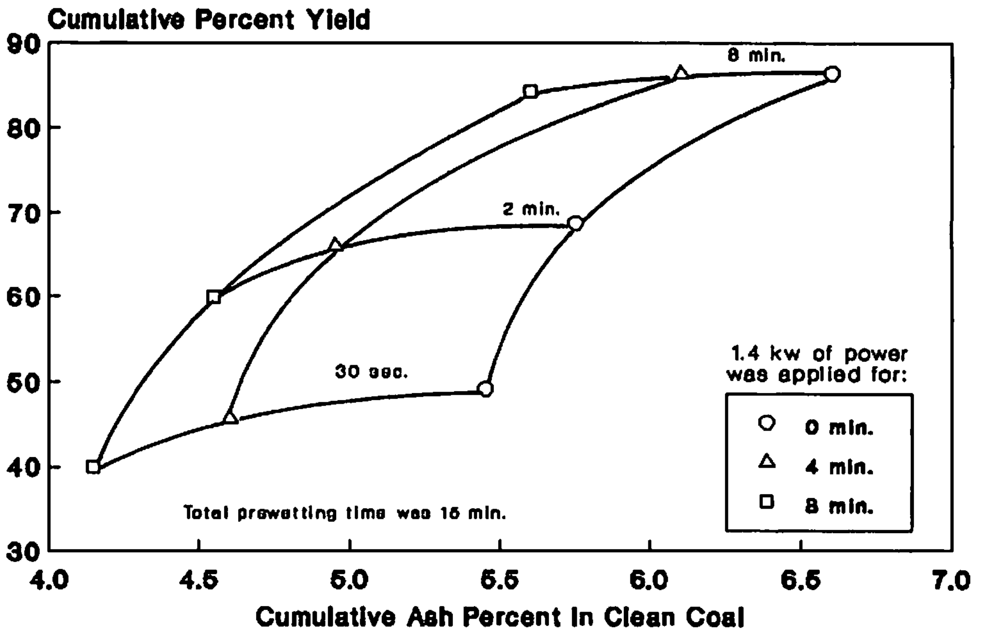


FIG. 7
EFFECT OF ULTRASONIC PREWETTING TIME
UPON COAL YIELD AND SULFUR CONTENT

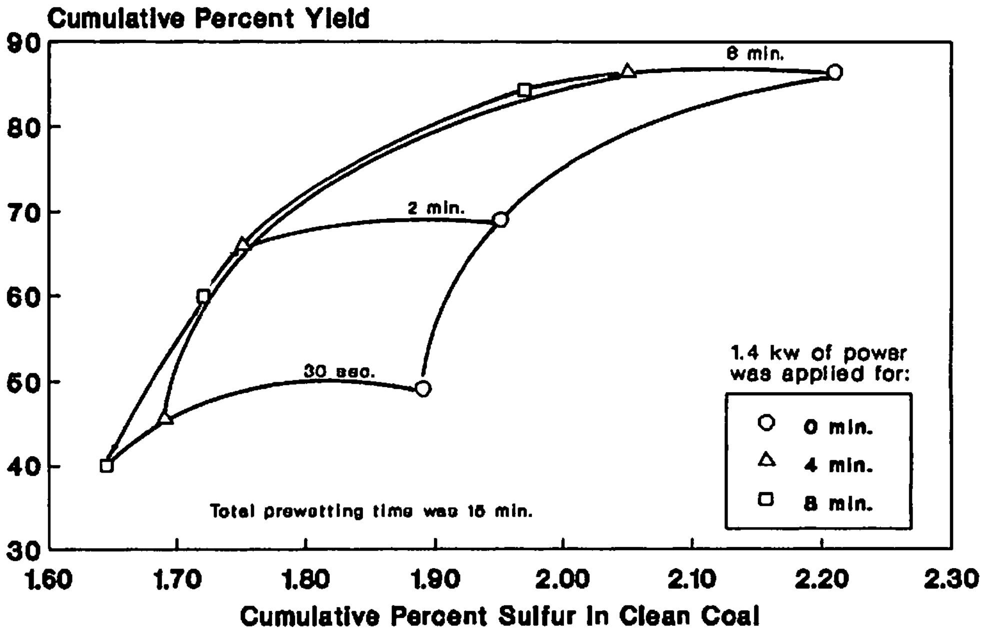


FIG. 8
EFFECT OF ULTRASONIC AMPLITUDE
UPON COAL YIELD AND ASH CONTENT

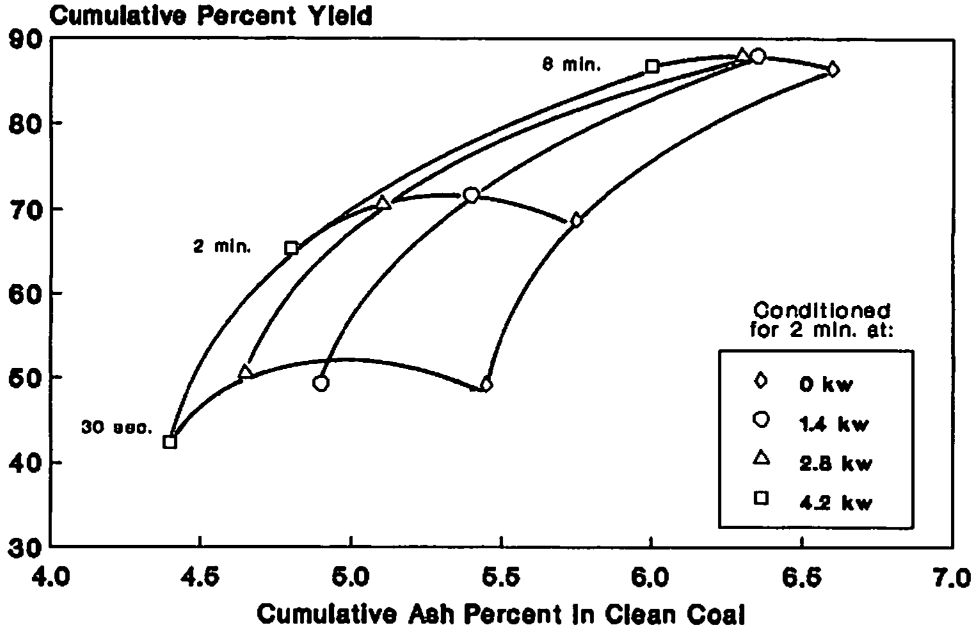


FIG. 9
EFFECT OF ULTRASONIC AMPLITUDE
UPON COAL YIELD AND SULFUR CONTENT

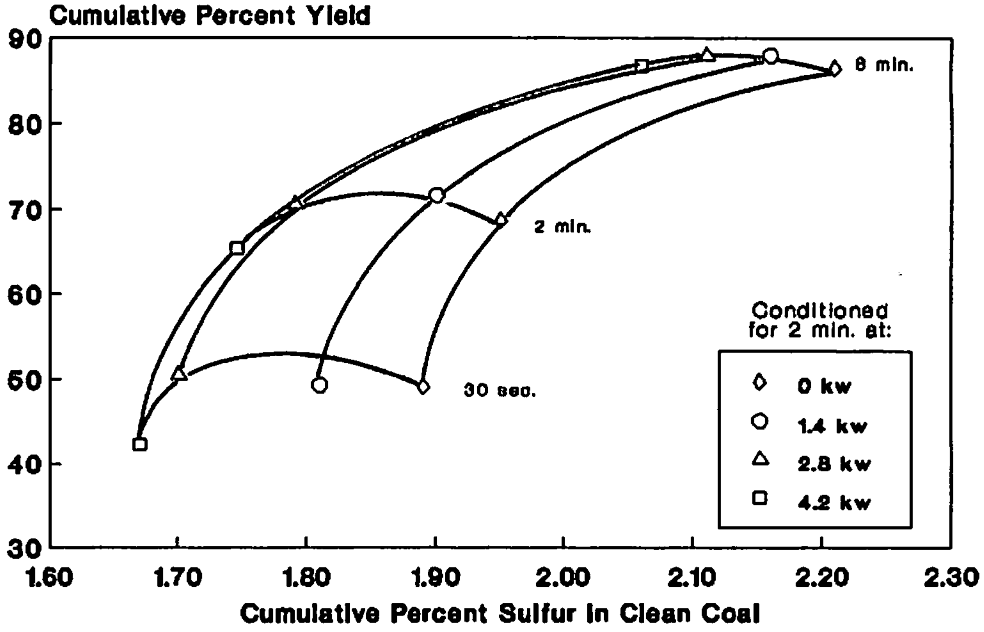


FIG. 10
EFFECT OF ULTRASONIC PREWETTING TIME
AND IMPELLER SPEED UPON YIELD AND ASH

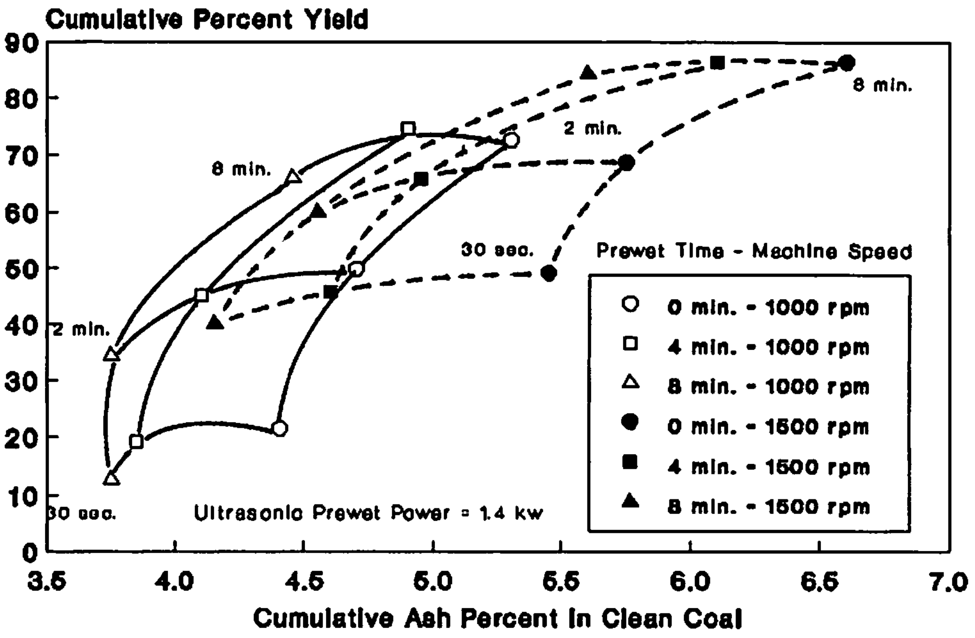
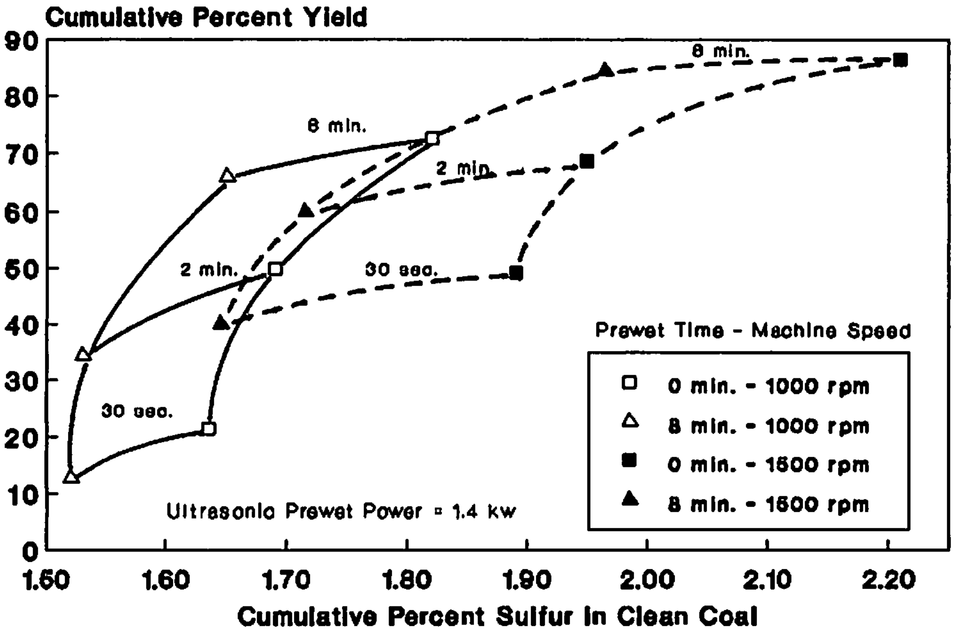


FIG. 11
EFFECT OF ULTRASONIC PREWETTING TIME
AND IMPELLER SPEED UPON YIELD AND SULFUR



rate decreased slightly after 4 minutes of exposure (TE). At 1000 rpm, the flotation rate decreased sharply after 4 minutes of exposure (TE), reflecting a combined effect that low impeller speed and lengthy ultrasonic exposure have upon yield. Due to slower flotation, the clean coal product obtained without ultrasound at 1000 rpm was substantially cleaner than its analog at 1500 rpm. However, when ultrasound was applied for 8 minutes, the product obtained after 2 minutes of flotation at 1500 rpm contained less ash and almost as little sulfur as the product obtained after 2 minutes of flotation with the baseline condition at 1000 rpm. Since the 2 minute yield at 1500 rpm was substantially higher, the impact of ultrasound on flotation selectivity is clear. In addition, the magnitudes of the leftward translation from baseline to 8 minute exposure were larger at the higher speed. At TE, followed by a 1500 rpm float, the clean coal analysis was approximately 1% lower in ash and 0.2% lower in sulfur. At TE, followed by a 1000 rpm float, the clean coal was about 0.6% lower in ash and 0.1% lower in sulfur.

B. Effect of Ultrasound Upon Particle Size Distribution

Figure 12 compares the particle size distributions of: 1) a head feed sample, 2) the head sample after flotation, and 3) the head sample after a combination of ultrasonic treatment and the same flotation. The particle size distributions of the first two of these are similar with one exception: a slight transfer of material from the 100 x 140 fraction to the 140 x 200 fraction occurred as a result of conventional conditioning and flotation. The third of these particle size distributions shows that ultrasound induced a net transfer of material from the 30 x 40 and 40 x 50 fractions to the 100 x 140 and 140 x 200 size fractions. Not much additional minus 200 material was created.

Figure 13 shows that the size changes caused by ultrasound resulted in enhanced liberation of ash and pyrite from the coal.

FIG. 12
EFFECT OF ULTRASOUND UPON
PARTICLE SIZE DISTRIBUTION

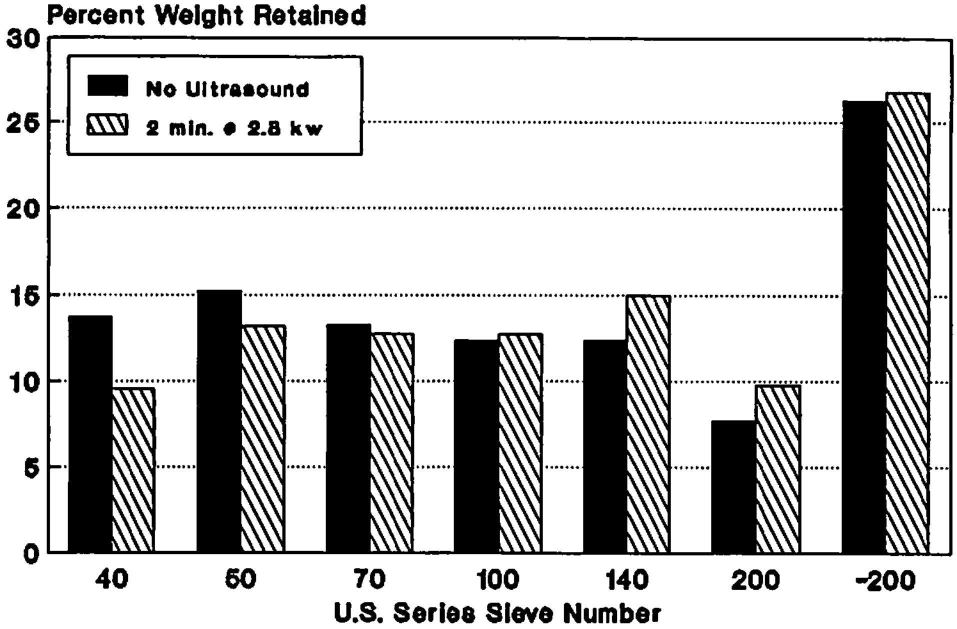
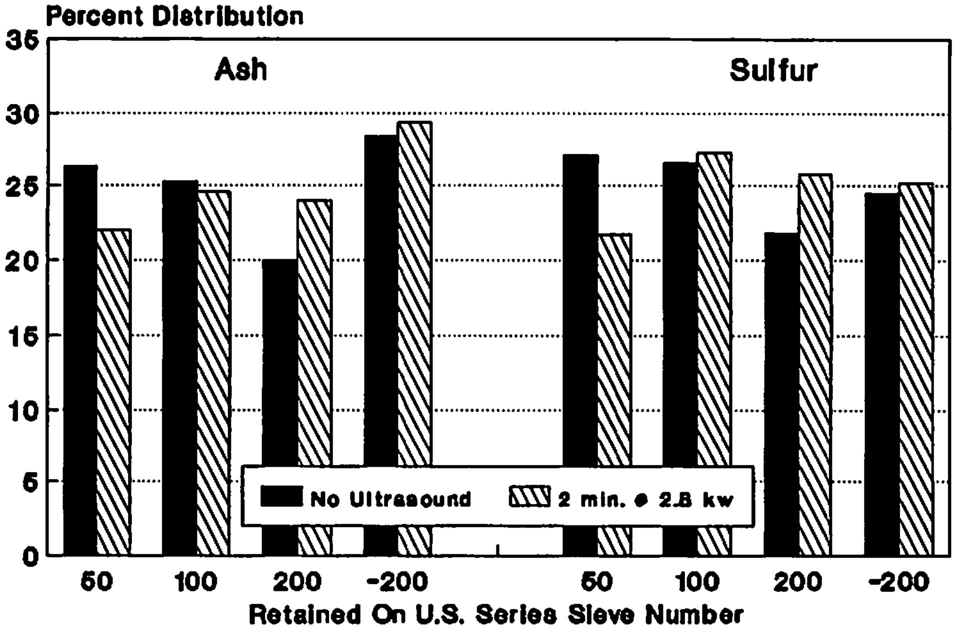


FIG. 13
EFFECT OF ULTRASOUND UPON
THE DISTRIBUTION OF COAL IMPURITIES



Ultrasonic conditioning transferred ash from the 30 x 50 and 50 x 100 ranges to the 100 x 200 and minus 200 size ranges. It also induced a transfer of total and pyritic sulfur from the 30 x 50 range to the finer three size ranges.

Figure 14 compares the distribution of mass, pyritic sulfur, and ash in the tails obtained for both conditions. Each tail accounted for 13% of the weight of the head feed. By comparing Figure 14 to Figure 12, it is apparent that ultrasound induced relatively less of the 40 x 50, 50 x 100, and minus 200 material to float. The pyritic sulfur distribution on Figure 14 suggests superior rejection of 50 x 100, 100 x 200, and minus 200 mesh pyrite. The ash distribution indicates superior rejection of minus 200 mesh ash.

This is verified by Table 2 and Figure 15, which present the calculated separation index (SI) values for the coal impurities according to size fraction. Table 2 also displays the percentage of improvement in the SI values that arose due to ultrasound. Ultrasound caused sharper separations in all of the size ranges. Selectivity towards sulfur was improved by at least 14% in each size range, while the overall improvement was 20%. Improvement for ash was highest (15%) in the minus 200 mesh fraction and nearly 10% overall.

TABLE 2. CALCULATED SEPARATION INDEX VALUES ACCORDING TO SIZE FRACTION

U.S. Series Size Fraction	CONVENTIONAL Separation Index			ULTRASONIC Separation Index			Percent Improvement		
	Ash	Total Sulfur	Pyrite Sulfur	Ash	Total Sulfur	Pyrite Sulfur	Ash	Total Sulfur	Pyrite Sulfur
30 x 50	47.8	30.7	51.5	51.6	36.4	57.6	7.9	18.6	11.8
50 x 100	52.2	30.0	48.0	53.4	37.5	59.3	2.3	25.0	23.5
100 x 200	51.9	29.1	43.9	55.1	33.2	52.2	6.2	14.1	18.9
minus 200	44.6	23.0	36.5	51.4	27.5	42.9	15.2	19.6	17.5
OVERALL	48.2	27.8	44.7	52.7	33.5	52.8	9.3	20.5	18.1

FIG. 14
WEIGHT AND COAL IMPURITY DISTRIBUTIONS OF THE FLOTATION TAIL

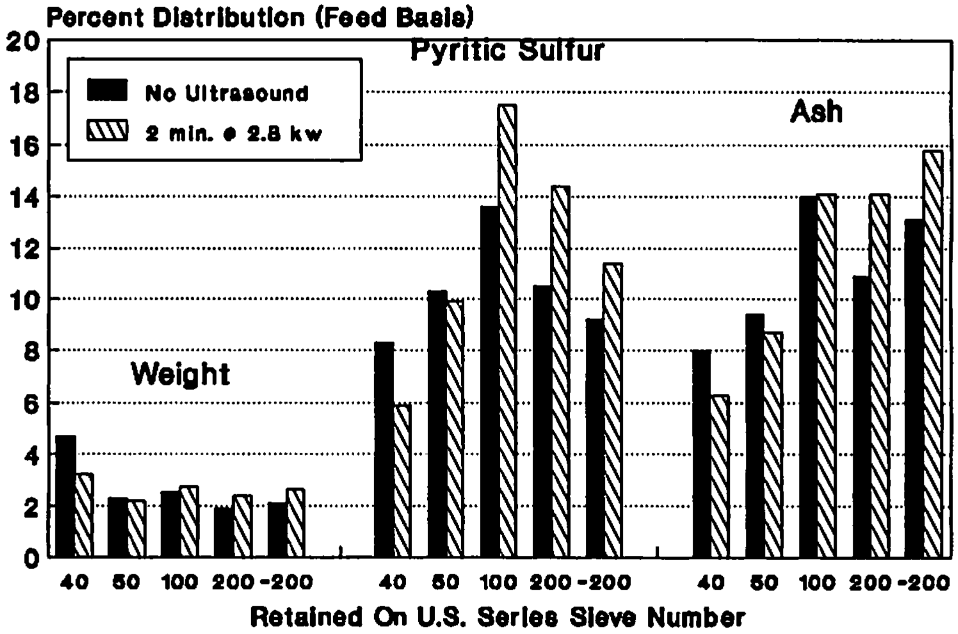
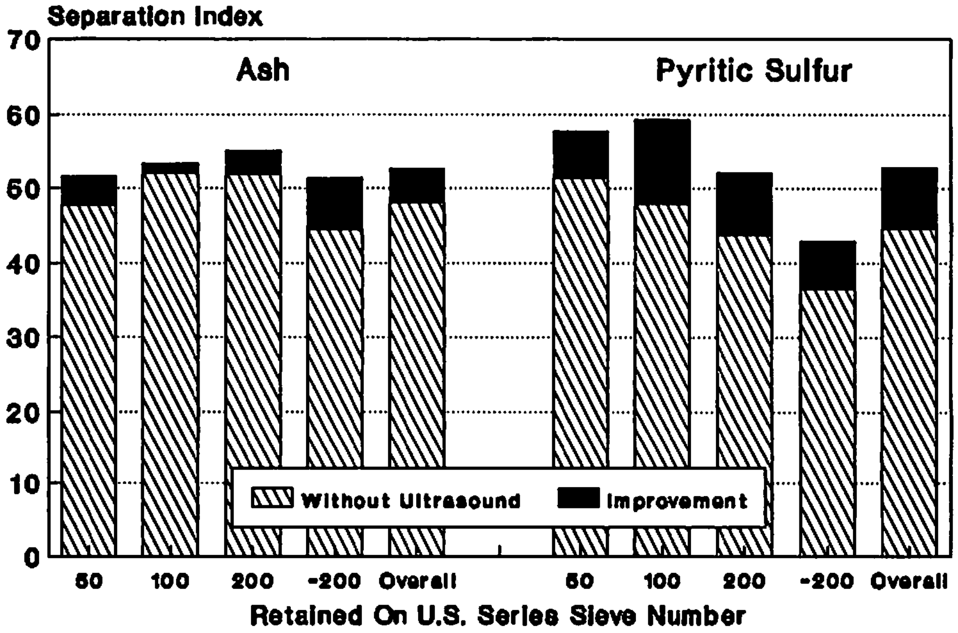


FIG. 15
IMPROVEMENT IN FLOTATION SELECTIVITY DUE TO ULTRASONIC CONDITIONING



These results suggest that the sharper flotation separation was caused by means of two mechanisms. First, surface and pore-bound ash, clay, and pyrite particles were liberated from the coarsest particles through scrubbing and breakage. This increased the probability of these impurities being rejected to the tails rather than floating as part of a coarse middling. In a similar vein, the coal from which these impurities were liberated resulted in a cleaner float product. Second, a larger proportion of minus 200 mesh clay and pyrite was rejected to the tails. Since this was not due to additional material entering that size fraction, it can only be attributed to: 1) ultrasonic surface polishing, 2) further liberation within this size range (which this experiment could not detect), or 3) both polishing and liberation. Either way, the effect was to increase the hydrophilicity of these particles so that more of them settled.

IV. SUMMARY AND CONCLUSIONS

The application of ultrasonic energy to a slurry of Pittsburgh No. 8 coal prior to flotation results in a cleaner coal product. For the ranges of energy employed in this experiment, the ash and sulfur contents of the clean coal decreased as the ultrasonic energy was increased. The magnitude of improvement in grade increases as the flotation impeller speed is increased. The yield of clean coal produced depends upon the total amount of energy applied to the slurry. As the energy is increased from zero up to a threshold energy (TE) of 0.094 kw-hr, overall yield remains the same or increases slightly. Beyond TE, the yield decreases as the energy is increased.

With Pittsburgh No. 8 coal, ultrasonic conditioning (at the TE level) prior to flotation at 1500 rpm increases the ash selectivity by almost 10% and the sulfur selectivity by 20%. A float product containing nearly 1% less ash and 0.2% less sulfur can be produced with no loss in yield.

The ultrasonic wave promotes cavitation erosion in the coal slurry, which causes a sharper flotation separation through two mechanisms: 1) liberation of surface and pore-bound ash and pyrite from the coarsest coal particles and 2) surface polishing of minus 200 mesh clay and pyrite particles to increase their hydrophilicity.

ACKNOWLEDGEMENTS

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