250
6-15-81
jwa

(2)

Dr-2743

DOE/ER/10466-1

Bins-162

Sp.- 5

NTIS-25

MASTER

**EFFICIENT ULTRASONIC GRINDING: A NEW TECHNOLOGY FOR
MICRON-SIZED COAL**

Final Report for Period September 15, 1979—December 14, 1980

By
W. B. Tarpley, Jr.
P. L. Howard
G. R. Moulder

January 1981

Work Performed Under Contract No. AC02-79ER10466

Energy and Minerals Research Company
Exton, Pennsylvania

U. S. DEPARTMENT OF ENERGY

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

"This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Printed Copy A03
Microfiche A01

EFFICIENT ULTRASONIC GRINDING: A NEW TECHNOLOGY FOR MICRON-SIZED COAL

Prepared for The U. S. DEPARTMENT OF ENERGY
Division of Advanced Energy Projects

W. B. Tarpley, Jr., P. L. Howard and G. R. Moulder

ENERGY & MINERALS RESEARCH COMPANY
964 E. SWEDES FORD ROAD, P.O. BOX 389
EXTON, PENNSYLVANIA 19341

Final Report
Contract No. DE-AC02-79ER10466
September 15, 1979 - December 14, 1980

January 1981

EFFICIENT ULTRASONIC GRINDING:
A NEW TECHNOLOGY FOR MICRON-SIZED COAL

Abstract

To burn coal most efficiently and cleanly, much smaller particle sizes are needed than can now be ground economically. This project was performed to demonstrate the technical feasibility of using ultrasonics to enhance grinding below the standard plant grind of 75 microns, and to extrapolate from this laboratory work the ultrasonic energy requirements for production use.

Successively improved laboratory arrays demonstrated a repeatable production of particulates from 2000-micron coal to the desired size ranges (approximately 35% below 7 microns, 95% below 44 microns) with selective liberation of ash and pyrite inclusions to facilitate removal, with equipment translatable to production use, and the possibility of only 37 kwh/ton energy input requirement.

TABLE OF CONTENTS

	<u>Page</u>
I. INTRODUCTION	1
A. Program Significance	1
B. Experimental Direction and Goals	2
C. Key Results	3
II. COAL WORK-SAMPLES	5
III. WORK OF PHASE 1	9
A. Cylinder Segment Apparatus	9
1. Experimental Design	9
2. Experimental Work	9
a. Selective Ash and Pyrite Liberation	11
b. Moist Versus Dry Ultrasonic Comminution	13
B. Dual-Roller Apparatus	17
1. Experimental Design	17
2. Experimental Work	20
C. Roller-Flat Plate Apparatus	23
1. Experimental Design	23
2. Experimental Work	23
IV. WORK OF PHASE 2	27
A. Roller-Curved Plate Apparatus	27
1. Experimental Design	27
2. Experimental Work	27
B. Energy Considerations	30
V. CONCLUSIONS AND RECOMMENDATIONS	34
A. Conclusions	34
B. Recommendations	34

APPENDIX A: Energy Considerations for Production Application

LIST OF TABLES AND FIGURES

<u>Table</u>	<u>Page</u>
I Ultrasonic Comminution - Cylinder Segment Dry Uncharacterized Coal HGI-86	12
II Pyritic Iron and Ash Analysis of Ultrasonically Comminuted Coal	14
III Iron Analysis of Ultrasonically Comminuted Coal	15
IV Comminution of Coal With and Without Ultrasonics - Moist and Dry	16
V Coal Comminution, Dry	21
VI Coal Comminution, Moist	22
VII Flat-Plate Moist Coal Comminution	26
VIII Ultrasonic Comminution of Moist Coal Repeatability Tests	29
IX Ultrasonic Comminution of Moist Coal	31

<u>Figure</u>	<u>Page</u>
1 Cylinder Segment Ultrasonic Comminution Apparatus . . .	10
2 Ultrasonic Dual Roller Apparatus	18
3 Flat Plate Modification of Dual-Roller Apparatus (Top View)	24
4 Flat-Plate Modification of Dual-Roller Apparatus (Side View)	25
5 Side View of Dual-Roller Apparatus with Curved Plate .	28

I. INTRODUCTION

A. Program Significance

Coal processing has become an increasingly important industry as America attempts to convert from petroleum. In order to provide coal with combustion performance approximately equivalent to oil or gas, much finer particle sizes will be needed than the now standard plant grind (75% -200 mesh).

Conventional grinding techniques cannot economically meet this goal. A new comminution technology, ultrasonic grinding, can offer a solution. Because it operates by methods not common to those of conventional grinding systems, it is expected that ultrasonics can significantly enhance grinding efficiency in the -7 micron range needed for various types of processing and "clean coal" applications. The objectives of the work performed in this project were to demonstrate such technical feasibility in the laboratory and to assess the economic promise, as a function of energy requirements, of the production use of this technology.

It was initially postulated that the mechanisms of ultrasonic grinding would be:

- . Very rapid (15-20 kHz range) vibratory promotion of fatigue fracture;
- . Promotion of stress corrosion;
- . Preferential energy delivery to discontinuities;
- . Prevention of small particle shielding by larger ones;
- . Cavitation and preferential shear in damp or paste media.

In the course of the laboratory work these mechanisms were all apparent and contributed to producing the desired particle size range, with a useful liberation of ash and pyrite inclusions, by a repeatable process entirely amenable to use in industrial equipment for high-volume production, and at energy requirements dramatically decreased over other fine-particle production methods.

B. Experimental Direction and Goals

The work was performed in two phases, the first to evolve a laboratory array and operating procedures optimized to the extent possible, the second to 1) demonstrate repeatable ultrasonic effect in the improved production of ultrafine coal particles, 2) determine if selective coal fragmentation occurs to liberate inclusions such as pyritic sulfur, and 3) define comminution energy requirements with extrapolation to the production environment.

Phase 1 effort, in which three laboratory arrays were devised and evaluated, considered factors such as the mode of application of ultrasonic energy (i.e., axial vs. shear), the rate of coal throughput and the ultrasonic power level, the most effective nip configuration, and the use of dry coal vs. a moist media.

In Phase 1 the ultrasonic grinding program was developed through three basic experimental arrays. These were the cylinder segment apparatus, the dual-roller apparatus and the roller plate apparatus. Each gave information which led to the final, extremely effective device which was a variant on the roller-plate unit. The cylinder segment apparatus is a longitudinally vibrated device for axial-mode impingement grinding and simulates a roller-plate type unit.

The dual-roller apparatus consists of an activated and a non-activated roller. Ultrasonic grinding at the nip is accomplished in the shear mode.

The roller-plate apparatus was designed to further investigate and take advantage of the axial mode effect. Work was started with a flat-plate coupler and advanced to a curved-plate, which was used for the Phase 2 work. The curved-plate coupler increased the area of ultrasonic activation and consequently of effective grinding by a factor of 12 over the flat-coupler. Also, the curved coupler provided a gradually decreasing passage space for the coal in process. These two conditions helped bring about the increase in fines production; typically, on a single pass approximately 35% of the coal ground was 7 microns or below, with over 95% smaller than 325 mesh (44 microns).

C. Key Results

The significant results of the program are summarized below. The background and data associated with these are detailed in the body of the report.

1. Ultrasonic comminution was repeatedly demonstrated as capable of producing -7 micron fines from coal 2,000 microns in size in an equipment configuration amenable to practical scaleup.

2. The grinding energy efficiency of 37 KWH/ton for ultrasonic comminution, extrapolated from our laboratory equipment measurements, demonstrates a substantial improvement, as much as 500% over conventional grinding methods for production of equivalent micron coal, based on the energy actually transmitted to the coal being ground, and suggests the direction of design modifications from the laboratory array to production equipment.

3. Preferential liberation of pyrite and ash inclusions was also repeatedly demonstrated during the fine grinding process, and can be utilized to assist coal cleaning.

II. COAL WORK-SAMPLES

The bulk of Phase 1 and Phase 2 testing was accomplished on three Penn. State Office of Coal Research (PSOC) graded coal samples selected by the following criteria:

1. Steam grade coal is preferred over metallurgical coal since the most beneficial application of the ultrasonic fine grinding technique would appear to be in the power generation industry.
2. A widely used coal seam is preferred for the test program results to be most directly applicable.
3. One fairly low and one fairly high Hardgrove Grindability Index (HGI) coal should be selected to fully establish the degree of ultrasonic grinding enhancement achievable. Hardgrove Grindability Index, HGI, is a measure of the ease with which coal may be ground. The higher the HGI rating, the easier the coal is to grind.
4. Coals with average or above average content of ash and inorganic sulfur should be selected to permit some measure of the degree of "selective" grinding (inclusion liberation) occurring during testing.

The characteristics of the selected coal samples are detailed on the following pages, reproduced from computer print-outs of Pennsylvania State University data.

 ** PSOC-688 **
 ** PAGE 4 **

COUNTRY U.S.A.
STATE WEST VIRGINIA

```

*****
*                                     *
*  CHEMICAL DATA 2  *
*                                     *
*****

```

ULTIMATE ANALYSIS	AS REC'D	DRY	DAF	DMF(PARR)
-----	-----	---	---	-----
				(21.53 %MM)
% ASH	19.32	18.55		
% CARBON	70.11	71.00	87.17	90.48
% HYDROGEN	3.80*	3.85	4.73	4.91
% NITROGEN	1.22	1.24	1.52	1.58
% SULFUR	2.69	2.72	3.34	
% CHLORINE	0.03	0.03	0.04	0.04
% OXYGEN (DIFF)	2.57*	2.60	3.21	3.00

SULFUR FORMS	% PYRITIC	% SULFATIC	% ORGANIC	% TOTAL
DRY	1.67	0.19	0.86	2.72
DAF	2.05	0.23	1.06	3.34
OPTICAL				

ELEMENTAL ANALYSIS	DRY	DMFM (MOD. P)	DMFM (DIR.)
		(21.76%MM)	(%MM)
% CARBON	70.73	90.41	
% HYDROGEN	3.58	4.57	
% NITROGEN	1.24	1.58	
% ORGANIC SULFUR	0.85	1.10	
% OXYGEN (DIFF)	1.83	2.30	
% CHLORINE	0.03	0.04	
% MINERAL MATTER	21.76		
(INCLUDES 3.12 % FES ₂)			

ATOM RATIOS (DMF)	PARR	MOD. PAR	DIRECT
ATOMIC H/C	0.651	0.607	
ATOMIC O/C	0.025	0.024	

MISC. CHEMICAL DATA	DRY	OF DMMF COAL	OF DMMF OXYGEN
% O AS COOH			
% O AS OH			
% S AS SO ₄ , IN ASH			
% CARBONATE AS CO ₂			
% CHLORINE	0.07		

(*) -EXCLUDES MOISTURE

INFRA-RED ANALYSIS

** PENN STATE COAL DATA BASE **

 ** PSOC-769 **
 ** PAGE 4 **

SEAM NAME LOWER PHILPOTT COUNTRY U.S.A.
 APPARENT RANK LOW VOLATILE BITUMINOUS (LVB) STATE ARKANSAS

 *
 * CHEMICAL DATA 2 *
 *

ULTIMATE ANALYSIS	AS REC'D	DRY	DAF	DMF(PARR) (6.33 %MM)
% ASH	5.31	5.39		
% CARBON	84.61	85.90	90.79	91.71
% HYDROGEN	4.00*	4.06	4.29	4.33
% NITROGEN	1.53	1.65	1.74	1.76
% SULFUR	0.92	0.93	0.98	
% CHLORINE	0.02	0.02	0.02	0.02
% OXYGEN(DIFF)	2.02*	2.05	2.17	2.18

SULFUR FORMS	% PYRITIC	% SULFATIC	% ORGANIC	% TOTAL
DRY	0.19	0.01	0.73	0.93
DAF	0.20	0.01	0.77	0.98

OPTICAL

ELEMENTAL ANALYSIS	DRY	DMF(MOD.P) (5.19%MM)	DMF(DIR.) (3MM)
% CARBON	85.82	91.49	
% HYDROGEN	3.99	4.25	
% NITROGEN	1.65	1.76	
% ORGANIC SULFUR	0.73	0.78	
% OXYGEN(DIFF)	1.52	1.71	
% CHLORINE	0.02	0.02	
% MINERAL MATTER (INCLUDES 0.36 % FES2)	6.19		

ATOM RATIOS (DMF)	PARR	MOD.PAR	DIRECT
ATOMIC H/C	0.558	0.558	
ATOMIC O/C	0.018	0.015	

MISC. CHEMICAL DATA	DRY	OF DMF COAL	OF DMF OXYGEN
% O AS COOH			
% O AS OH			
% S AS SO4, IN ASH			
% CARBONATE AS CO2			
% CHLORINE	0.04		

INFRA-RED ANALYSIS

** PENN STATE COAL DATA BASE **

 ** PSOC--275 **
 ** PAGE 4 **

SEAM NAME OHIO #6A COUNTRY U.S.A.
 APPARENT RANK HIGH VOLATILE A BITUMINOUS (HVAB) STATE OHIO

 *
 * CHEMICAL DATA 2 *
 *

ULTIMATE ANALYSIS	AS REC'D	DRY	DAF	DMF (PARR) (8.32 %MM)
% ASH	6.40	6.61		
% CARBON	73.84	76.30	81.70	83.22
% HYDROGEN	5.40*	5.58	5.97	6.09
% NITROGEN	1.84	1.90	2.03	2.07
% SULFUR	2.07	2.14	2.29	
% CHLORINE	0.12	0.12	0.13	0.14
% OXYGEN (DIFF)	7.10*	7.35	7.87	8.50

SULFUR FORMS	% PYRITIC	% SULFATIC	% ORGANIC	% TOTAL
DRY	1.41	0.00	0.73	2.14
DAF	1.51	0.00	0.78	2.29
OPTICAL				

ELEMENTAL ANALYSIS	DRY	DMF (MOD.P) (8.19%MM)	DMF (DIR.) (8.01%MM)
% CARBON	76.20	83.00	82.83
% HYDROGEN	5.47	5.95	5.94
% NITROGEN	1.90	2.07	2.07
% ORGANIC SULFUR	0.73	0.80	0.79
% OXYGEN (DIFF)	7.69	8.06	8.24
% CHLORINE	0.12	0.14	0.14
% MINERAL MATTER (INCLUDES 2.64 % FFS2)	8.01		

ATOM RATIOS (DMF)	PARR	MOD. PAR	DIRECT
ATOMIC H/C	0.878	0.862	0.862
ATOMIC O/C	0.077	0.079	0.075

MISC. CHEMICAL DATA	DRY	OF DMF COAL	OF DMF OXYGEN
% O AS COOH			
% O AS OH			
% S AS SO4, IN ASH			
% CARBONATE AS CO2			
% CHLORINE	0.25		

INFRA-RED ANALYSIS

(*) - EXCLUDES MOISTURE

III. WORK OF PHASE 1

A. Cylinder Segment Apparatus

1. Experimental Design

The cylinder segment was the initial apparatus used to evaluate the longitudinal or axial mode.

Figure 1 presents a schematic of this first laboratory ultrasonic comminution apparatus. The unit was hopper-fed at the juncture of the cylinder segment and the grinding plate. The coal was fed to the "nip" or working surface, giving a good simulation of actual grinding conditions. For use in Phase II equipment design, data was accumulated on several parameters including power, time, velocity of coal through nip area, vibratory force and strain amplitude.

The power amplifier used is an ENI E6B1600, which has continuously variable power and frequency controls. With the aid of a proper impedance-matching network, the amplifier supplied the desired power level. Oscilloscope monitoring of the current and voltage applied to the transducer was carried out to track any possible shift in resonant frequency in the acoustic system. Information taken on frequency drift was then also applied to Phase II design.

2. Experimental Work

Uncharacterized coal of HGI-86 hardness was comminuted. The ultrasonically comminuted coal in the -325 mesh size was 26% compared to 14% of the coal passed through the non-activated fixture. The -325 mesh products of both the control and activated samples were then subjected to sedimentation analysis in water to determine the quantity of -7 micron fines generated. For the ultrasonic product, 18.1% of the -325 mesh samples

Figure 1

CYLINDER SEGMENT ULTRASONIC COMMINUTION APPARATUS

fell into the -7 micron range compared to 13.6% for the control. This translates to a total -7 micron production of 4.73% for the ultrasonically comminuted sample versus 1.97% for the control, which represents a 140% increase in produced -7 micron fines attributable to ultrasonic activation (Table I).

a. Selective Ash and Pyrite Liberation

The next experiment was designed to provide a preliminary measure of the degree of selective pyrite and ash liberation associated with ultrasonic comminution, in comparison to reference values determined on a sample of unground coal.

The initial step was evaluation of the pyrite and ash levels in the unground coal. The Phenathraline iron determination method was used as an indicator of pyrite level; although the absolute accuracy of this method is affected by the trace levels of other metals in the coal, accuracy is sufficient to indicate relative liberation of pyrite in various size categories. Ash content was determined by standard combustion techniques, i.e. "ashing".

Following determination of base line values for pyrite and ash in a small unground coal sample, a sample was ground ultrasonically and sized (in the -200+325 mesh and -325 mesh ranges and within the -325 category to the -10 micron range by sedimentation). The iron and ash analyses indicate the occurrence of selective liberation and the size of any liberated inclusions. For example, if the iron and ash percentages are identical in all size categories, there would be a high probability that these inclusions had remained homogeneously bound within the coal particles. If a given size-category sample contains a higher percentage of inclusions than another or than the base line sample, the indication is that preferential liberation of inclusions is occurring, permitting sedimentation separation, and that the inclusion size is within the size category being observed and that the comminuted coal is smaller.

Table I

ULTRASONIC COMMINATION - CYLINDER SEGMENT
DRY UNCHARACTERIZED COAL HGI-86

<u>Size Range</u>	<u>Non-Activated Control % in Size Range</u>	<u>Ultrasonically Ground % in Size Range</u>
+200 mesh	78.30	64.56
-200+325 mesh	7.20	9.32
-325 mesh +30 microns	5.38	5.54
-30+15 microns	4.29	9.56
-15+7 microns	2.85	6.29
-7 microns	1.97	4.73

Particle size analysis within the -325 mesh size category was conducted by the sedimentation method; ash and pyrite inclusions are more dense and thus settle faster than coal particles of the same size.

The test results are included in Table II. The data indicate that significant preferential liberation is occurring with ultrasonic comminution. The inclusions are predominantly in the -325 mesh range, although the increase in percentage of iron and ash in the -200+325 mesh area indicates a substantial portion of the inclusion distribution is also in this range. The very marked decrease in iron and ash percentage in the -10 micron size range strongly suggests that the majority of the inclusions were liberated from the comminuted coal and amenable to sedimentation separation.

In the next experimental series, two characterized coals, PSOC-688 and PSOC-275, were ultrasonically ground and sized in the -200+325 mesh and -325 mesh ranges and within the -325 category to the -10 micron range. The results, given in Table III, indicate that preferential liberation of pyritic iron is occurring in the -200+325 mesh size range. The decrease in the -10 micron size range suggests that the majority of the inclusions were liberated from the comminuted coal and settled early during sedimentation. The 5:1 reduction in pyritic iron indicates significant preferential liberation.

b. Moist Versus Dry Ultrasonic Comminution

Comparative tests were then conducted, using PSOC-769, to evaluate moist versus dry grinding. The samples were ground both dry and moist with ultrasonics and moist only without ultrasonics since a dry control run (Table I) had previously been made. Table IV indicates an increase

Table II

PYRITIC IRON AND ASH ANALYSIS OF ULTRASONICALLY
COMMUNUTED* COAL

<u>HGI-86 Coal Sample</u>	<u>% Total Iron</u>	<u>% Ash</u>
Bulk Unground (Control)	0.300	4.1
<u>Size Category</u>		
-200+325 mesh	0.416	4.6
-325 mesh	0.456	4.5
-10 microns	0.100	3.2

*Test conducted with cylinder segment apparatus.

Table III

IRON ANALYSIS OF ULTRASONICALLY COMMINUTED COAL

<u>Coal Type</u>	<u>Size Range</u>	<u>% Pyritic Iron</u>	<u>% Non-Pyritic Iron</u>	<u>Total Iron</u>
PSOC-688 (HGI-97.5)	+200 mesh	1.30	0.20	1.50
	-200+325 mesh	1.51	0.43	1.94
	-325 mesh	1.25	0.48	1.73
	-10 microns	0.21	0.22	0.43

PSOC-275 (HGI-56.7)	+200 mesh	0.91	0.14	1.05
	-200+325 mesh	1.98	0.31	2.29
	-325 mesh	1.68	0.66	2.34
	-10 microns	0.33	0.59	0.92

TABLE IV

COMMINUTION OF COAL WITH AND WITHOUT ULTRASONICS
MOIST AND DRY

<u>Size Range</u>	<u>Dry Grind With Ultrasonics (% in Size Range)</u>	<u>Moist Grind With Ultrasonics (% in Size Range)</u>	<u>Moist Grind With- out Ultrasonics (% in Size Range)</u>
+200 Mesh	57.70	35.00	73.00
-200+325 Mesh	13.99	17.00	8.00
-325 Mesh +30 Microns	3.23	11.23	14.82
-30+15 Microns	18.82	12.43	1.84
-15+7 Microns	4.62	12.24	1.43
-7 Microns	1.64	12.10	0.91

in -7 micron fines content of 7:1 to 12% of the total sample. There is a marked skewing of the size distribution toward the small sizes, with a 70% increase in -325 mesh content. Also, there is a 13:1 increase in -7 micron fines during moist grinding when ultrasonics is used.

It is possible that more than one mechanism is working to grind moist coal with ultrasonics. In addition to the normal grinding action of cylinder segment against moving plate, there is also impingement due to ultrasonic activation. Energy coupling into moist coal can be expected to be greater than for dry coal. Additionally, during moist grinding, cavitation is present (and was detected audibly); when a cavitation void collapses, considerable energy is released and very high stresses are exerted on the particles, a possible additional source of grinding enhancement.

B. Dual-Roller Apparatus

1. Experimental Design

The dual-roller apparatus (Figure 2) consists of one activated and one non-activated roller. The activated roller is composed of two transducers, each with a force-insensitive mount and set of slip-rings. The design includes a differential roller-speed adjustment to permit controlled slippage and attrition, which may be beneficial. The two-transducer system was constructed to establish standing waves as well as traveling waves in the roller, in order to compare the benefits of each mode. With the second, or receiving, transducer connected to a resistive load and properly adjusted for maximum power absorption, minimum energy will be reflected back into the driving transducer. When there is no reflected energy, the transmitted ultrasonic wave travels down the entire roller length; since a majority of the energy is absorbed into the coal being ground or into the receiving transducer, no nodes or antinodes are

Figure 2

ULTRASONIC DUAL ROLLER APPARATUS

established in the roller. Conversely, if the receiving transducer is disconnected from a dummy load, then some energy is reflected and standing waves are established on the roller with defined nodes and antinodes. While the standing wave mode theoretically requires less mechanical complexity and could use somewhat less power, the traveling wave mode could, by avoiding vibrational nodes, provide somewhat more uniform grinding and slightly higher power delivery to the coal being ground.

The mechanism of effect in ultrasonic comminution is mechanical fatigue due to the very rapid tension/compression cycles to which the contacted coal is subjected by the driven ultrasonic surface. To couple ultrasonics, the coal particle must be "clamped" by the nip between rollers, and nip gap affects size of particles generated. This gap is reduced by the amplitude of radial motion of the ultrasonically excited roller, thus further reducing the size of particles generated. The nip gap and the radial motion amplitude of the ultrasonically excited roller combine to determine the particle size generated.

The 7"-diameter passive drive roll is supported on bearings in a structure that can be precisely adjusted to optimize coal nip gap dimension and uniformity as required for maximum production of -10 micron coal fines.

The 2.75"-diameter ultrasonically activated drive roll and the passive drive roll are rotated by two drive motors with fixture provision for synchronous operation at speeds up to 350 RPM (of the excited drive roll) and with the provision to introduce a slight variation in relative speed, resulting in a small amount of "slippage", to allow determination of the relative contribution of the attrition mechanism to ultrasonic comminution.

The ultrasonically excited roller (Figure 2) is supported on bearings connecting the support frame to a pair of force-insensitive transducer supports designed to minimize the ultrasonic energy loss through the

bearing into the rigid support structure. Transducer excitation of the roll may provide either standing or traveling wave operation as controlled by the configuration of the ultrasonic load employed at the opposite end of the excited roll. The transducers, 2.4-kw, 15-kHz tension shell, air-cooled piezoelectric crystals, were obtained from Sonobond Corp.; Eenergy & Minerals Research Company custom designed the transducer coupling system, a force-insensitive mount and cylindrical halfwave tuned coupler. ENI custom designed a matching transformer for the 3200-power supply used.

B. Experimental Work

A metered flow of coal was introduced evenly across the 6½-inch nip distance. The resulting fines were collected in a pan designed to receive only coal particles passing through the nip, and not to collect any particles that by-passed the nip.

The dual-roller apparatus, with the two rollers at the same surface speed, was used first in the traveling wave mode with dry grinding. The coal used was PSOC-688 (HGI-97.5). Ultrasonics produced 4.61% -7 microns, in contrast to 2.79% without ultrasonics. Application in the standing wave mode similarly produced 4.34% of -7 micron particles (Table V).

Moist grinding in the traveling wave mode was accomplished with the dual-roller apparatus using the same coal. It was found that the moist-ground coal would stick to the large roller and pass through the nip several times. In order to compare to dry processing, these fines were collected before multiple grinding occurred. The data in Table VI show the results with and without cleaning the roller and without ultrasonics. It is evident from these data that moist grinding is superior to dry in production of fines.

TABLE V

COAL COMMINUTION, DRY

<u>Size Range</u>	<u>Without Ultrasonics (%)</u>	<u>Traveling Waves (%)</u>	<u>Standing Waves (%)</u>
+200 mesh	51.30	40.40	48.70
-200+325 mesh	13.00	14.40	10.70
-325 mesh + 30 microns	16.74	24.05	16.20
-30+15 microns	10.50	9.36	12.55
-15+7 microns	5.68	7.19	7.51
-7 microns	2.78	4.61	4.34

Total -325 mesh	35.70	45.21	40.60

Table VI

COAL COMMUNUTION, MOIST

<u>Size Range</u>	<u>No Ultrasonics Roller Cleaned % in Size Range</u>	<u>Ultrasonics Roller Cleaned % in Size Range</u>	<u>Ultrasonics Roller Not Cleaned % in Size Range</u>
+200 mesh	41.06	29.84	12.25
-200+325 mesh	7.05	10.91	7.4
-325 mesh			
+30 microns	21.24	18.98	14.14
-30+15 microns	13.58	16.81	28.04
-15+7 microns	9.45	11.45	20.17
-7 microns	7.61	12.00	18.00
- - - - -	- - - - -	- - - - -	- - - - -
Total -325 mesh	51.88	59.24	80.35

C. Roller-Flat Plate Apparatus

1. Experimental Design

The dual-roller apparatus design was modified to simulate roller operation against an activated plate (Figures 3 and 4). A flat plate was designed to be activated in the axial or longitudinal mode. For testing this configuration, the ultrasonic coupler flat-plate was adjusted axially to establish the optimum nip gap, after which gap uniformity was maintained. The drive roll was rotated at a variety of speeds representing various degrees of slip.

2. Experimental Work

Coal was ground using several power levels and roller speeds. The results, as can be seen in Table VII, showed no significant improvement over the dual-roller apparatus. It was decided that more exposure of the coal to ultrasonic activation was needed. Thus, a curved plate coupler was designed and used for the work of Phase 2, as discussed in following pages.

Figure 3

FLAT PLATE MODIFICATION OF DUAL-ROLLER APPARATUS

(Top View)

Figure 4

FLAT-PLATE MODIFICATION OF DUAL-ROLLER APPARATUS

(Side View)

Table VII

FLAT-PLATE MOIST COAL COMMINUTION

<u>Size Range</u>	<u>No Ultrasonics % in Size Range</u>	<u>Ultrasonics % in Size Range</u>
+200 mesh	32.70	24.40
-200+325 mesh	25.50	26.40
-325 mesh+30 microns	24.34	13.38
-30+15 microns	8.58	14.23
-15+7 microns	5.32	10.17
-7 microns	3.56	11.42

IV. WORK OF PHASE 2

The experience gained in the evolving equipment designs of Phase 1 led to a laboratory-optimized array involving the configuration of a roller against an activated curved plate. Using this equipment, final program data were obtained on fines production, repeatability effect of ultrasonic selective liberation of inclusions, and ultrasonic energy requirements.

A. Roller-Curved Plate Apparatus

1. Experimental Design

By a modification of the flat plate coupler used in Phase 1 to a curved configuration (Figure 5) the area of ultrasonic activation and grinding is increased by a factor of twelve. The curved plate provides a longer residence time of material in the grinding nip, increases the active work area, and provides a gradually decreasing passage space for the coal. This wedging effect decreases the size of the ground coal as it passes through the array; coupled with a moist grinding medium for the coal, this design has significantly increased the number of fines over Phase 1 results, and demonstrates a clearly cost-effective level of required energy input.

2. Experimental Work

The curved-plate coupler was designed primarily for the enhancement of moist grinding, and with dry grinding the results were not as good as achieved with the dual-roller. (In the -7 micron range the curved-plate produced only 1.15% as compared to 4.34% for the dual roller.) With the use of a moist medium the results were by far the best obtained in the program. Coal PSOC-688 was first used for comparison with previous work and for setting parameters. As reported in Table VIII, a series of eleven runs was made with PSOC-688 moist ground through the curved-plate coupler.

Figure 5

SIDE VIEW OF DUAL-ROLLER APPARATUS WITH CURVED PLATE

Table VIII

ULTRASONIC COMMINUTION OF MOIST COAL
REPEATABILITY TESTS
 PSOC-688 (HGI-97.5)

<u>Size Range</u>	<u>No. 1</u>	<u>No. 2</u>	<u>No. 3</u>	<u>No. 4</u>	<u>No. 5</u>	<u>No. 6</u>	<u>No. 7</u>	<u>No. 8</u>	<u>No. 9</u>	<u>No. 10</u>	<u>No. 11</u>
	<u>(% in Size Range)</u>										
+200 mesh	2.40	2.60	2.90	3.40	3.40	2.80	2.80	3.10	1.40	1.60	2.60
-200+325 mesh	1.50	2.30	1.20	1.40	3.20	1.90	1.94	2.90	1.10	1.10	2.10
-325mesh											
+30 micron	3.80	2.44	0.96	2.70	6.28	5.03	9.28	8.14	3.60	3.51	8.50
-30+15 micron	35.81	29.48	26.63	28.66	30.32	30.89	34.13	26.68	34.72	35.68	30.67
-15+7 micron	23.21	27.43	27.52	25.07	20.03	22.35	16.59	24.95	24.66	24.50	22.77
-7 micron*	33.29	35.75	40.79	38.77	36.77	37.13	35.25	34.23	34.52	33.61	33.46
Total of -325:	96.11	95.10	95.90	95.20	93.40	95.40	95.25	94.00	97.50	97.30	95.40

*-7 micron: Average = 35.78%
 Standard Deviation = 2.40%

Note: Coal would not pass through this configuration without ultrasonics.

The average percentage of -7 micron fines is 35.78% with a standard deviation of 2.40%. This work clearly demonstrates the repeatability of ultrasonic effect in grinding. These results were obtained with only a single pass through the "nip" area, that is, one exposure to ultrasonic comminution followed by collection was the standard process. PSOC-275 was also ground under the same conditions in a shorter series, with results shown in Table IX. Although there seem to be little difference in the number of fines smaller than 30 microns for PSOC-688 and PSOC-275, the grinding time for the same volume for PSOC-275 was approximately 4 times that of PSOC-688.

The PSOC-688 coal from these runs was then tested for pyritic and non-pyritic iron. The results in Table X indicate that preferential liberation of inclusions is occurring in the pyritic iron in the -200+325 mesh range. In the -10 micron range the decrease in pyritic iron indicates that the majority of the inclusions were liberated and settled during sedimentation. The non-pyritic iron is probably due to particles ground from the curved-plate coupler.

B. Energy Considerations

As noted in Appendix A, which gives the calculations and discussion in some detail, the ultrasonic power that does the work of comminuting coal is the power actually coupled to the coal being processed. To arrive at the value of 37 KWH/ton, which could be achieved with production equipment, oscilloscope measurements were taken with the roller-curved plate apparatus to determine the system loss and the power used to heat the water in the laboratory-array grinding process. Scale-up of the technique to production equipment will include system redesign to eliminate these losses.

Table IX

ULTRASONIC COMMINUTION OF MOIST COAL
PSOC-275 (HGI-56.7)

<u>Size Range</u>	<u>Trial Number 1</u>	<u>Trial Number 2</u>
	<u>(% in Size Range)</u>	
+200 mesh	4.30	5.30
-200+325 mesh	4.80	6.80
-325 mesh +30 microns	0.75	5.54
-30+15 microns	21.60	25.93
-15+7 microns	24.73	26.14
-7 microns	43.82	30.19
- - - - -	- - - - -	- - - - -
Total of -325 mesh	90.90	87.80

Table X

IRON ANALYSIS OF ULTRASONICALLY COMMINUTED COAL
(PSOC-688)

<u>Size Range</u>	<u>% Pyritic Iron</u>	<u>% Non-Pyritic Iron</u>	<u>Total Iron</u>
+200 mesh	0.76	0.10	0.86
-200+325 mesh	1.75	0.31	2.06
-325 mesh	1.54	0.21	1.75
-10 microns	0.11	0.35	0.46

A comparison with other methods of the 37 kwh/ton energy requirement gives:

	<u>Ultrafine Coal for Diesel, Gas Turbine and/or Deep Cleaning</u>	<u>Grinding Requirement*</u> kwh/ton
Less than 10 micron	Standard Ball Milling	330 (1)
	Jet Mill Grinding	330 to 1000 (2)
	Stirred Ball Mill (Experimental)	up to 326 (3)
	E&MR Co. (This contract work)	37

Ref. (1) Perry, Chemical Engineers Handbook, 5th Edition, Chapter on Grinding.

Ref. (2) Private Communication, Fluid Energy Representatives at Engineering Foundation Conferences (June 19, 1977).

Ref. (3) Private Communication, Dr. William Peters, DOE, PETC, (December 8, 1978). Value depends on Hardgrove Grindability Index.

* Order of magnitude best values from various sources of different grindability.

V. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

It was clear throughout the work of the project, and particularly as equipment and techniques were refined, that ultrasonic energy can contribute significantly to national coal use in providing a uniquely energy-efficient, cost-effective method to produce ultrafine coal particles. As noted in the Introduction, the most significant results appear to be:

- 1) repeatable production of ultrafine particulates in the desired size range,

	<u>% -325 mesh</u>	<u>% -7 micron</u>
HGI 97.5	95.51	35.78
HGI 56.7	89.35	37.00

;
- 2) equipment amenable to scale-up for production;
- 3) an energy efficiency which extrapolates to 37 kilowatt-hours per ton of coal vs. 330-1000 by fluid energy grinding; and
- 4) selective liberation of inclusions such as pyrite and ash during the ultrasonic grinding process, to provide a separable beneficiated coal product.

B. Recommendations

Scale-up of the laboratory array to production equipment is recommended and should incorporate redesign to increase system efficiency. This type of redesign has been a routine step for our personnel in the development continuum from research to production equipment, and is the work which historically has enabled practical, industrial use of ultrasonic equipment. We therefore recommend a development effort which we anticipate can be achieved both rapidly and economically.

Additionally, the technology appears equally applicable and economically beneficial for a broad spectrum of comminution applications, and should be extended to size ranges including gross crushing and plant grind.

APPENDIX A

ENERGY CONSIDERATIONS FOR PRODUCTION APPLICATION

The delivered power of an acoustic system is the power which does the work. As described in preceding sections of this report, the work done was grinding the coal, heating the moistening agent and overcoming residual system inefficiencies. The delivered power is the applied power divided by the standing wave ratio, and when the equipment is optimally designed, the standing ratio approaches 1, and the applied power is appropriately reduced.

Therefore:

$$P_t = \frac{P}{\text{SWR}} \quad (1)$$

where:

P_t = transmitted power

P = power applied to acoustic system

SWR = standing wave ratio = $\xi_{\text{max}}/\xi_{\text{min}}$

ξ = particle displacement.

The power applied (P) was determined from observing the current and voltage applied to the transducer on an oscilloscope.

The standing wave ratio (SWR) was determined by placing crystal pickups on the loop and node of a wavelength long straight coupler. The crystal pickups were calibrated and the bar coupler was placed in the curved-coupler acoustic system. Impedance-matching the bar to the system was closely observed so that the SWR remained the same. Signals from the

crystal pickups were displayed on an oscilloscope. The resultant lissajous pattern indicated the SWR. A value of 3.57 was obtained:

$$\begin{aligned} P &= 263.5 \text{ watts} \\ \text{SWR} &= 3.57. \end{aligned}$$

Therefore from equation (1)

$$P_t = 73.81 \text{ watts}$$

As noted, the transmitted power ground the coal and raised the temperature of the moistening agent:

$$P_{(H_2O)} = 37.41 \text{ watts.}$$

Therefore:

36.4 watts used to grind 30 grams of coal for
2 minutes = 36.7 KWH/ton.