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Microwave Drying of Fine Coal

By David P. Lindroth

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	K/s	kelvin per second
cal/g	calorie per gram	kW	kilowatt
cm	centimeter	kW•h	kilowatt hour
ft	foot	lb	pound
ft^3	cubic foot	min	minute
ft/min	foot per minute	m/s	meter per second
gal	gallon	mW/cm^2	milliwatt per square centimeter
GHz	Gigahertz	pct	percent
h	hour	st/h	short ton per hour
in	inch	V/m	volt per meter
kg	kilogram	W/m^3	watt per cubic meter
kg/h	kilogram per hour	wt pct	weight percent
kg/(kW•h)	kilogram per kilowatt hour		

MICROWAVE DRYING OF FINE COAL

By David P. Lindroth[1]

ABSTRACT

The objective of this research by the Bureau of Mines was to determine the technical feasibility and associated pilot data for drying minus 1/4-in coal with microwave energy at a frequency of 2.45 GHz. The drying data were obtained experimentally on three coal types: bituminous, subbituminous, and lignite. The experiments were performed with a custom-designed conveyorized microwave oven having a continuous power capability of 12 kW. Drying efficiencies near the theoretical maximum of 1.54 kg of water per kilowatt hour of energy input were achieved for two coals and two sizes; overall drying efficiencies averaged 77 pct.

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INTRODUCTION

Fundamental problems exist with the drying of fine coal. The moisture content of fine coal after mechanical dewatering is often too high to allow the coal to be added directly to the coarser (plus 1/4 in) fractions and it must be further dewatered. Also, fine coal is lost and expelled with sludge in most current coal washing processes, creating two significant problems: The loss of usable coal is estimated to be as high as 10 to 15 pct of the coal mined (1);[2] and failure to recover the fine coal increases the volume of sludge expelled into the waste ponds, increasing safety and environmental hazards.

The three main problems existing because of current drying methods are (1) fugitive dust, (2) potentially explosive mixtures in stacks, and (3) environmental problems associated with settling ponds. Industry acknowledges that to meet an increasing demand for coal, research programs in the area of thermal drying of coal are imperative.

Venkatesan (2) established the need for additional research to improve the thermal drying of coal:

> Handling of a finer, dirtier, and wetter coal is a problem facing the coal industry because of the increased use of continuous mining machines, the exploitation of poorer quality seams of coal, and the adoption of mining dust control regulations.
>
> The water applied for dust control often increases the run-of-mine coal surface moisture content to a 5 to 7 pct level. With surface moisture at this level, coal preparation plant operators usually resort to wet cleaning methods to clean the fine coal because pneumatic methods are generally ineffective at this moisture level.
>
> The wet cleaning and subsequent dewatering of the fine coal is accomplished through various methods. Often clean coal, 1/4 in by 28 mesh, is drained on vibrating screens and is further dewatered by centrifuges to about an 8 to 9 pct moisture content. The 28 mesh by 0 coal, sometimes a combination of hydroclone clean coal (28 by 100m) and flotation froth (100m by 0), is dewatered by vacuum filters to a 22 to 23 pct surface moisture content.

Because of the increased surface area with decreased particle size, the fines will absorb and retain considerably more moisture than the coarser fractions. This complicates the cleaning process, and the additional step of thermal drying must be included to remove excessive moisture. This step, however, is one of the preparation steps for coal that results in substantial economic savings (3).

The thermal drying of coal is performed to--

1. Decrease transportation costs.
2. Reduce heat loss due to the evaporation of surface moisture from the coal in the burning process and, therefore, increase the heating efficiency.
3. Avoid freezing difficulties and make handling easier during shipment, storage, and transfer to the points of use.
4. Improve the quality of coal used for special purposes, such as in the production of coke, briquettes, and chemicals.
5. Make easier the dry coal-cleaning process.
6. Maintain high pulverizer capacity.

If a more efficient method of thermal drying of the coal fines was developed that eliminated the fugitive dust, explosive stack mixture, and environmental problems, it would be of benefit to the industry. To this end, the Bureau of Mines Twin Cities Research Center initiated a research program to determine the drying rates and power required in drying fine coal using microwave energy at the standard industrial frequency of 2.45 GHz. The research was performed in the laboratory using a 12-kW continuous-belt microwave system.

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[2]Underlined numbers in parentheses refer to items in the list of references at the end of this reoprt.

It has been established that coal is a poor absorber of microwave energy (4) and water is a good absorber (5). Unlike the current methods of drying fine coal, which heat both the coal and the water, this research demonstrates a method to heat and drive off only the water. This method is more energy efficient and will minimize the generation of fugitive dust.

The heating by microwave energy is based on excitation of a molecular dipole at its resonant frequency. At 2.45 GHz, the resonant rotational frequency of a liquid water molecule, the electric field changes direction at the rate of 4.9 billion times per second, causing rotation of the molecules at the same rate. This rapidly alternating electric field exerts a force on the molecule whose resulting violent motion results in instant heating. The amount of heat generated in the material is directly proportional to the square of the electric field, the frequency, and the loss factor. This is expressed as the power absorbed per unit volume of material exposed to the microwave energy,

$$P = 55.63\times10^{-12}E^2 f\varepsilon''_r,\ \text{W/m}^3 \qquad (1)$$

where f is the frequency in hertz, E is the rms local field intensity in V/m, and ε''_r is the relative dielectric loss factor (6). The material heating rate is dependent upon the power absorbed, specific heat, (C), and density (ρ) as shown by the equation

$$\frac{\Delta T}{\Delta t} = \frac{5.71\times10^{-11}\ P}{C\rho},\ \text{K/s}. \qquad (2)$$

The dielectric loss factor is the dominent variable, for a given frequency and field intensity, in determining the microwave power absorbed and resulting temperature rise in a material. The loss factor is approximately 0.1 for coal and 12.0 for water. Therefore, with the given power output and frequency, the power absorbed in the water is 120 times greater than that in the coal. Since water absorbs microwaves and coal essentially does not, the energy concentrates in the wetter areas. In the water removal process, the power absorbed in the mixture decreases as evaporation nears completion. This limits the tendency toward overheating the coal, and the microwave energy is automatically utilized in the most needed areas.

EXPERIMENTAL APPARATUS

A continuous microwave drying system (fig. 1) manufactured to the Bureau's specifications, consists of two main components: a conveyorized oven and two microwave power generators.

The oven is 6 ft long and has a fiberglass-Teflon[3] mesh belt running through it. The belt speed is continuously variable from 0 to 30 ft/min to adjust the product residence time in the oven. A thermocouple continually monitors the output product temperature and displays this temperature on a meter (0° to 430° C) mounted on the control cabinet.

The thermocouple is a grounded, iron-constantan type J with a stainless steel sheath. The meter resolution over the temperature range of interest in this work is ±5.6° C. A microwave leakage detector is located at the oven entrance and exit. There is a meter for each detector at the control panel, each having a scale reading from 0 to 2 mW/cm^2. The leakage detector alarm will trip at 1 mW/cm^2, an alarm will sound, and the microwave power will be shut down. An exhaust blower is provided to remove vapors after they leave the heated product. A blast gate is included to control the air exhaust rate. An access door, with a wire-embedded glass insert window, is located at the rear center of the oven to permit cleaning.

A closed-circuit television camera was used to monitor the coal on the belt and the inside of the oven. The video monitor was located above the generator controls for easy viewing. The master control panel is located at the right front of the system.

[3]Reference to specific products does not imply endorsement by the Bureau of Mines.

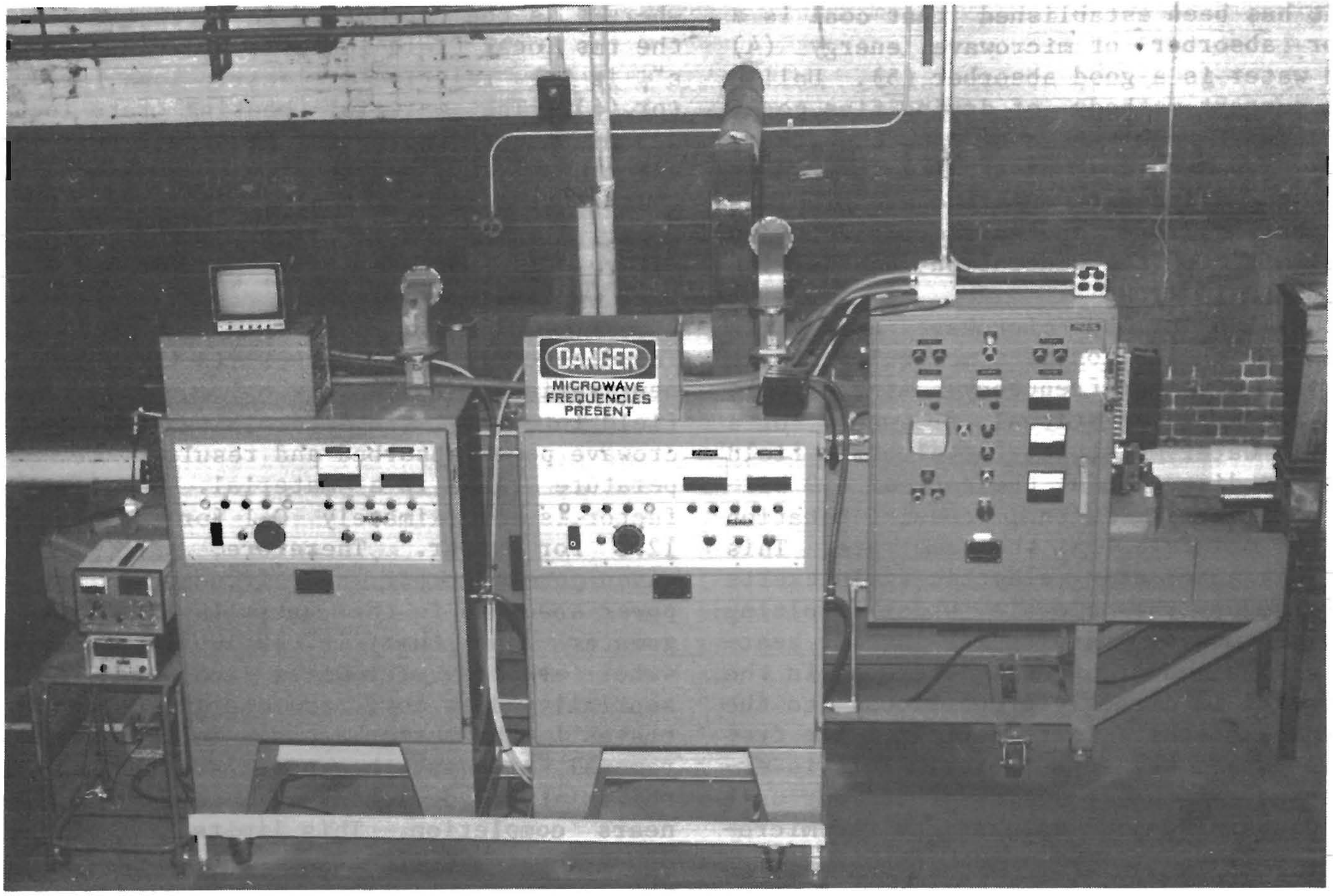

FIGURE 1. - Microwave drying system.

Each microwave generator is a complete, self-contained, power source. It is rated at 6 kW continuous power output and operates at the internationally assigned ISM frequency of 2.45 GHz. The generator is housed in a cabinet with all the necessary operating controls and indicators mounted on the front door. Air, to cool the cabinet, is brought in through a heat exchanger mounted on top of the cabinet. Two of the major components, the magnetron tube and the circulator, are directly water cooled. Power meters (0 to 7 kW) are provided to monitor both forward and reflected power. With least scale readings of 0.2 kW, readings accurate to ±0.1 kW are achievable. With the variable airflow through the oven, feeder speed, belt speed, and power level, this system allows for a wide variety of drying rates and output temperatures.

A dry materials feeder was used to feed the coal onto the belt. This feeder contained a 2.5-ft^3 hopper and a mechanical variable-speed drive. The vibrating hopper moves the coal down into a conditioning chamber where the larger of two augers preconditions it to a constant density and provides for the precise volumetric filling of the smaller auger. This smaller metering auger displaces the coal accurately through the discharge cylinder and onto the belt.

A platform transducer was used to continuously measure the weight of the dried output product. The platform transducer employs four strain gage sensing elements to which is transmitted the force of a load placed on the platform. This force changes the stress pattern in the sensing elements, which are electrically interconnected to produce an output voltage proportional to the applied weight. The transducer is accurate to ±0.5 pct with a repeatability of 0.10 pct.

COAL SAMPLES AND PREPARATION

Three coal types were used for the drying tests, a bituminous, a subbituminous, and a lignite. The bituminous coal was Illinois No. 6 from the Streamline Mine near Percy, Randolph County, IL (7). Samples of approximately 1.5 ft^3 were obtained from the run-of-mine stockpile, transported by Bureau personnel, and stored in a high-humidity chamber until ready for preparation. The subbituminous coal was supplied by the Colowyo Coal Co. from the Colowyo Mine near Meeker, Moffat County, CO (8). The lignite was supplied by North American Coal Corp. Indian Head Mine near Beulah, Mercer County, ND. Both the lignite and the subbituminous coal were shipped by rail from the mine and delivered to the Bureau by truck. The analysis of each coal is given in table 1.

Approximately 900 kg of each coal type was selected for crushing, grinding, and screening to two sizes (minus 1/4 in plus 28 mesh, minus 28 plus 100 mesh) for the

TABLE 1. - Analyses of coal samples

	Illinois No. 6 coal	Colowyo coal	Indian Head lignite
Coal type	Bituminous	Subbituminous	Lignite
Proximate analysis,[1] wt pct:			
Moisture	7.96	10.8	30.8
Volatile matter	34.22	36.2	29.1
Fixed carbon	46.74	46.2	34.0
Ash	11.07	6.8	6.1
Total	100.00	100.00	100.00
Ultimate analysis, wt pct:			
C	62.09	63.4	45.4
H	4.21	5.4	6.5
N	0.85	1.3	0.6
O	9.66	22.0	40.8
S	4.16	0.7	0.6
Ash	11.07	6.8	6.1
Heating value, cal/g:			
As received	6,106.3	6,122.4	4,224.1
Moisture free	6,634.7	6,868.9	6,104.6
Moisture and ash free	6,432.1	7,429.6	6,696.3
Free swelling index (FSI)	1	0	0
Ash fusibility temperature, °C:[2]			
Initial deformation	1,237.8	1,371.1	1,115.6
Softening	1,279.4	1,398.9	1,137.8
Fluid	1,354.4	1,471.1	1,165.6
Ash chemistry, wt pct:			
Al_2O_3	11.5	19.4	9.3
CaO	9.0	2.0	18.5
Fe_2O_3	31.9	12.0	12.0
K_2O	1.9	1.1	0.5
MgO	0.7	0.7	6.5
Na_2O	0.6	1.0	8.3
P_2O_5	0.02	0.6	0.9
SiO_2	34.9	48.1	18.1
SO_3	9.2	1.6	12.5
TiO_2	0.6	0.8	0.5

[1]As received. [2]ASTM reducing conditions.

drying tests. After screening, the samples were stored in new, plastic-lined 55-gal drums, and the lids were sealed.

Head samples were taken from each size fraction, and the standard tests for determining the total moisture were performed in accordance with ASTM Designation D3302-74 as given by Merritt (9). Table 2 shows the results of these determinations. The mean ($\bar{x}$) and standard deviation(s) of three samples are given for the air dry loss and residual moisture.

EXPERIMENTAL PROCEDURE

Each coal sample was prepared by using a fine water spray to wet a measured amount of coal to a predetermined moisture level based on percent weight. This sample was placed in a container sealed against moisture loss and allowed to equilibrate for 24 h prior to the microwave drying test. When ready, the sample was weighed, removed from the container, and poured into the feeder. Next, the microwave oven conveyor belt was started and set to a predetermined speed. The feeder was then started, and coal was fed onto the belt. When the coal entered the oven, the microwave power generators were turned up to the desired power level (12 kW for most tests). The oven interior was continuously observed on the video monitor. The forward and reflected power and the output coal temperatures were monitored during each test to ensure adequate absorption was taking place but that the coal was not overheated. To determine pretest and posttest moisture levels (9), equal volumes were periodically sampled during the test, from the wet feed into the oven and the dried coal coming out of the oven.

The dried coal was allowed to fall off the belt about 2 ft into a container placed on top of the platform transducer. This output weight was continuously monitored, and the final dried weight was recorded at the end of the test. The airflow through the system was set at an exhaust velocity of 8.89±0.03 m/s (0.66 pct of maximum) for the entire series of tests.

Air was drawn into the system at the entrance and exit points of the belt and exhausted from the top center of the microwave oven. This airflow was adequate to remove the microwave-generated steam from the oven cavity, but low enough to eliminate dust entrainment from the coal on the belt. The relative humidity remained at 65±5 pct and the ambient temperature at 23°±3° C for the entire test series.

TABLE 2. - Head sample moisture levels,[1] percent

Coal	-1/4 in +28 mesh		-28 +100 mesh	
	Mean	Std dev	Mean	Std dev
Illinois No. 6:				
Air dry loss...............	0.97	0.32	3.03	0.95
Residual moisture..........	7.10	.17	7.40	.20
Total moisture..........	8.00	NAp	10.21	NAp
Colowyo coal:				
Air dry loss...............	4.13	.47	4.73	.40
Residual moisture..........	12.83	.12	10.93	.40
Total moisture..........	16.43	NAp	15.14	NAp
Indian Head lignite:				
Air dry loss...............	5.57	.93	5.80	.46
Residual moisture..........	13.37	.70	13.43	.31
Total moisture..........	18.20	NAp	18.45	NAp

NAp Not applicable.
[1]3 samples for all data.

RESULTS AND DISCUSSION

The experimental microwave drying values obtained for the three coal types are listed in table 3. The higher moisture levels tested in the minus 28 plus 100 mesh coal samples correspond to troublesome moisture levels encountered in the mechanical dewatering systems.

The drying efficiency achieved for each test is given in the last two columns. The actual kilogram(s) of water removed by the given microwave energy input is listed first, followed by corresponding percent of theoretical maximum. Microwave energy is able to evaporate a maximum of 1.54 kg of water per kilowatt hour of energy input.

Typical drying rate curves achieved with this continuous process microwave system are shown in figure 2. The curves shown are for Illinois No. 6 coal (minus 1/4- plus 28-mesh) tests 1 and 4, which represent the shape of all coal drying rate curves obtained during these experiments. The system control parameters of power, feed rate, and belt speed make it possible to achieve any desired final moisture level. The power level was set at the beginning of the test and remained constant for the entire drying time. Within 2 min after startup, the entire system was equilibrated and the output moisture levels approached the desired value. Figure 2 shows that a moisture reduction of +60 pct is easily achieved. This instantaneous control of energy input demonstrates one of the advantages of microwave heating. The output coal temperatures were monitored for all tests. The mean peak temperature was 73° C with a standard deviation of ±8° C. Throughout the entire set of experiments, only one brief excursion of 88° C was observed, for Indian Head lignite, test 1. No arcing or fires occurred throughout this whole series of tests.

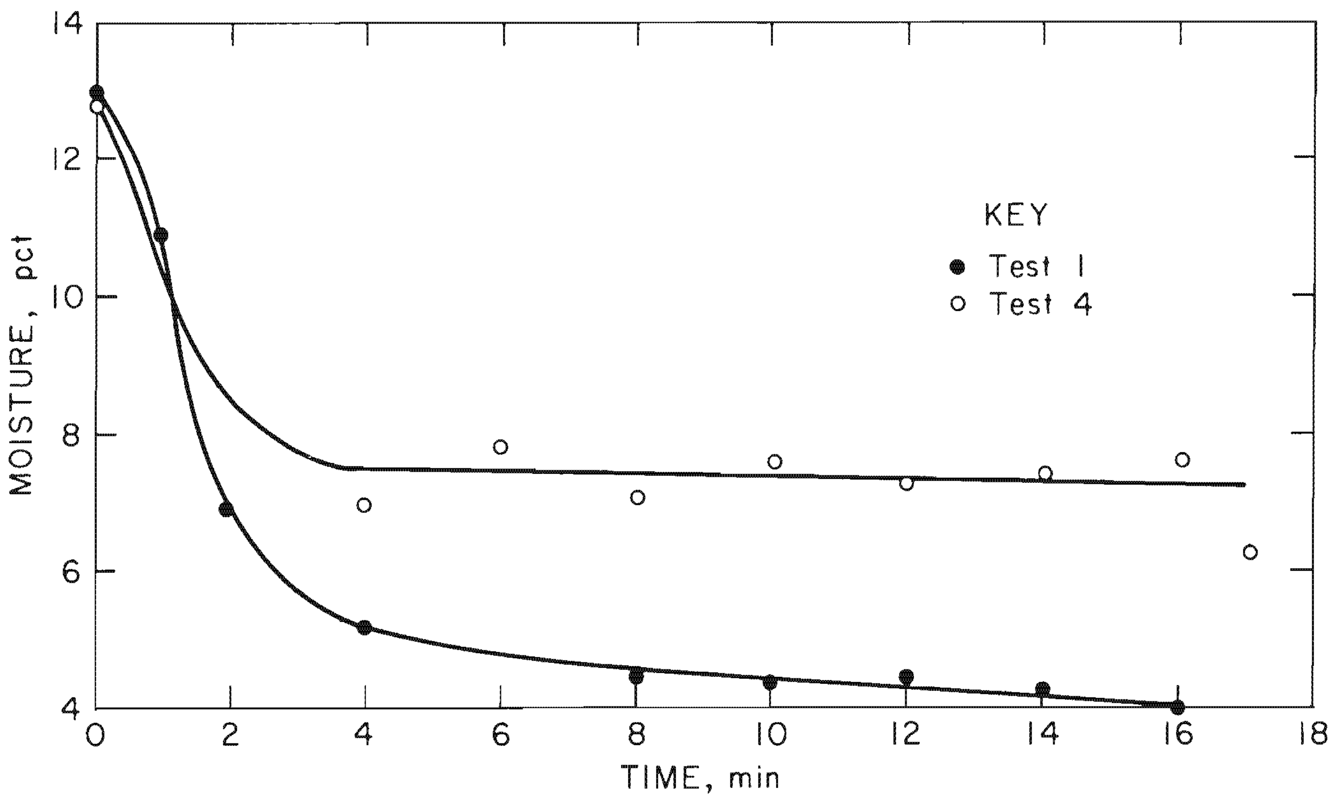

FIGURE 2. - Drying rate curves, Illinois No. 6 coal, minus 1/4 in plus 28 mesh.

TABLE 3. - Experimental drying data

Coal sample and screen size[1]	Microwave power, kW (±0.1)	Wet input, kg (±0.2)	Feed rate, kg/h (±5%)	Belt speed, m/s (±5%)	Drying time, h (±3%)	Feed moisture, pct H_2O		Water removed,[2] kg (±0.02)	Drying efficiency	
						Mean	Std dev		H_2O, kg/(kW•h)	pct
ILLINOIS NO. 6										
-1/4 in +28 mesh:										
Test 1	10.2	45.6	114.4	0.087	0.410	13.	1.9	4.49	1.08	70
Test 2	10.2	44.0	114.4	.087	.397	12.6	.95	4.04	1.00	65
Test 3	10.4	43.7	152.5	.073	.298	13.	.86	3.54	1.14	74
Test 4	10.4	43.7	152.5	.073	.298	12.8	1.4	3.27	1.05	68
-28 +100 mesh:										
Test 5	9.8	17.1	57.2	.060	.250	25.2	1.6	2.86	1.17	76
Test 6	7.9	15.2	68.1	.060	.242	24.5	1.4	2.77	1.45	94
Test 7	7.9	16.8	81.7	.047	.212	23.7	1.5	2.5	1.49	97
COLOWYO										
-1/4 in +28 mesh:										
Test 1	9.7	49.5	239.7	0.068	0.208	16.5	2.	2.72	1.35	87
Test 2	9.4	49.5	245.2	.048	.210	19.3	2.2	2.68	1.36	88
Test 3	9.1	49.5	223.4	.038	.225	16.6	.7	2.	.98	63
Test 4	9.4	44.4	201.6	.038	.233	19.8	4.1	3.27	1.49	97
Test 5	10.0	44.3	286.	.049	.167	9.3	.7	2.	1.19	77
Test 6	9.7	45.4	166.2	.030	.275	10.6	.5	3.09	1.16	75
-28 +100 mesh:										
Test 7	9.8	18.2	48.1	.030	.378	17.6	.5	2.95	.79	52
Test 8	9.9	18.2	50.8	.030	.359	18.8	.5	3.13	.88	57
INDIAN HEAD LIGNITE										
-1/4 in +28 mesh:										
Test 1	10.2	44.0	149.8	0.060	0.304	14.3	2.2	3.	0.97	63
Test 2	9.9	45.4	149.8	.030	.303	15.7	.8	3.63	1.21	78
Test 3	10.1	45.4	125.3	.030	.361	15.7	.8	4.72	1.29	84
-28 +100 mesh:										
Test 4	10.1	45.1	111.7	.030	.400	14.6	.6	5.63	1.39	90
Test 5	10.2	22.8	100.8	.030	.227	14.6	.6	2.72	1.18	76

[1]Tyler standard screen scale sieve series.

[2]Determined from the mass difference in feed and output samples as weighed on the platform transducer.

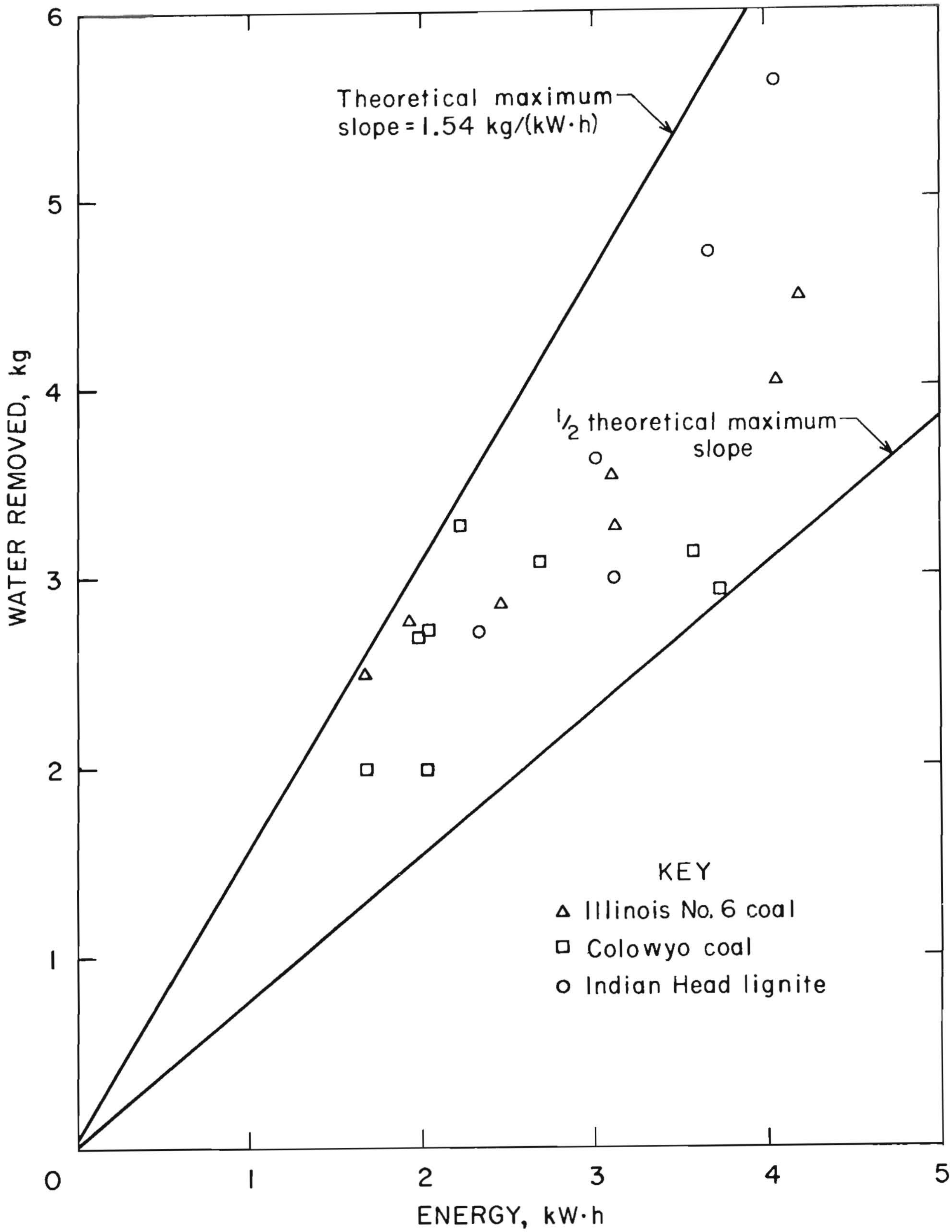

FIGURE 3. - Drying efficiency.

Figure 3 shows the amount of water removed as a function of the input microwave energy for all tests performed. An envelope of the data consisting of an upper and lower bound having constant slopes is presented. The left line represents the theoretical maximum amount of water (1.54 kg) that can be evaporated by 1 kW•h of microwave energy. Notice that the ordinate value is 1.5 kg at the abscissa value of 1 kW•h. For this work with coal, all experimental values were above 60 pct of the maximum value, except for two values of Colowyo minus 28 plus 100 mesh size. The operating parameters selected for Illinois No. 6, test 7, and Colowyo, test 4, were near optimum. Efficiencies of 97 pct were achieved.

The microwave attenuation per unit depth (α) of material is plotted as a function of temperature for water (fig. 4). Contrast the values for lignite and Illinois No. 6 coal given below for ambient temperature (25° C). Relative to water, the attenuation of coal is near zero.

Some of the lower efficiencies observed for lignite compared with Illinois No. 6 are due to differences in the dielectric properties of the coal. At the 2.45-GHz operating frequency, the loss factor for lignite is 0.21 (4), compared with 0.10 for Illinois No. 6 (6). If all other conditions are held constant, the lignite absorbs twice as much energy as Illinois No. 6 coal. The normalized power absorption per unit depth for lignite is 3 pct greater than for Illinois No. 6. However, as shown in figure 4, water with a loss factor of 12.0 at the same ambient temperature (25° C) has a normalized power absorption per unit depth 124 pct greater than that of lignite. As the water temperature increases, the absorption decreases (5). At 95° C the water power absorption is 18 pct greater than that of the lignite. These data show the relative transparency of the coal to

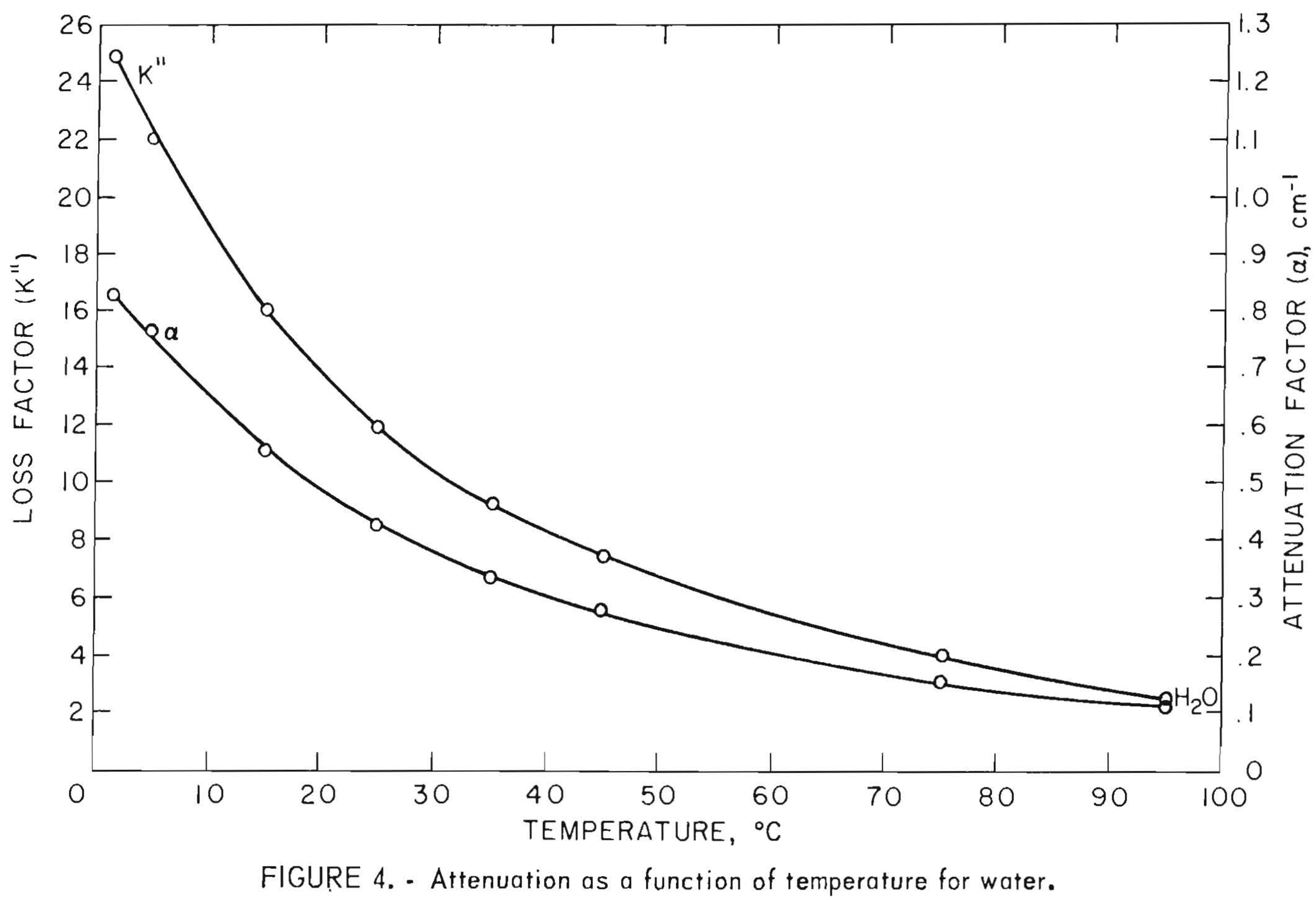

FIGURE 4. - Attenuation as a function of temperature for water.

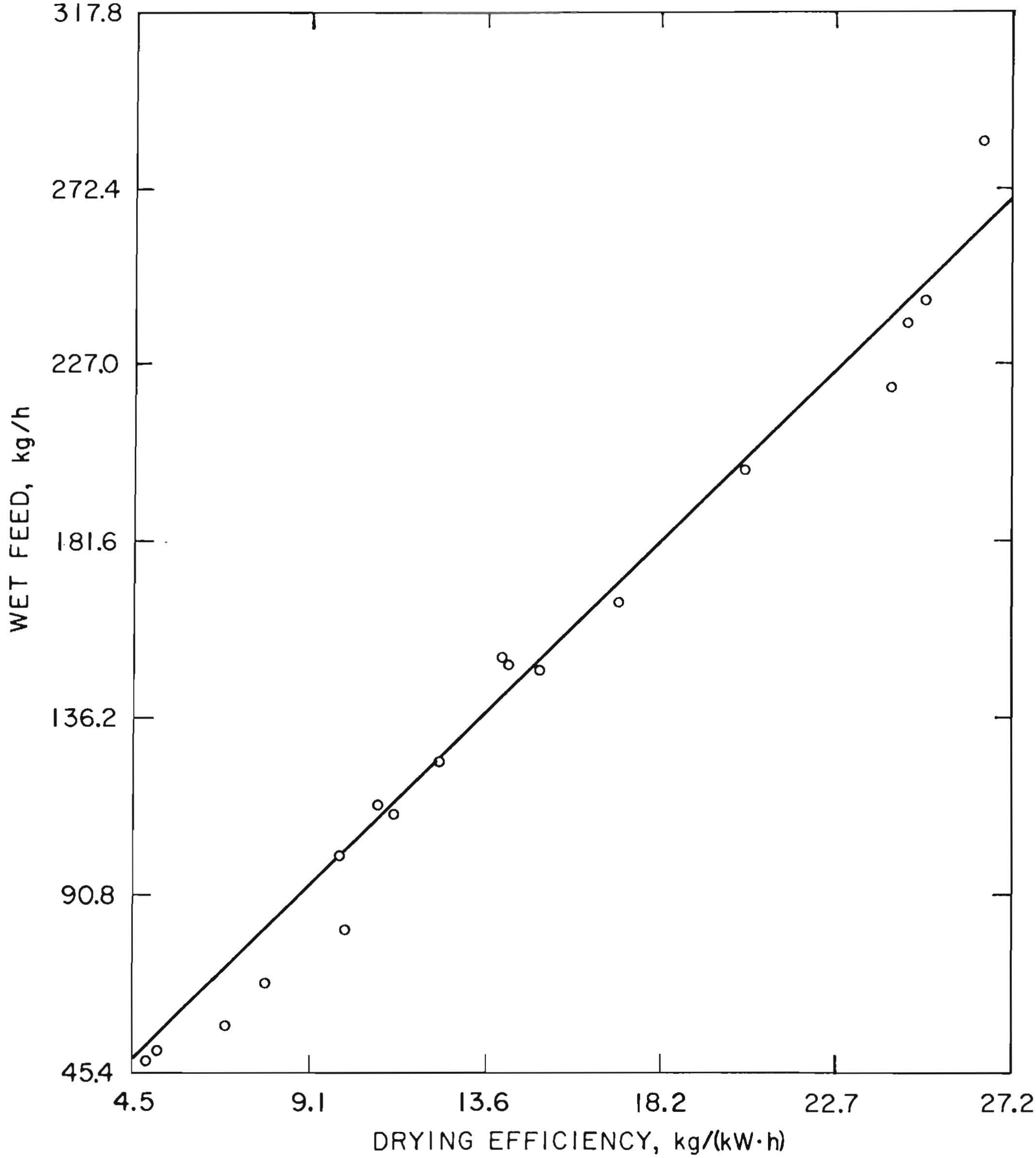

FIGURE 5. - Wet feed rate as a function of efficiency.

microwave energy at a frequency of 2.45 GHz. In contrast, water is a very good absorber. This differential absorption in the feed material allows the energy to be selectively placed in the water to effect efficient drying, in contrast to existing thermal drying methods, where hot air heats both the coal and water. This selective energy absorption is one of the advantages of microwave heating.

In actual processing practice, the operating parameters would be adjusted until the efficiency approached 100 pct. Given the dielectric and thermal properties of the material to be processed, the available generator power at the fixed frequency becomes the controlling factor. This is shown in figure 5 with the wet feed rate plotted as a function of the drying efficiency for all three coal types and sizes tested. The slope of the line is in kilowatts, which is the available microwave power. The point scatter is due to the nonconstant power levels (mean of 9.7 kW) used in the experiments, as shown in table 3, column 2, and the varying amounts of moisture removed.

Using the above data, estimates for large-scale drying can be projected. For example, to process a wet feed of 10 st/h (9,080 kg/h) and remove 10 pct moisture with an overall microwave absorption efficiency of 95 pct, 620 kW of microwave power would be required. This assumes that 1 kW•h of microwave energy evaporates 3.4 lb (1.54 kg) water.

An overall system efficiency for a system of this size, assuming large 50-kW magnetron tubes are used, would be about 66 pct. Efficiencies are as follows: from the power source to the magnetron tubes, about 95 pct; from the high voltage to microwave energy, about 82 pct; and from microwave energy to the coal-water load, about 85 pct. The expected operating life of these large magnetron tubes is 6,000 to 8,000 h.

CONCLUSIONS

The technical feasibility of drying -1/4-in coals by microwaves was demonstrated using a pilot-scale continuous processing system. Drying efficiency near the theoretical limit was achieved by proper adjustment of the process parameters. Maximum efficiencies of 97 pct for both Colowyo minus 1/4 in plus 28 mesh and Illinois No. 6 minus 28 plus 100 mesh were obtained during these experiments. Efficiency as low as 52 pct was observed, and average efficiency for all tests was 77 pct.

The differential absorption of microwave energy in the coal-water feed material allows the energy to be selectively placed in the water to effect efficient drying of the coal.

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