SELF-HEATING OF COAL IN BARGES

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I. INTRODUCTION

Self-heating, or spontaneous heating, is a process which results in an increase in temperature of a thermally-isolated mass of coal or other combustible material. This phenomenon is caused by the heat-generating chemical reactions between the oxidant (oxygen) and the fuel (coal). If the generated heat is removed or absorbed by the surrounding environment, then only low temperature oxidation will occur. However, if nothing is done to change the condition of the coal undergoing a self-heating process, spontaneous combustion will eventually occur.

Self-heating in coal has been observed for more than 100 years for many coals around the world. It is a problem that affects the mining, transportation, and storage of coal and contributes to the deterioration in its quality. Several comprehensive reviews have been written on the factors that may contribute to the self-heating in coal (1-8). These factors are numerous and include intrinsic properties such as rank, heat of wetting, porosity, exposed surface area, ash content, content of pyrites and other sulfur containing species, hardness, methane content, and thermal conductivity of the coal. Handling conditions that may contribute to coal self-heating include changes in moisture content of the surrounding environment, large variations in the temperature when the coal is shipped, and to the movement of air through the coal.

The purpose of this research was to examine the factors which may contribute to the self-heating of coal in barges. A data bank containing analytical data and barging information on 2283 barges was used to help identify the principal factors contributing to the self-heating of barged coal. Barging studies to examine coal handling and barging techniques designed to minimize the occurrence of self-heating were conducted.

II. EXPERIMENTAL

Two separate barging studies were carried out over a period of two summers. The studies took place on the Ohio and Mississippi rivers and involved 15 barges of coal in the first study and 10 barges in the second tow. The work performed and the number of researchers that could accompany the tows were restricted by the room available on the towboats, the safety considerations during tow work by the boat crew, and the availability of barges filled with a particular type of coal and loaded in a particular manner.

The coal studied in the barging experiments was steam coal (high volatile bituminous) loaded at four different river ports. The coal loaded at each port had been mined in the same general area and had been crushed, stockpiled, and handled by the same equipment. Consequently, the coal loaded at each port had the same general physical and chemical properties, and exhibited the same general behavior toward self-heating.

Two different loading schemes were used in the studies, single chute loading and loading with a "diffuser." The diffuser is a device added to a normal coal chute which splits the falling stream of coal into five streams. This loads the coal in a pattern of five rows of "cones" instead of a single row in the center of the barge. The diffuser was much more effective in preventing size segregation of the coal which would minimize the formation of channels for uneven air flow through the coal in the barge.

A second variable monitored during the study was the effect of compacting coal to minimize self-heating. Three methods of compacting coal in barges were studied. Two barges were lightly compacted using a "clam shell" bucket from a loading crane and this light compacting left voids in the ends of the barges. A second method studied did not compact the coal very much but simply leveled the tops of the cones of coal produced during loading. This method is often referred to as "trimming" and leaves large voids (3-10 ft.) in the ends of the barges. Five barges were prepared in this manner. The third method of compacting studied in this project was the most efficient method used. A small "Bobcat" front-end loader was hoisted into the barges and used to move the coal around to fill voids in the corners and sides of the barges. The weight of the coal in the loader bucket plus the weight of the loader itself compacted the coal under the rubber tires of the loader. Eight barges were compacted with the front-end loader. As an illustration of the difference in compacting, the coal in barges compacted with the front-end loader had a depth of about 13.5 ft., whereas the coal in "trimmed barges" had a depth of about 15.5 ft. All barges in a tow had approximately the same tonnage.

Daily temperature measurements of the coal in the barges were recorded in order to have a record of self-heating rates for different coals and at different positions in a barge. Care was taken that a representative temperature profile of the barges was obtained and recommendations for temperature measurements as presented in a report by the Coal Exporters Association/National Coal Association Task Force on Coal Handling, Storage and Transportation were used (9). Twenty-seven positions uniformly spaced down the sides and center of each barge were chosen for temperature measurements and temperatures were measured at depths of 3, 6, and 9 ft. at each position. The temperature probes used were constructed from 1/4 in. I.D. galvanized steel pipe and fitted with a metal tip machined to a point so that the probe could be pushed into the coal. Type J thermocouple wires were attached with epoxy cement at three 1/4 in. holes drilled at 1 in., 3 ft. and 6 ft. from the probe tip. The thermocouple wires were attached to an Atkins Model 39658J Digital Readout Meter with a three-position switch for reading the temperatures at the three depths. The probes were carefully calibrated before use and found to be accurate to within +/-1^{o}F. After inserting the probes in the coal they were allowed to equilibrate for a minimum of 3 minutes before any temperature readings were made.

The movement of air through the coal in the barges loaded and compacted by different methods is closely related to the self-heating that occurs. To follow the movement of air through the coal a tracer gas, sulfur hexafluoride, was released at a depth of 10 ft. in some of the barges and its movement through the coal was monitored by measuring the concentration of SF_6 in gas samples collected at regular intervals. Bendix Model 44 Air Sampling Pumps were used to draw gas samples from the bottom of the barges through 1/4 in. I.D. steel pipes with holes drilled near the bottom end of the pipe. Gas samples were collected in 250 cc polypropylene gas collection bulbs and immediately analyzed using a gas chromatograph set up in the towboat. A Carle Model 6500 gas chromatograph with an 8 ft. x 1/8 in. activated alumina (80-200 mesh) column connected to a Hewlett-Packard Model 3390A Reporting Integrator was used for the analysis.

During the course of the project, 230 samples of coal being transported by barge to ports in the New Orleans area were obtained for analysis at the Western Kentucky University laboratory. Moisture, ash, volatile matter, carbon, hydrogen, nitrogen, sulfur and calorific values were determined using microcomputer-controlled instrumentation from LECO Corporation in St. Joseph, MI. Forms of sulfur, free-swelling index and Hardgrove grindabilities were determined using ASTM methods D 2492, D 720 and D 409, respectively. Fixed carbon and oxygen values were calculated by difference. Transportation histories of the barged coals were also obtained.

III. RESULTS AND DISCUSSION

The self-heating of coal is brought about through oxidation of coal surfaces, and the amount of air available to the coal is important. The air flow rate through the coal is a complex factor to consider since air both provides oxygen for oxidation of the coal and dissipates the heat generated by the oxidation process. Conditions which permit only a small amount of air to come into contact with the coal will keep oxidation at a minimum and little or no self-heating will occur. A very high flow rate of air provides sufficient oxygen for the oxidation process, but dissipates heat efficiently. In between these two limits is a state where the air flow is sufficient to promote oxidation of the coal surfaces but is not sufficient to dissipate the heat produced by the exothermic reaction. In this case the heat produced will raise the temperature of the coal and accelerate the rate of oxidation until, ultimately, ignition of the coal will occur (5,6,10,11).

A. Barge Loading and Compacting Methods

The techniques employed in loading barges with coal will affect the air flow rate through the coal. When coal is loaded from a single chute, the resulting conical piles tend to have the fines concentrated at the center of the cone with larger particles segregated around the surface at the base. Quite often at a point somewhere between the outer edges of the cone and the center the air flow rate is sufficient to initiate and support heating. The cone then acts as a "chimney" to draw air from around the base into the center to maintain the heating. The simple process of leveling the cones seals the coarser coal with the fines and restricts air flow through the coal. Compacting the leveled coal further limits its access to air by reducing interparticle voids. The reduction of these voids also results in an increase in thermal conductivity which helps dissipate any heat produced.

A comparison of the temperatures of coal in barges compacted by two different methods is given in Table 1. The barge number used in the table represents the order in which the barges were loaded. All the barges were loaded at the same port and with the same type of coal. The temperatures reported are those of the coal in the barges prior to unloading when the ambient temperature was 90^{o}F. The average temperature is the average of 81 individual readings for each barge (27 positions and depths of 3, 6, and 9 ft.). At ports in the New Orleans area, the temperature of coal being exported has to be below 105^{o}F before it can be loaded onto ocean-going vessels. As can be seen from the data there is a dramatic difference between the results obtained for the two methods of compacting coal, with nearly one-third of the temperature readings above 105^{o}F for the lightly compacted coal. From these examples one can conclude that compacting coal in barges offers considerable protection against self-heating.

Table 2 shows temperatures of coal in barges loaded by two different methods. All the barges were loaded at the same port and with the same type of coal. The barge numbers again refer to the order of loading the barges and the average temperatures are the average of the 81 readings taken prior to unloading when the ambient temperature was 90^{o}F. A comparison of the temperatures for the barges loaded by two different methods shows an average of 91.3^{o}F for the barges loaded with the diffuser, whereas the barges loaded with the single chute have an average temperature of 95.2^{o}F. The difference in average temperatures can be attributed to the fact that loading with the diffuser produces an even distribution of coal particles, whereas the single chute loading method yields a segregated mass of coal particles. The even distribution of particles yields a more uniform air flow through the coal which results in less self-heating.

The heating that took place in several of the barges was "triggered" by the occurrence of a heavy rain on the ninth day after the initial barges were loaded. On the morning following the rain a uniform layer of warm coal was noted in the barges while making temperature and gas flow measurements. This layer was first apparent at a depth of about 6 inches, but later moved to a depth of 3 feet by the end of the day. It is believed that the layer of warm coal was caused by the water from the rain percolating down through the coal. This triggered self-heating in the coal, which was obvious by the higher temperature readings obtained on the days following the rain. It should be noted that the conditions for self-heating were already present and the rainfall simply initiated self-heating in the barges.

TABLE 1

Coal Temperatures in Barges Compacted by Different Methods

Barge No.	Method of Loading and Compacting*	Days in Barge	Average Temp (°F)	Maximum Temp (°F)	Number of Temp Readings >105°F
1	diffuser loaded and lightly compacted	11	105	133	23
2	diffuser loaded and lightly compacted	11	102	126	25
3	diffuser loaded and well compacted	11	92	115	1
4	diffuser loaded and well compacted	10	91	104	0
5	diffuser loaded and well compacted	10	91	102	0

* Lightly compacted - with a clam shell bucket.
Well compacted - with a Bobcat loader.

TABLE 2

Coal Temperatures in Barges Loaded by Different Methods

Barge No.	Method of Loading*	Days in Barge	Average Temp (°F)	Maximum Temp (°F)	Number of Temp Readings >105°F
3	diffuser loaded	11	92	115	1
4	diffuser loaded	10	91	104	0
5	diffuser loaded	10	91	102	0
6	single chute loaded	10	97	112	11
7	single chute loaded	9	97	111	12
8	single chute loaded	9	95	111	3
9	single chute loaded	9	97	119	9
10	single chute loaded	9	90	102	0

*All barges were well compacted with a Bobcat loader.

B. Air Flow Studies

Sondreal and Ellman (12) studied air flow through piles of North Dakota lignite and assumed that air convection through the lignite was unidirectional and only due to pressure gradients induced by the wind. They also assumed that natural convection resulting from thermal gradients were negligible. In this work it was also assumed that air movement through barges was primarily due to pressure gradients induced by the apparent wind created by the moving barges and that natural convection was minimal. The raw data from the gas flow studies indicated there were definite flow patterns in the barges studied. However, the data represented concentrations taken at different times and at different distances away from the point of injection, and was too complicated to present and try to explain in raw form. A correction for the tracer gas flow rate was determined by calculating the percent reduction in SF_6 concentration at each point in the barges where multiple sampling was done. Two, and sometimes three, samples were withdrawn from each of the sampling positions down the middle of each barge. The percent reduction in SF_6 was then plotted against time intervals between sampling and the best fitting line was used to determine a correction factor for SF_6 flow rates at various time intervals. The raw data were then multiplied by the correction factors to produce a distribution pattern represented by the contour maps shown in Figures 1 and 2. The numbers used in each of the figures to represent the concentration of SF_6 are relative.

The contour maps shown in Figures 1 and 2 illustrate various air flow patterns in the barges. Barge 3 was loaded with the diffuser, whereas barge 6 was loaded from a single chute. The contour map for barge 3 shows a relatively even lateral flow of tracer gas, whereas the contour map for barge 6 shows an uneven lateral flow. The coal in barge 3 was more evenly dispersed and less segregated by particle size than the coal in barge 6. The uneven air flow in barge 6 resulted in an increase in the rate of self-heating in the coal as was illustrated in Table 2.

The movement of the tracer gas away from the point of injection in each of the barges presents an interesting pattern. The relative concentration of SF_6 decreased between the injection point and the stern (back) of each barge, while it increased between the injection point and the bow (front) of the barges. As previously mentioned, it was assumed that air movement through the coal in barges was primarily due to pressure gradients induced by the apparent wind created by the moving barges. The contour maps given in Figures 1 and 2 illustrate the horizontal movement of the tracer gas and support this assumption. Air flow through the coal would push the tracer gas rapidly away from the point of injection and toward the back of the barge. The rate of dissipation of the tracer gas depended on how well the coal was compacted in the barges.

Sulfur hexafluoride has a density approximately five times as great as that of air. Because of this, SF_6 will flow to, and accumulate in, areas where the air flow is minimal. The accumulation of SF_6 in the front of the barges indicates there is little air flow through the first 25 or so feet of each barge. There is strong evidence that shows the most frequent area of the barge in which self-heating begins is the first 25 feet of the barge. This has been observed during the examination of data from over 600 barges (8). The fact that SF_6 accumulated in the same section of the barge where self-heating begins is a very important observation. This indicates that self-heating in barges is likely to begin where there is a sufficient supply of air to provide enough oxygen for the slow oxidation of the coal, but not enough air to carry away the heat produced in this oxidation. More importantly, it is probably the uneven air flow throughout the barge that provides the conditions for the initiation of self-heating.

The data from the gas flow studies was used to determine the relative gas flow rate through the barges. The percent reduction in tracer gas was plotted against the time interval between sampling for the points in the barges where multiple sampling was done. A linear regression of the data in each of these plots yielded slopes that are equal to the relative gas flow rates in each of the barges. Table 3 lists the relative gas flow rates obtained for the various loading and compacting methods used in this study.

TABLE 3

Relative Gas Flow Rates in Barges

Loading Method	Compacting Method	Relative Gas Flow Rate
Diffuser loaded	Well compacted with Bobcat loader	0.096
Single chute loaded	Well compacted with Bobcat loader	0.39
Diffuser loaded	Lightly compacted with clam shell bucket	0.66
Single chute loaded	Trimmed with small dozer	1.39

C. Chemical and Physical Properties of Barged Coals

A comparison of the mean values of the various chemical and physical properties of two types of coal studied in the barging experiments is given in Table 4. Five barges of coal were loaded at one river port and had a low potential for self-heating as is illustrated in the table. Ten barges were loaded at a different river port and had a relatively high potential for self-heating. A number of interesting differences between the two types of coal can be noted. The type of coal with the higher potential for self-heating exhibits a lower carbon content, a lower hydrogen content, and higher nitrogen, sulfur, and oxygen contents. The coal type with the higher self-heating potential has a higher sulfate sulfur content, a lower free-swelling index, and a lower heating value. These latter three properties are indicators that the coal has undergone "weathering" (13). What is not known about these particular barges of coal, however, is whether the apparent weathering of the coal is due to a long stockpile storage or to the inherent property of the coal to undergo weathering (oxidation) rapidly.

The computer-based data bank established as part of this project has made it possible to examine the behavior of coals during barging operations. In particular, information in the data bank has been used to determine the general characteristics of coal that undergoes self-heating and the average rate of self-heating during barging, the deterioration in the quality of barged coal, and the relative importance of various factors that contribute to self-heating in barged coal (8). Statistical analysis of the information in the data bank has been carried out using the SAS package developed by the SAS Institute, Inc., Cary, North Carolina.

Most of the barges of export coal included in the data bank have temperature measurements that were taken at the time the coal was unloaded from the barges. This information along with the extensive analytical data collected on samples of the barged coal makes it possible for one to compare the chemical and physical characteristics of coals that do, and do not, undergo self-heating during barging. For this particular comparison, it was arbitrarily decided to compare barges of coal with a maximum temperature reading less than $10^{o}F$ above ambient temperature (low potential) with barges that had a maximum temperature reading 20oF or more above ambient temperature (high potential). With these guidelines the data bank was used to generate the last two columns of data listed in Table 4. These data compare very well with that obtained in the barging study. The coals with the higher potential for self-heating had lower carbon and hydrogen contents, lower free-swelling indexes, and lower heating values. These coals also had higher nitrogen, sulfur, oxygen, and sulfate sulfur contents. This information indicates that coals with characteristics of weathered coals have higher potentials for self-heating.

TABLE 4

Characteristics of Coals in Barging Study and Data Bank
With Low and High Potentials for Self-Heating

Parameter*	Barging Study**		Data Bank***	
	Low Potent.	High Potent.	Low Potent.	High Potent.
Moisture, as-received (%)	14.16	13.43	14.16	14.05
Ash, dry (%)	9.04	11.94	8.38	9.23
Volatile Matter (%)	39.49	39.13	41.96	41.55
Fixed Carbon (%)	60.45	60.72	58.05	58.48
Heating Value (Btu/lb)	14,650	14,309	14,582	14,562
Carbon (%)	81.65	80.24	81.09	80.27
Hydrogen (%)	5.41	5.31	5.43	5.26
Nitrogen (%)	1.70	1.82	1.69	1.73
Sulfur (%)	2.07	2.31	1.62	1.86
Oxygen (%)	9.17	10.32	9.18	9.54
Pyritic Sulfur (%)	1.57	1.48	1.12	1.14
Sulfate Sulfur (%)	0.03	0.16	0.14	0.22
Organic Sulfur (%)	0.45	0.66	0.95	0.67
H/C Atom Ratio	0.794	0.797	0.798	0.782
O/C Atom Ratio	0.082	0.095	0.084	0.091
Free-Swelling Index	3.3	1.7	2.38	1.88
Hardgrove Grindability	39.0	44.1	43.6	47.9
Average Barge Temp (^{o}F)	87	96	74.5	84.9
Average Barge Temp (^{o}F)	95	114	81.4	108

* All values are reported on a dry, ash-free basis unless otherwise noted and all temperatures refer to the temperature of the coal at the time of unloading.

** Barging Study -- a fifteen barge tow with five barges having a low potential for self-heating (maximum barge temperature less than 10^{o}F above the ambient temperature) and ten barges having a high potential for self-heating (maximum temperature greater than 10^{o}F above the ambient temperature).

*** Data Bank -- 127 barges with a low potential for self-heating (maximum barge temperature less than 10^{o}F above the ambient temperature) and 100 barges with a high potential for self-heating (maximum barge temperature greater than 20^{o}F above ambient temperature).

IV. CONCLUSIONS

In conclusion, there are several recommendations that can be made with regard to protecting coal from self-heating during barging. The method of loading coal in the barge is important, and a method that disperses the coal more evenly through the barge and minimizes segregation of the particles of coal will reduce the amount of self-heating. Leveling and thoroughly compacting the coal in the barge reduces self-heating. Finally, coals with characteristics similar to those of weathered coals appear to undergo self-heating more readily than coals without these characteristics.

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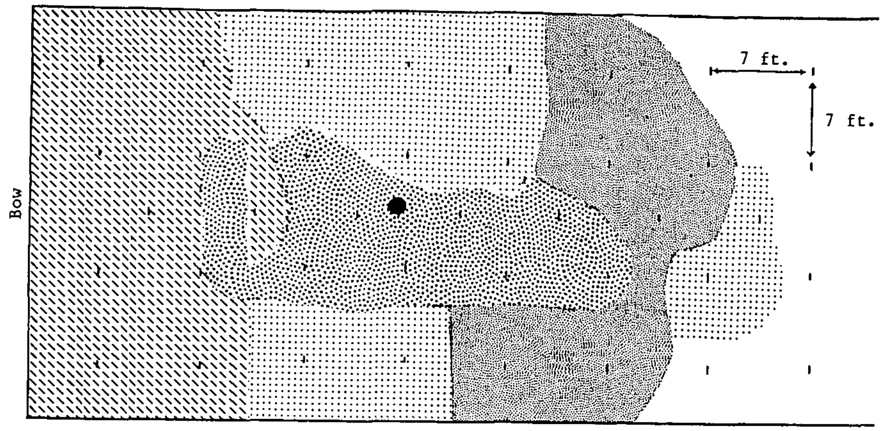
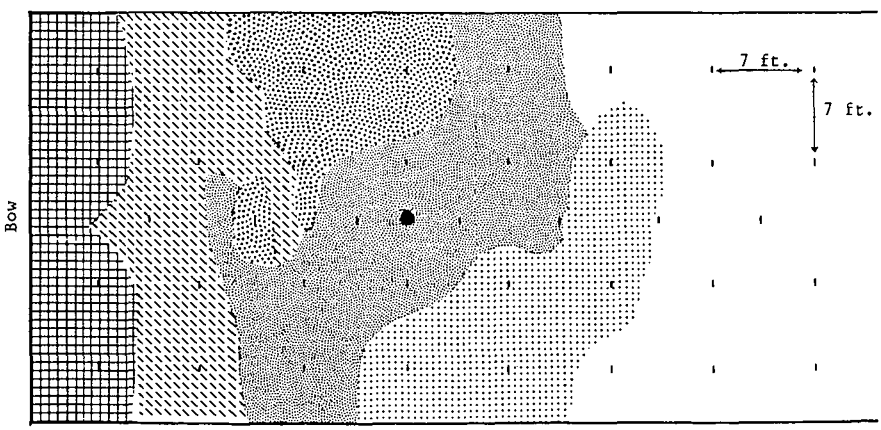


Relative Concentration of Tracer Gas

= 1-10 = 10-20 = 20-30 = 30-130

(- marks indicate sampling points; ● indicates gas injection point)

Figure 1. Gas flow pattern in barge No. 3.



Relative Concentration of Tracer Gas

= 0-5 = 5-15 = 15-30 = 30-50 = 50-380

(- marks indicate sampling points; ● indicates gas injection point)

Figure 2. Gas flow pattern in barge No. 6.