Hot water drying and briquetting of lignites
by Kevin Jess Poor

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering
Montana State University
© Copyright by Kevin Jess Poor (1986)

Abstract:
The objective of this research was to characterize the effects of hot-water drying on a Montana lignite and to see if this drying process changes the briquetting ability of the coal. A Savage lignite was hot-water-dried at temperatures between 200°C and 300°C in a cold-charge autoclave. Hot and cold off-gases of the drying processes were tested for their contents. The dried coals were tested for their moisture content, ash content, gross heating value and ultimate elemental contents. Briquets were made from the raw lignite and the dried coals using 5 different binders in varying concentrations. Water was. included in the briquetting mixture in some trials. All. briquets were tested for compressive strength.

The off-gases mainly consisted of CO2 and nitrogen. With increasing drying temperature the dried coals exhibited a higher carbon content, lower oxygen content and a higher heating value than did the raw lignite. The moisture content of the lignite decreased with increasing drying temperature. An increase in the moisture reduction occured at a drying temperature between 240°C and 260°C. This is a temperature where significant CO2 production has been shown previously to occur.

Compressive strength of briquets made without water decreased with increasing lignite drying temperature. Briquets made with water as part of the briquetting mixture showed a compressive strength minimum with respect to drying temperature for briquets made with a lignite dried at 2400C. Binder choice made little difference in briquet strength for briquets made using lignite dried at:300°C. Binder choice had a larger impact for briquets made with the raw lignite. Water in the briqueting mixture didn't increase briquet moisture content.

HOT-WATER DRYING AND BRIQUETTING OF LIGNITES

by

Kevin Jess Poor

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Chemical Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

December 1986

MAIN LIB.
N378
P791
Cop.2

APPROVAL

of a thesis submitted by

Kevin Jess Poor

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citation, bibliographic style and consistency, and is ready for submission to the College of Graduate Studies.

Dec 24, 1986
Date

John T. Sears
Chairperson, Graduate Committee

Approved for the Major Department

Dec. 24, 1986
Date

John T. Sears
Head, Major Department

Approved for the College of Graduate Studies

January 9, 1987
Date

Henry L Parsons
Graduate Dean

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his absence, by the Dean of Libraries when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my permission.

Signature Kevin J Poor

Date December 24, 1986

TABLE OF CONTENTS

	Page
APPROVAL	ii
STATEMENT OF PERMISSION TO USE	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	vi
LIST OF FIGURES	vii
ABSTRACT	ix
INTRODUCTION	1
REVIEW OF LITERATURE	3
Hot Water Drying	5
Coal Briquetting	8
Research Objective	11
EXPERIMENTAL	12
Drying Procedure	14
Briquetting	17
Analyses	19
RESULTS AND DISCUSSION	21
Effect of Drying Temperature on Moisture Content	22
Moisture Reabsorbtion	24
Size Reduction	26
Off-Gas Composition	27
Ultimate Elemental Analyses	29
Heating Value	40
Ash Content	40

TABLE OF CONTENTS--Continued

RESULTS AND DISCUSSION-Continued.....

Dried Lignite Briquet Strength..... 42
Briquets Made Without Water..... 42
Briquets Made With Water..... 47
Briquet Moisture Content..... 52

SUMMARY AND CONCLUSIONS..... 55

RECOMMENDATIONS..... 57

REFERENCES CITED..... 59

APPENDIX..... 63

LIST OF TABLES

Table Page

1. Proximate Analysis of Savage Lignite.....21

2. Moisture Content of Dried Lignites.....22

3. Ultimate Elemental Analyses Results.....30

4. Briquet Mixture Combinations.....43

5. Temperature History of Coal-Water Contacting Vessel to 255°C.....64

LIST OF FIGURES

Figure Page

1. Coal/Water Contacting Vessel and Gas Sampling Apparatus.....13

2. Moisture Reduction of Lignite as a Function of Drying Temperature.....23

3. Moisture Reabsorbtion of Dried Coals.....25

4. Carbon Content of MF and AD Dried Lignites as a Function of Drying Temperature.....31

5. Oxygen Content of Dried Coals After Desication as a Function of Drying Temperature.....33

6. Nitrogen Content of Dried Lignites After Desication as a Function of Drying Temperature....34

7. Nitrogen Content of Moisture Free Dried Lignites as a Function of Drying Temperature.....35

8. Hydrogen Content of Dried Lignites After Desication as a Function of Drying Temperature....36

9. Hydrogen Content of Moisture Free Dried Lignites as a Function of Drying Temperature.....37

10. Sulfur Content of Dried Lignites After Desication.....39

LIST OF FIGURES--Continued

11. Gross Calorific Value of Raw and Dried Lignites as a Function of Drying Temperature.....41

12. Compressive Strength of Briquets Made Without Water as a Function of Drying Temperature.....45

13. Compressive Strength of Concrete Binder Briquets Made With Water.....48

14. Compressive Strength of Corn Starch Briquets.....49

15. Lignite Briquet Moisture Content as a Function of Drying Temperature.....53

ABSTRACT

The objective of this research was to characterize the effects of hot-water drying on a Montana lignite and to see if this drying process changes the briquetting ability of the coal. A Savage lignite was hot-water-dried at temperatures between 200°C and 300°C in a cold-charge autoclave. Hot and cold off-gases of the drying processes were tested for their contents. The dried coals were tested for their moisture content, ash content, gross heating value and ultimate elemental contents. Briquets were made from the raw lignite and the dried coals using 5 different binders in varying concentrations. Water was included in the briquetting mixture in some trials. All briquets were tested for compressive strength.

The off-gases mainly consisted of CO_2 and nitrogen. With increasing drying temperature the dried coals exhibited a higher carbon content, lower oxygen content and a higher heating value than did the raw lignite. The moisture content of the lignite decreased with increasing drying temperature. An increase in the moisture reduction occured at a drying temperature between 240°C and 260°C. This is a temperature where significant CO_2 production has been shown previously to occur.

Compressive strength of briquets made without water decreased with increasing lignite drying temperature. Briquets made with water as part of the briquetting mixture showed a compressive strength minimum with respect to drying temperature for briquets made with a lignite dried at 240°C. Binder choice made little difference in briquet strength for briquets made using lignite dried at 300°C. Binder choice had a larger impact for briquets made with the raw lignite. Water in the briqueting mixture didn't increase briquet moisture content.

INTRODUCTION

Large quantities of easily mined, relatively low sulfur lignite and sub-bituminous coal lie mostly unused in Montana. In fact, as of 1976, Montana had 120.6 billion tons of demonstrated coal reserves (1), largest of any state in the U.S. Despite these huge reserves, only about 32.87 million tons were mined last year in Montana (2). It is estimated a similar amount will be mined in 1986. This would rank Montana tenth nationally out of a total estimated U.S. production of 901.9 million tons.

Several reasons appear to account for the apparent under-use of these vast energy reserves. In addition to the currently very soft market for coal of all kinds, the coal in Montana is generally high in moisture content, 20-40 percent, and correspondingly low in heating value. These attributes make it uneconomical to transport coal over the great distances to the major coal markets in the mid-west. However, new federal pollution standards (3) of 1 pound of SO_2 per 10^6 B.T.U., as opposed to the previous standards of 1 pound of sulfur per 10^6 B.T.U., make Montana's low sulfur lignite more attractive to major coal users.

The thrust of this investigation is to obtain technical

data on steam/hot-water drying of a Montana lignite in order to analyze if it could become a more marketable product. Most of the previous work in this area have been looking at hot water drying as a step in a proposed coal-slurry system. Because problems with water acquisition and right-of-way acquisition for pipeline siting have arisen for coal-slurry systems this investigation also explores the effect of hot water drying on the briquetting ability of the lignite. Briquetting the dried lignite will make it a more weather resistant and transportable product. Parameters being investigated include the effect of drying temperature on the coal moisture content, the reabsorption of water in the dried samples, the off-gas composition during drying,the elemental content of the product coal, and the briquet strength.

REVIEW OF LITERATURE

Major advantages of coal dewatering include decreased transportation costs, improved heating value, and a reduction of the likelihood of freezing during transport. In the case of fine coals, it is estimated that a 1% moisture reduction can reduce transportation costs by $310,000 to $1 million per year (4). It can be shown that a 1% increase in the moisture content of a fine coal can offset a 4.5% decrease in ash content.

At present, moisture reduction in coal is either done by mechanical means, such as filtration or centrifugation, or by thermal processes by heating the coal with hot gases or steam. An alternate dewatering technique is hot-water-drying of coal. It has been called the most under-used coal drying technology available today.

Steam drying is the treatment of low rank coal with saturated steam at pressure. It was first investigated by Fleissner in the 1920's (5). Treatment with steam removes water, causes shrinkage, and results in a stable lump of coal with improved weathering properties (6).

Klein (7) first speculated as to the mechanisms involved in steam drying. During treatment, carboxylic

groups in the coal decompose, forming carbon dioxide which pushes water out of the pores of the coal. Secondly, chemical reaction causes the coal surface to become more hydrophobic. Additionally, water has a lower viscosity at high temperatures, allowing it to run more freely from the coal.

The Fleissner (steam drying) process has been studied extensively with a variety of coals, and has been used commercially in Europe since 1927 (6).

Rao and Wolff steam dried a sub-bituminous C coal and found a 20 percent weight reduction of 2 inch chunks in 5 minutes with 550 psia steam (8). They reported a 30 percent increase in heating value and found their dried coals to be as stable as their raw coals. Although they had some moisture readsorption at 98 percent humidity, the weight gain was much less than the weight loss during drying.

Rozgonyi and Szigeti steam dried a high moisture content lignite at pressures up to 4.053 MPa, 588 psia (9). About 80 percent of the total lignite moisture was removed. Smaller sizes of coal released their water more easily and exhibited better heat transfer characteristics. A smaller coal particle will also have a shorter distance for the water to travel for it to get from the inside of the coal particle to the surface. Rozgonyi and Szigeti assumed that the moisture content of a coal cannot be reduced to zero

without a radical reorganization of the coal matrix. Each grain size of a lignite has a minimum water content at different pressures and temperatures. This critical water content cannot be reduced without a drastic change in the coal. A gross calorific value increase of 50 to 75 percent was achieved in their work.

Koppelman(10) has patented a lignite drying process where the coal is put into an autoclave and heated to between 750°C and 1250°C. During cooldown, the coal is then contacted with the off gases that were created during heating. This allows the deposition of any of the condensible gases onto the coal.

Hot-Water Drying

More recently, hot water, under pressure, has been used to dewater coal. Hot-water drying is advantageous in that all of the water expelled from the coal comes out in the liquid form. The latent heat of vaporization for the water in the coal does not have to be supplied. Additionally, because the coal is under water, the explosion problems associated with the thermal drying of fine coal are avoided. Hot-water drying reduces the sodium content of the coal,

leaving it dissolved in the water. This lower sodium content helps reduce ash fouling during combustion. Significant sulfur extraction has also been reported (10,11).

Baria, Maas, and Paulson (12) have shown that hot-water drying would work well in a slurry system as some of the slurry water could come from the water driven out of the coal during the drying process. Baria et al. studied hot-water drying of lignite with cold-charge and hot-charge autoclaves. They found that moisture reduction was completed in the first five minutes of drying and that the moisture removal is a function of the interior temperature of the particle. In the cold-charge tests, moisture reduction was a linear function of drying temperature. The hot-charge tests showed a higher drying rate above 240°C, coinciding with the temperature at which significant carbon dioxide forms to increase the water removal in the coal pores. A decrease in carboxylic acid groups was found with increasing temperature. They found a significant decrease in carboxyl groups in coals dried above 260°C. Baria, Maas, and Paulson found that the gross heating value of the coal increases with temperature. They also reported significant sodium removal during treatment.

Maas (11) hot-water dried a North Dakota lignite in a cold-charge system, and found that the major portion of the gases left in the autoclave after cool down was carbon

dioxide, but that there were also very significant concentrations of nitrogen. In this case, the gross heating value ranged from 6225 calories per gram when dried at 200°C, to about 6500 calories per gram when dried at 280°C. Maas found a decrease in the sodium content of the coal, but no significant decrease in the ash content of the coal.

T.A. Potas et al. (13) found that the amount of organic matter lost to gases and liquids vary, depending on the processing time and temperature. They also found reductions in the mineral content of the coal. Under certain conditions with given coals, all of the sodium could be removed. However, they also found a reduction in ash content occurred during treatment in a hot-charge autoclave. The particle sizes of their coal also became smaller with increasing processing temperature.

Lynch and Webster (14) used proton nuclear magnetic resonance, N.M.R., to show that there is a rapid reduction in the water binding ability of coals under heat treatment above 150°C.

Cole et. al.(15) patented a technique for upgrading low rank coals. In this system a coal/water slurry is heated to above 300°F. After cooldown, a hydrocarbon liquid is added to the slurry. The hydrocarbon forms an agglomerate with the coal, making it easier to separate from the water.

Coal Briquetting

Briquetting converts a solid fuel into one of higher quality. Briquetting consists of applying pressure to a mass of particles to compact them into a single agglomerate, sometimes with the aid of a binder (6). The important interactions in briquetting are the cohesive forces between solids, and the adhesive properties of the binders.

Briquetting has been used commercially for over 200 years. Most briquetting knowledge is empirical in nature, as opposed to exact physical or chemical theory. Generally, the higher the rank of coal, the harder it is to briquet without a binder. In many places, especially Europe, brown coal briquets are made without any binder. Most U.S. coals are of high enough rank that a binder is required.

A review of the basic fundamentals of coal briquetting by Berkowitz (16) contrasts the differences between briquetting with, and without, a binder. Without a binder the strength of the briquet is limited by the characteristics of the coal; with a binder, the briquet strength is determined by the coal characteristics, the binder dispersal, and by the interaction between the coal and the binder.

Berkowitz goes on to define the variables involved in briquetting. In binderless briquetting, maximum briquet strength will occur when both the modulus of elasticity and the rigidity modulus are low. First order variables in binderless briquetting include time, pressure, temperature, degree of comminution, and the presence of a film-forming material in the solid.

Time is involved because any process where deformation of a solid is involved is a rate process. Pressure increases produce larger deformations of the solid, and temperature increases reduce the modulus of elasticity of the solid.

The degree of comminution is a variable involved with the size of the coal particles. It involves the particle size range, the maximum particle size, and the particle size distribution. Briquet strength is proportional to the packing density of the particles. The maximum briquet strength is where the particle size distribution allows the maximum packing density. Generally, the larger the top particle size, the weaker the briquet. However, if the particles are too small they can act as air traps and reduce briquet strength.

The presence of a film-forming material, such as water, influence briquet strength by 1. acting as a lubricant, allowing the particles to rearrange into a more dense briquet, 2. reducing the surface tension of the solid

allowing for increased deformability, and 3. extending the range of the solid-solid cohesional forces.

When briquetting with binders, interactions between the binder and the coal particles can become much more important than the characteristics of the coal. Many substances can be used as binders: asphalts, pitches, starches, cement binders, and sulphate liquor are common. For coal briquetting, binders should be cheap and should not increase ash content or decrease heating value. Binders should have an affinity for the coal surface. Different binders have different affinities for different coals. The best binder for one coal-briquetting application may not be the best binder for for a different coal.

In binderless briquets moisture was shown to be a factor in high briquet strength, but in briquetting with a binder it can reduce briquet strength. A binder may adhere to the water, instead of to the coal surface. The contact angle a binder forms with the coal surface can affect the strength of the briquet. Binders with contact angles less than 90° will wet the coal surface and give higher adhesion energies than binders with contact angles greater than 90°. Surface roughness will change the contact angle between the liquid and the solid (17). If the contact angle is less than 90°, roughness lowers the angle, while if it is greater than 90°, roughness increases the contact angle.

Lin (18) studied thermally dried coals and briquetting ability. He used varying concentrations of corn starch, Kraft sulfate liquor, and #6 fuel oil as binders. A briquet made with 5 percent corn starch and 95 percent dried coal was found to be best.

Research Objective

The structure of this study will be first to characterize a hot-water-dried Montana lignite, and second to investigate the dried lignite's briquetting ability using various binders. The coal will be hot-water dried over a range of temperatures. Samples of the hot off-gases will be tested for their contents. Elemental content of the dried coals will be determined, along with moisture content and heating value. Briquets will then be made and tested for strength, using five different binders in varying concentrations.

EXPERIMENTAL

The coal-water contacting vessel consists of a high pressure bomb with four ports in the top: one port for a pressure gauge, another for a thermowell, a third port for a helium flush, and the fourth port for a gas exit line. The vessel is surrounded by a steel sleeve, a heating mantle, and insulation to facilitate good heating (Fig 1).

As illustrated in Figure 1, the gas exit line has one valve adjacent to the outlet of the bomb to allow a gas sample to be obtained during an experiment. A second needle valve, further up the line, traps a sample and acts as a water trap. Downstream from the second valve are a desicant water trap and a third valve leading to a vacuum pump and allowing for evacuation of the entire system. The gas exit line continues on to a gas sampling valve leading to a gas chromatograph and ends in a valve allowing for a completely closed system. All valves are needle valves. Up to the dessicant water trap the exit line is constructed of 1/4 inch stainless steel tubing, i.d. 0.167 inch. The balance of the line is constructed with 1/8 inch tubing, i.d. 0.042 inch.

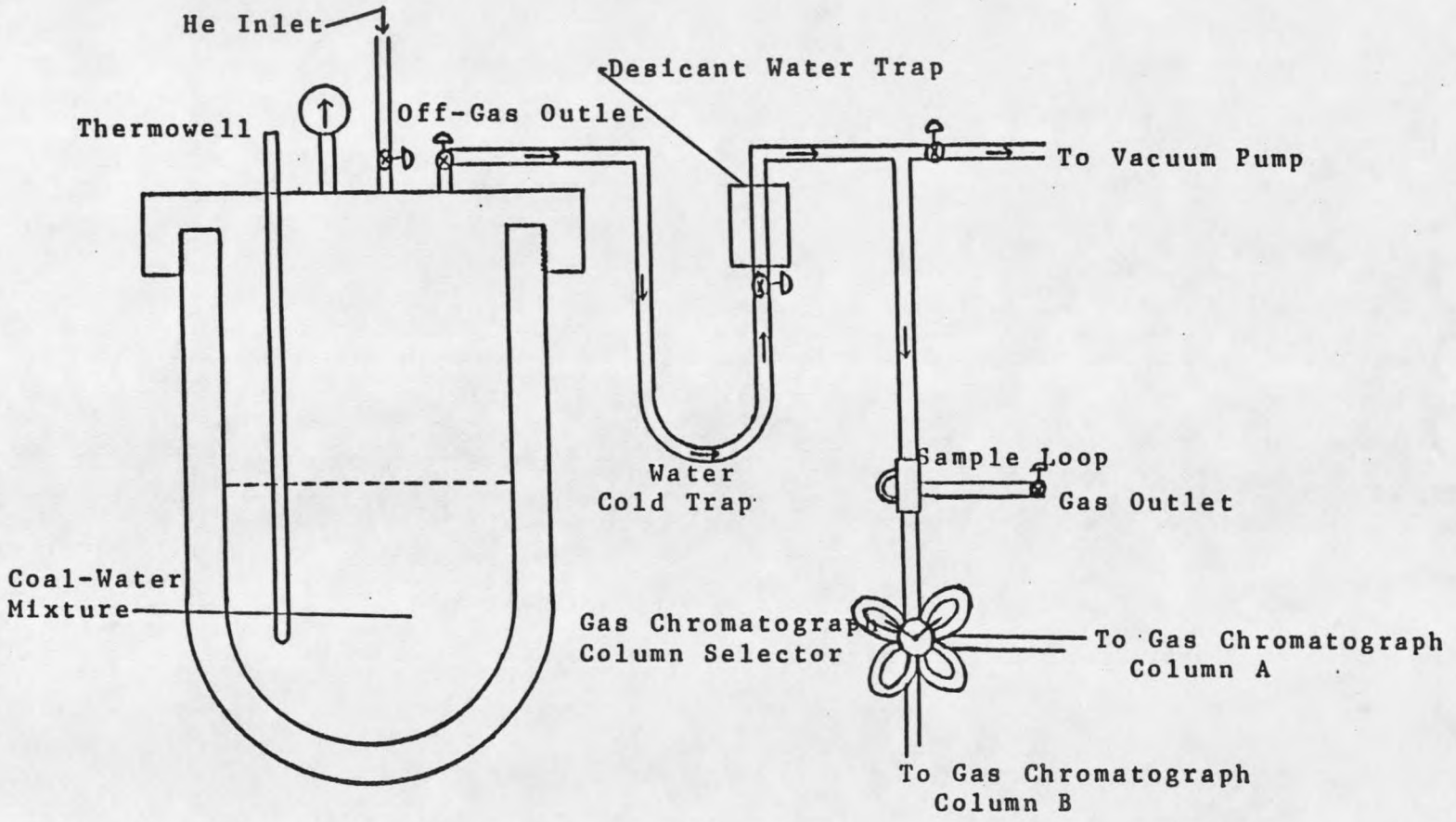


Figure 1. Coal/Water Contacting Vessel and Gas Sampling Apparatus.

The gas sampling valve, at the end of the gas exit line, is connected to an eight port valve which allows injection of the sample into either of the two columns in the gas chromatograph. One column is packed with Moleseive 5A, and detects oxygen, nitrogen, methane, carbon monoxide, and ethane. The second column is packed with Porpack Q, and detects ethane, oxygen, nitrogen, carbon monoxide, ethane and carbon dioxide.

Briquets were made on a Rimac spring tester, (Rinck-McIlwaine Inc.), with a stainless steel die. In the making of briquets every effort was made to insure consistency of conditions between experiments. In all cases a hand press was used to make cylindrical pellets of diameter 0.5 cm. A pressure of 245 p.s.i. was sustained on the briquetting mixture for a period of 20 seconds. All briquets were stored in airtight containers.

Drying Procedure

Before making a run the entire gas exit line is evacuated overnight to remove water, air, or any other contaminents.

The experiments in this investigation were done using a

Savage lignite supplied by Montana-Dakota Utilities. This coal was ground with a mortar and pestal to between 0.0328 inches and 0.0098 inches, 20-60 mesh, and dried within 24 hours of grinding. The ground coal was kept in a sealed container until just prior to use.

For the coal-water slurry a known weight of coal is put in the bomb with an amount of demineralized water such that the liquid-solid ratio is 2:1 by weight. The bomb is sealed and put in the heating mantle where it is connected to the gas exit line, helium flush, and thermowell.

Helium, at thirty p.s.i.g., is let into the vessel to check the vessel for leaks. Helium is then let into the gas exit line and all connections are pressure tested for leaks. The end valve in the gas exit line is then opened and the entire system is purged for fifteen minutes. This rids the system of much of the air that was in the bomb when it was sealed. The gas purge is turned off and the pressure in the bomb is reduced so that an excessive overpressure is not present during the coal-water contacting. To ensure that the majority of the air is out of the system a sample of gas from the exit line is put into the gas chromatograph. Any air in the system will come out as a peak on the recorder chart. If all of the air is not out of the system, the helium flush is continued.

The bomb is then isolated from the exit line. The

heating mantle is turned on, and the bomb is allowed to heat to the desired temperature. During the coal-water slurry heating the exit line is again evacuated with a vacuum pump.

The bomb is allowed to heat to four degrees below the desired temperature, which takes approximately two hours. A heating profile of the bomb is provided in Table 5, located in the Appendix. The heating mantle is then turned down to twenty percent of full power. The bomb continues to heat to the desired temperature and stays there for at least fifteen minutes before starting to cool. If the heat is completely turned off, the bomb starts to cool off too rapidly. The bomb is considered to be at the desired temperature when it is plus or minus 2°C of the nominal temperature.

After the coal-water slurry has been at the desired temperature for fifteen minutes a sample of the steam and off gases are let into the cold trap. Here they are cooled to approximately -30°C with an antifreeze-water mixture frozen with liquid nitrogen. After the off-gas sample has been frozen for at least five minutes to get rid of the majority of the water, it is let into the rest of the gas exit line. Any water not frozen out in the cold trap is absorbed on the desicant. The desicant was periodically changed to insure a water-free gas sample. Samples were then drawn and injected into the gas chromatograph for exit gas analysis. On some runs an additional gas sample was

taken after the bomb was allowed to cool to room temperature and compared with those taken hot.

After the bomb had cooled it was disassembled, and the coal-water mixture was filtered for one hour in a 11.5 cm Buchner funnel. The filtered, hot-water-dried coal was then stored in air-tight containers while awaiting further testing.

Briquetting

Although finding the optimum binder was not a goal of this research, several different binders were tried in an attempt to produce a viable product. Fuel oil, corn starch, wheat paste, vinyl wallpaper paste, and a water- soluble concrete binder(Elmers Concrete Bonder) were tried in varying concentrations. Briquetting schemes with, and without, the addition of water were tried. Water was added in some cases to see if any of the binders could be used where the binder is added directly to the coal slurry and immediately briquetted without further filtering or treatment.

A good quality corn starch paste was prepared to combine with the dried coal in the corn starch pellets. The corn starch paste was made by first heating a mixture of 5 parts water, one part dry corn starch at 60°C with constant

stirring. After the mixture thickened to the point where the magnetic stirrer would no longer turn, the lid was removed. The mixture was then stirred by hand until a good quality paste was obtained, less than one minute. Initially the lid was in place to reduce the amount of water evaporating during heating, thus keeping the paste close to the original 5-1 ratio.

The starch paste is an amalgam of dry starch and water. The briquets are based on the weight of dry starch in the paste, not on the weight of the paste. To make the briquets using corn starch as the binder, an amount of starch paste was weighed out and an appropriate weight of coal was added to make the desired briquetting mixture. The starch paste was then folded into the coal until the paste was evenly distributed. The mixture was quickly briquetted and stored in airtight containers.

A similar procedure was followed in making the briquets with the other binders. A quantity of binder was weighed and combined with the desired amount of coal, water, quickly briquetted and stored until testing. In all cases the briquetting was done at the ambient air temperature. This was done because heating the briquetting mixture would change the moisture content of the briquets.

Analyses

Proximate analyses were done in accordance with standard ASTM methods D3172-73(19). A sample of coal weighing approximately 1 gram was put into a crucible and placed in an oven at 104 to 110°C for one hour. The weight change corresponds to the moisture content of the coal. This moisture-free coal was then covered and put in a 930-970°C oven for 7 minutes. The weight loss from this heating is the volatile matter. The sample was then placed, uncovered, in a 700-750°C oven until a constant weight is reached. The weight of the sample left is the ash content of the coal. The percent fixed carbon equals 100% minus the percentages of moisture, volatile matter, and ash.

Elemental analyses were done using a Carlo Erba Strumenzione ultimate analysis instrument (20). Samples of coal of between 0.5 and 1.5 mg were placed in tin containers cleaned with water, acetone, and carbon tetrachloride. This cleaning eliminated most of the dust and dirt on the containers, providing for more consistent, reliable results. These filled containers were incinerated at 1025°C for carbon, nitrogen, and hydrogen determination and at 930°C for sulfur determination. Elemental fractions are determined by comparing the exhaust-gases gas chromatograph signal of

these samples with known samples. Because of the inconsistencies inherent with coal work, multiple samples of all coals were incinerated to obtain a good average value of the elemental contents.

Heating value data were obtained using a Parr adiabatic bomb calorimeter in accordance with ASTM method D2015-66(21). Corrections were made for heat of formation of nitric acid, amount of fuse wire used, and for the amount of sulfur in each sample.

Compression tests on the briquets were performed on an Instron Universal Testing Instruments tension compression tester model TT-D, using a CCT compression cell(22). This cell has a resolution down to 0.01 pounds. Briquets were tested vertically, down the length of the cylinder. Results were given on a strip chart recorder, and given as a percentile of the total range of the instrument. The compression on the pellet at the moment of pellet failure was recorded. This corressponded to the maximum pressure placed on the pellet. The pressure at briquet failure is recorded in pounds force. To obtain the value in pounds per square inch the total pressure must be divided by 0.030 $in.^2$, the area of the end of a briquet.

RESULTS AND DISCUSSION

Table 1 shows the proximate analysis of a representative sample of the Savage lignite used in this study. It is reported in the as-received and moisture-free bases. The proximate analyses were performed on the same size coal as was used in the drying process, 20-60 mesh. As typical of lignites, this coal has a relatively high moisture content and correspondingly low fixed carbon content. High rank coals, like anthracite, can have fixed carbon contents of 95% or more.(23)

Table 1. Proximate Analysis of Savage Lignite.

Component	As Received %	MF %
Moisture	36.95	----
Volatile Matter	25.74	40.82
Fixed Carbon	30.78	48.82
Ash	6.53	10.36
	100.00	100.00

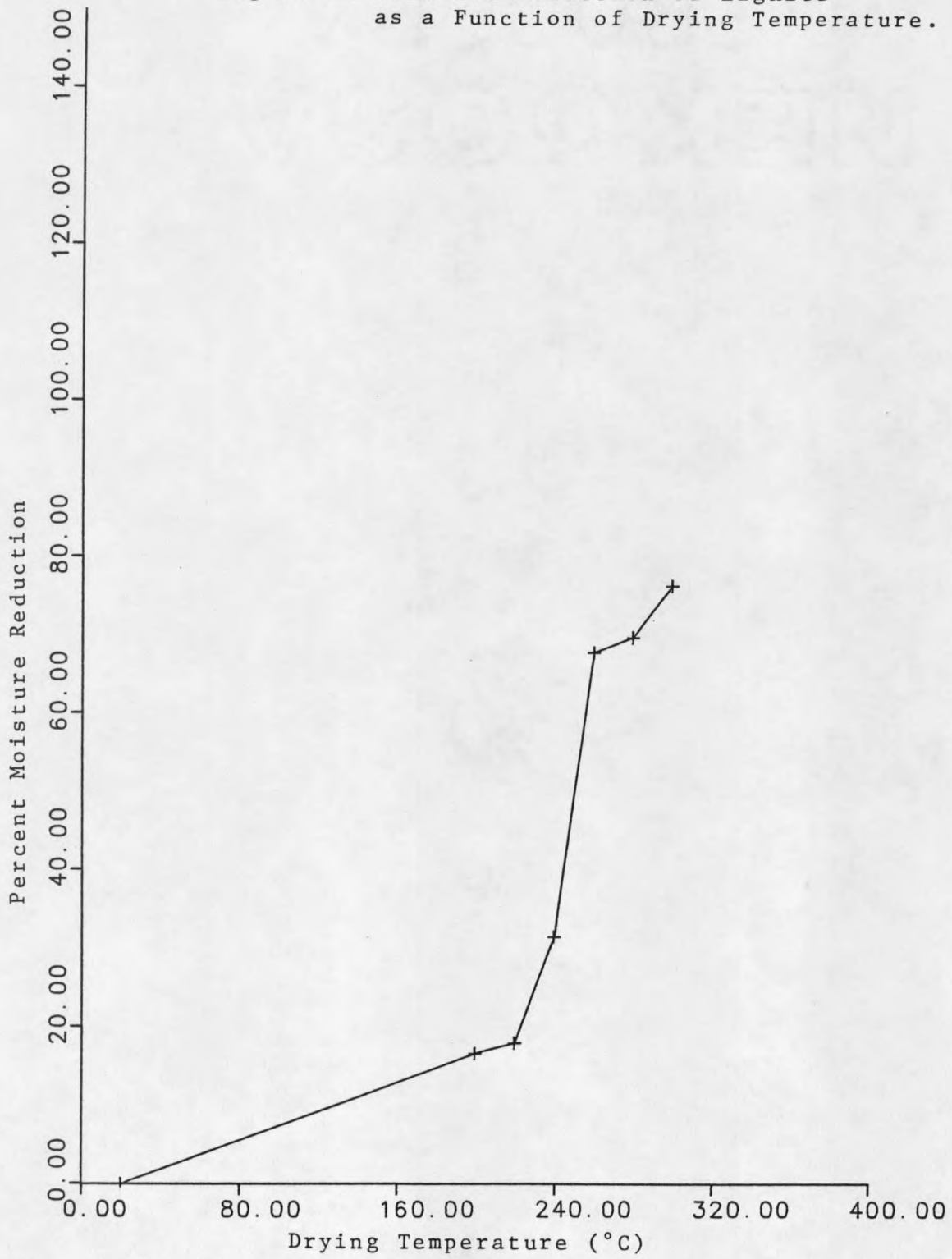
Effect of Drying Temperature on Moisture Content

Table 2 shows the moisture content of lignite samples after they have been hot-water dried at temperatures ranging between 200°C and 300°C. Figure 2 shows the moisture reduction in the coals as a function of drying temperature. In all figures where drying temperature is the ordinate of the graph the appropriate value obtained for the raw coal is listed at 20°C. The moisture content stayed relatively level through the 240°C run. Only small amounts of moisture reduction were obtained. At these lower temperatures the small amount of drying that takes place is just from a reduction in the physically adsorbed surface moisture associated with the coal.

Table 2. Moisture Content Change In Lignite With Drying Temperature

Drying Temp., °C	Moisture Content, %
200	30.82
220	30.32
240	25.33
260	11.91
280	11.22
300	8.79

Figure 2. Moisture Reduction of Lignite as a Function of Drying Temperature.



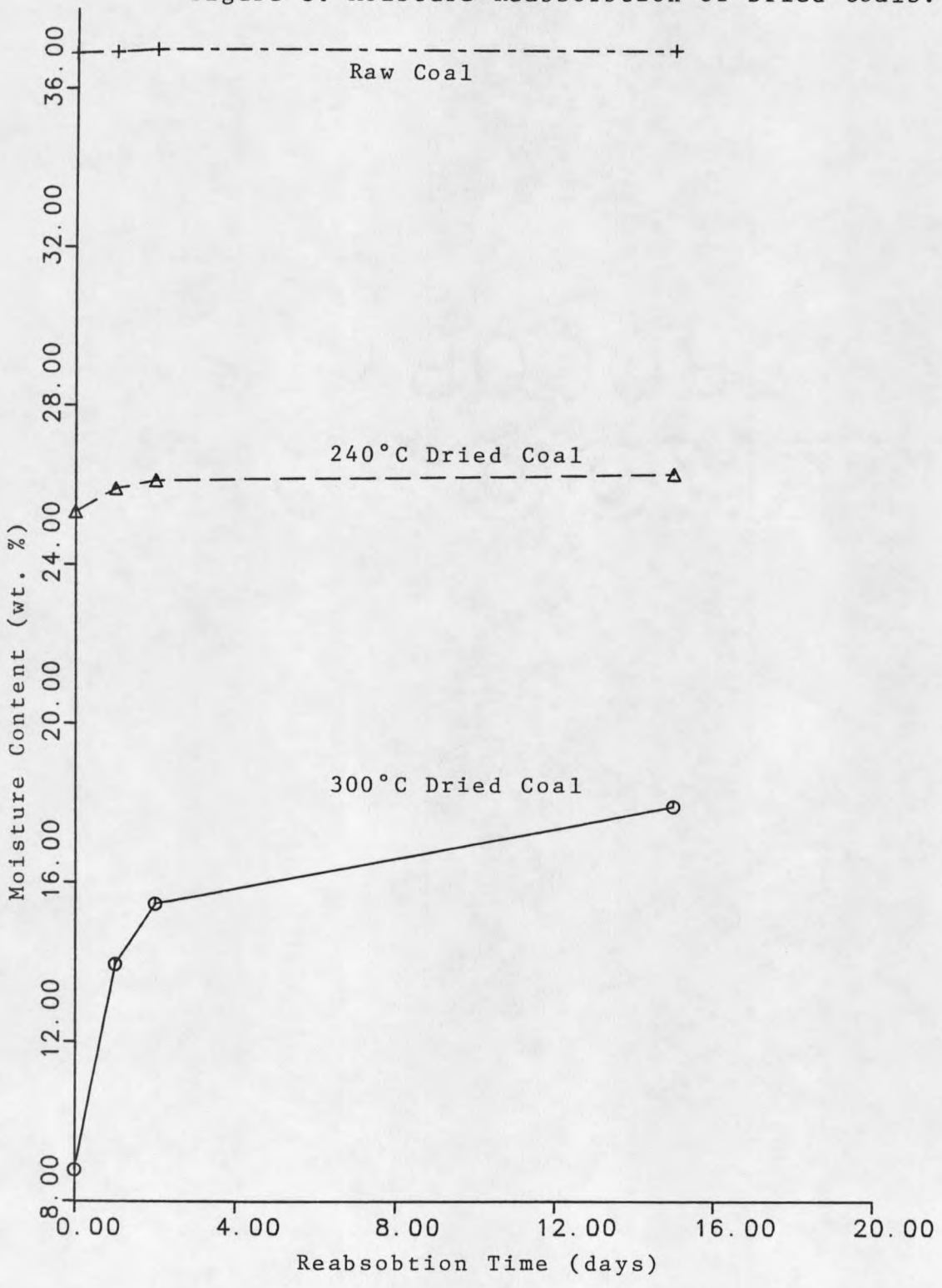
Above 240°C a rapid increase in moisture reduction takes place. The large increase in moisture reduction between 240°C and 260°C occurs at the temperature where an increase in the carbon dioxide formation has been shown to take place (12). This CO_2 formation removes many of the polar carboxylic groups from the coal allowing the chemically adsorbed moisture to escape. This accounts for the reduction in carboxylic groups found at 260°C in other lignites.(11,12)

Above 260°C, while still increasing, the rate of moisture loss slows. Thus, the majority of the moisture loss occurred in a small temperature range. Pressures during runs were nominally the saturated steam pressures corresponding to the temperature of the run.

Moisture Reabsorption

Samples of the raw coal and of the lignite hot water dried at 240°C and 300°C were kept in a 100% humidity chamber at room temperature for 15 days. The moisture content of these samples was checked after 1, 2, and 15 days in the chamber to check for moisture reabsorption. Some moisture reabsorption did occur as illustrated in Figure 3. The coal dried at 300°C exhibited the most moisture reabsorption. It reabsorbed 32.52% of the moisture lost

Figure 3. Moisture Reabsorbtion of Dried Coals.



during hot-water drying. The resulting lignite is still a vast improvement over the raw coal. The majority of the reabsorption took place in the first two days in the chamber. The raw coal showed no absorption of water during its time in the humidity chamber. It should be pointed out that actual conditions would be nowhere near those found in the humidity chamber. Moisture reabsorption in actual practice would be much less and much slower than was produced in the 100% humidity chamber.

Size Reduction

During the drying process a small amount of lignite particle size reduction was expected to take place. To test for size reduction the raw coal and coals dried at 240°C and 300°C were sized using standard mesh screens. The amount of coal in each screen was weighed and recorded. The raw coal put in the hot-water drying apparatus was all between 20 and 60 mesh. The dry coals were sized using standard mesh screens sizes 20, 32, 40, 60, 80, 100, and 140.

Both the mean particle size and the particle size distribution decreased during hot water drying of the Savage lignite. The raw coal had a mean particle diameter of 0.0259 inches, while the coal dried at 240°C had a mean particle diameter of 0.0236 inches. The lignite hot-water-dried at

300°C was even smaller, with a mean particle diameter of 0.0190 inches. This size reduction is expected as portions of the coals molecular structure react during drying to form CO_2, methane, and other off-gases, causing the coal to contract slightly. Pieces of coal will break off during repeated handling. However, the two hot-water-dried coal samples had equal handling. This indicates that the reduction in the mean particle diameter between the 240°C and 300°C runs is caused by the drying process.

Off-Gas Composition

Results of the off-gas determinations were largely inconclusive, however some interesting sidelightes did appear. Because of limitations in the gas chromatograph and sampling system used in these experiments, small concentrations of many gases, which have been shown elsewhere to exist in similar systems, could not be detected.(11)

The gases that were readily detected were nitrogen/oxygen and carbon dioxide. In several runs one sample of gas was taken while the system was hot, and another sample was taken after the system had been allowed to cool overnight. On gas samples taken while the system was hot the majority of the gas was nitrogen with a small

fraction of carbon dioxide and carbon monoxide. However, on samples taken after cooldown the gas fractions had changed substantially. The amount of carbon dioxide was now equal or greater than the amount of nitrogen/oxygen present.

Because the system was thoroughly flushed and checked before each run, it is believed that some air had adsorbed onto the surface of the coal. This air then desorbed during heating. Nitrogen has been found elsewhere to be a large component of cooled off-gases in similar systems (11), but was assumed to be a function of the error in the system. Moore(24) found that, upon heating, all coals produced carbon dioxide and that a large proportion of them produced nitrogen. He also found that when peat was heated the gas given off consisted chiefly of nitrogen with smaller amounts of methane and carbon dioxide.

While the nitrogen desorbs rapidly during heating, the CO_2 formation may take more time. This would account for the reversal in gas fractions in the off-gas samples. The time needed for significant CO_2 formation depends on the coal and the treatment temperature.(12) For example, run 32, at 240°C, had a hot gas sample that was 89% N_2 and O_2, and 11% CO_2. After cooldown the gas sample was 63% CO_2 and 37% N_2 and O_2.

Carbon dioxide is roughly twenty times as soluble in water at the pressure and temperature present when the

system is hot as it is when the system is at ambient temperature and pressure.(25) Houghton (26) showed that temperature affects CO_2 solubility in water much more strongly than for less soluble gases like nitrogen and hydrogen. This could help explain why the CO_2 concentration in the off-gases increases as the system cools. Carbon dioxide that was dissolved in the water at high temperatures is released into the off-gases at lower temperatures.

Ultimate Elemental Analyses

Table 3 is a listing of the ultimate elemental analyses of the raw and hot-water-dried lignites. The standard deviation of the sample, S, (27) is also listed for each entry. Elemental analyses are presented for the moisture-free coals and the coals after they have been left in a vacuum desicator overnight. The lignites were left in the desicator to see what differences, if any, resulted from removal of all of the moisture in the coal, as opposed to removing just the surface moisture. Results are listed as weight percents.

The carbon content of the hot water dried lignite is plotted as a function of drying temperature in Figure 4. For the moisture free samples the carbon content increased from 59.74%,when dried at 200°C, to 66.34% at 300°C. This 11%

Table 3. Ultimate Elemental Analysis Results

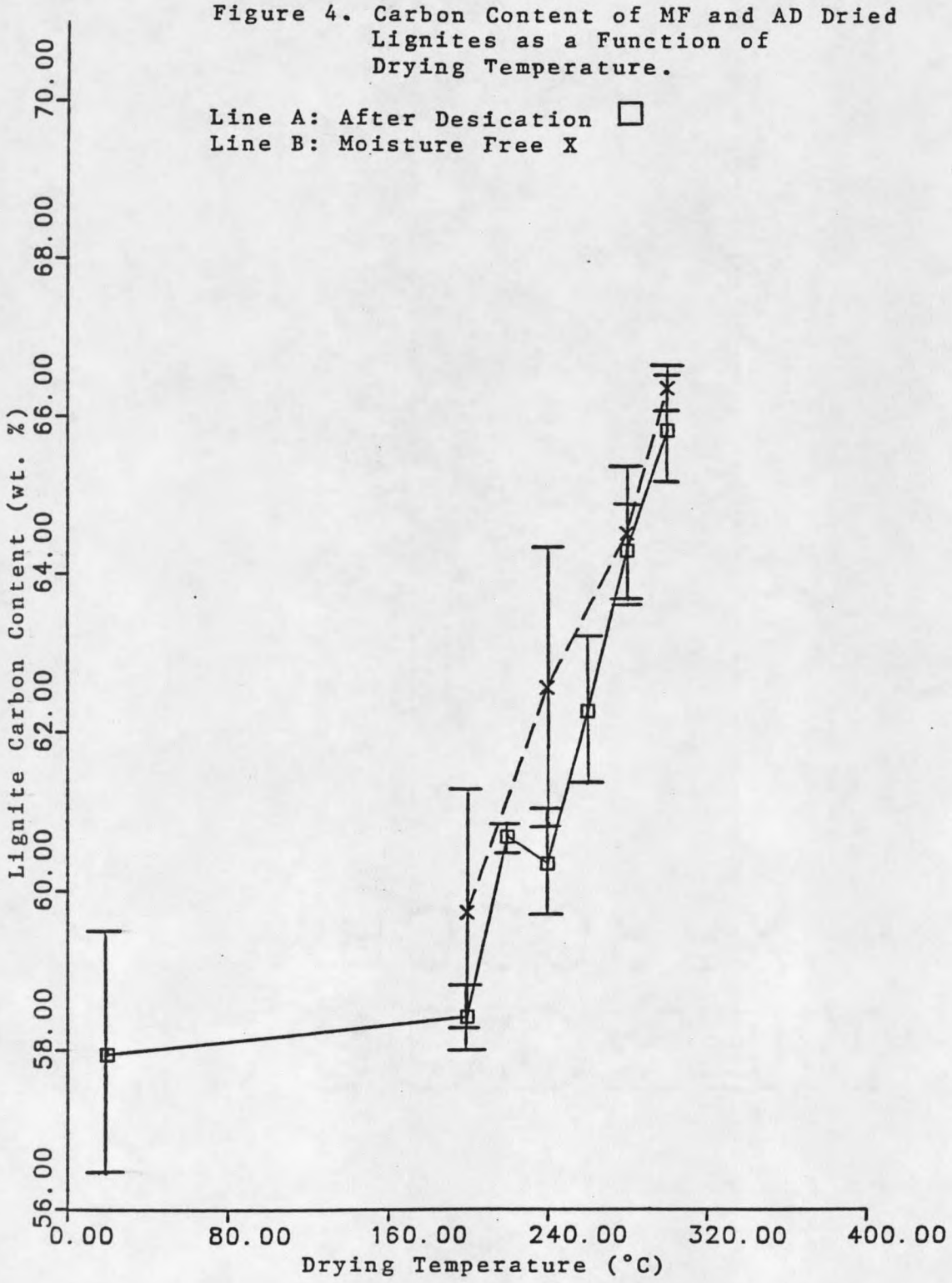
Drying Temp(C)	% Carbon-AD	S	% Hydrogen-AD	S
---	57.95	1.740	3.944	0.111
200	58.43	0.399	4.011	0.116
220	60.69	0.087	4.074	0.100
240	60.35	0.664	4.108	0.166
260	62.26	0.885	4.129	0.170
280	64.28	0.608	4.056	0.134
300	65.81	0.746	4.178	0.129
	% Carbon-MF	S	% Hydrogen-MF	S
200	59.74	1.715	3.495	0.123
240	62.56	1.830	4.069	0.236
260	64.50	0.794	3.824	0.115
300	66.34	0.261	4.032	0.093
	% Nitrogen-AD	S	% Nitrogen-MF	S
---	1.171	0.129	-----	-----
200	1.161	0.079	0.881	0.045
220	1.051	0.107	-----	-----
240	0.978	0.046	0.928	0.015
260	0.920	0.106	-----	-----
280	0.889	0.087	0.906	0.046
300	-----	-----	1.005	0.113
	% Sulfur- AD	S	% Oxygen- AD	
---	0.834	0.158	36.10	
200	1.616	1.033	34.78	
220	0.877	0.153	33.30	
240	0.937	0.177	33.63	
260	0.587	0.193	32.12	
280	0.728	0.529	30.04	
300	1.186	0.393	28.00	

MF= Moisture Free AD= After Desication

S= Standard Deviation of the Sample

Figure 4. Carbon Content of MF and AD Dried Lignites as a Function of Drying Temperature.

Line A: After Desication □
Line B: Moisture Free X



increase is expected. As the off-gas production proceeds throughout the drying process the carbon content will increase.

The change in oxygen content with drying temperature is plotted in Figure 5. As expected, the oxygen content decreases as the coal drying becomes more complete. The oxygen content decreases more rapidly above 240°C. Again, this corresponds to where CO_2 formation increases to more completely dry the coal.

The effect of drying temperature on nitrogen content of the dried lignite is presented in Figures 6 and 7. While the general trend for the desicated coal is for the nitrogen content to decrease with temperature, the trend for the moisture free lignite is for the nitrogen content to increase with drying temperature. Perhaps some of the nitrogen in the coal reacts during the hot-water drying to form small amounts of ammonia and NO_x (11,12). This would tend to increase as the drying temperature increases. The ultimate analysis method used in these tests is less accurate as the object element content gets close to zero. The possibility also exists that the nitrogen content trends are just an anomaly indicative of the error in the system. The large standard deviations in the nitrogen determinations indicate this to be the case.

Figures 8 and 9 show the hydrogen content of the dried

Figure 5. Oxygen Content of Dried Coals After Desication as a Function of Drying Temperature.

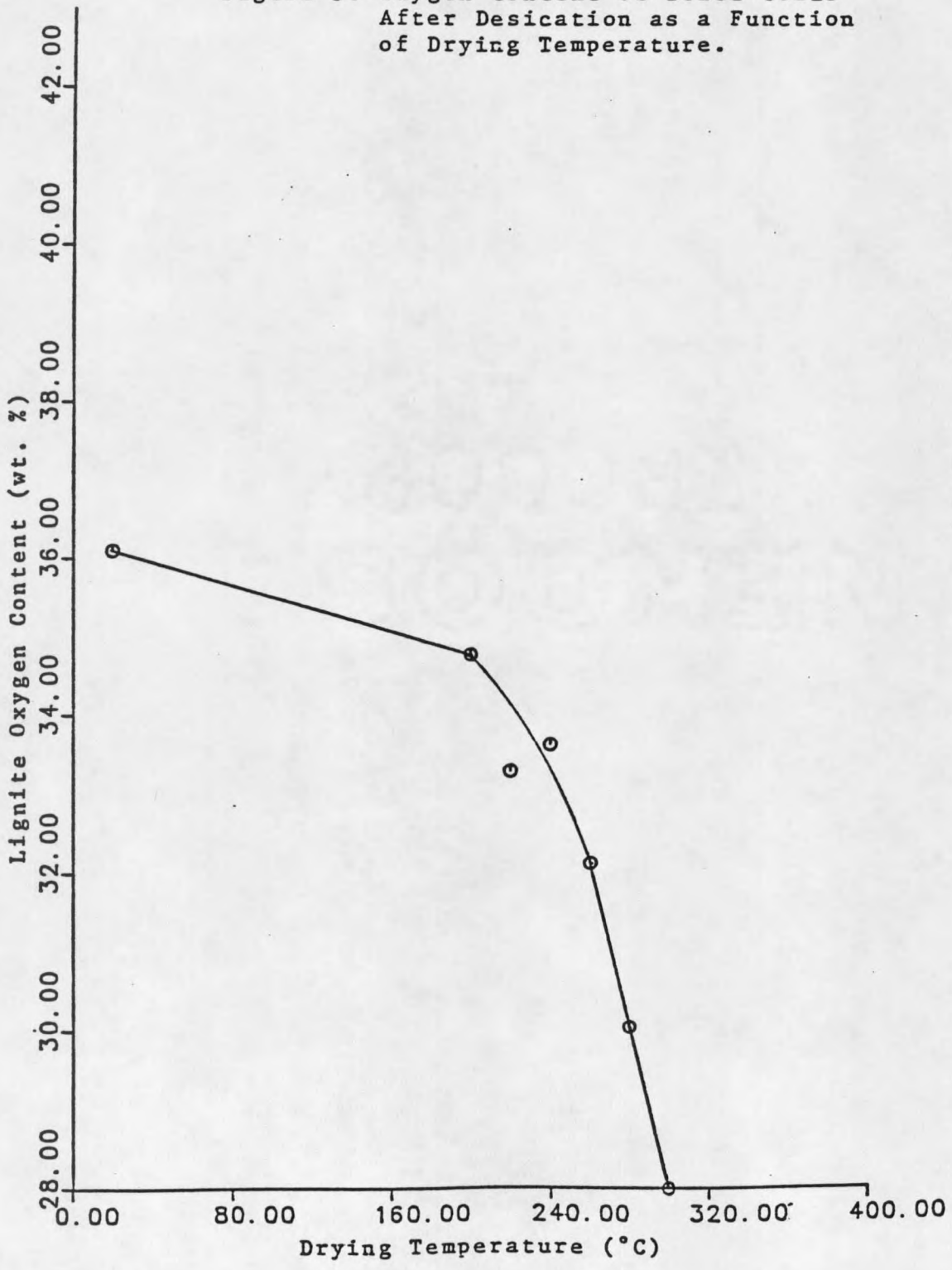


Figure 6. Nitrogen Content of Dried Lignites After Desication as a Function of Drying Temperature.

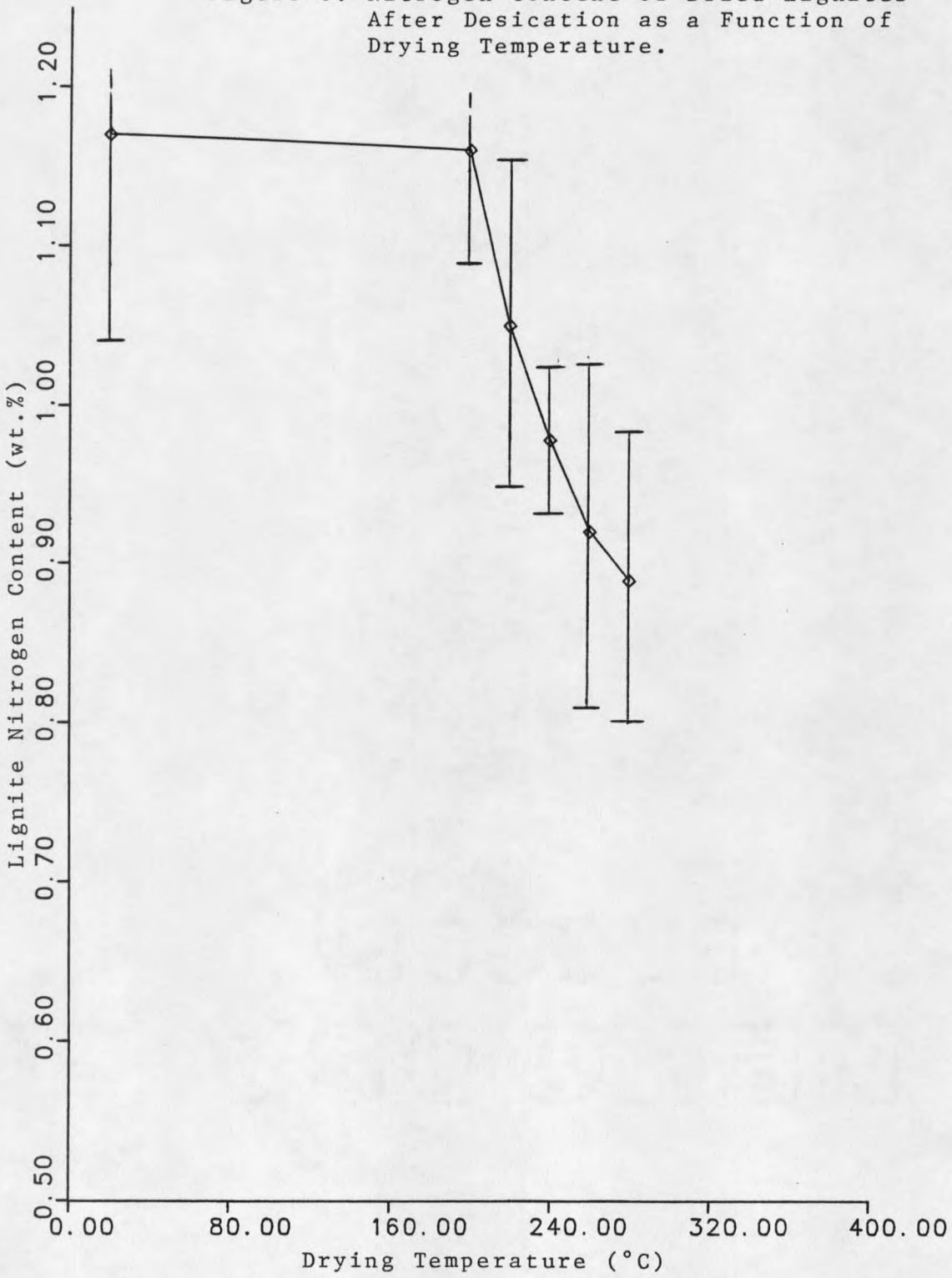


Figure 7. Nitrogen Content of Moisture Free Dried Lignites as a Function of Drying Temperature.

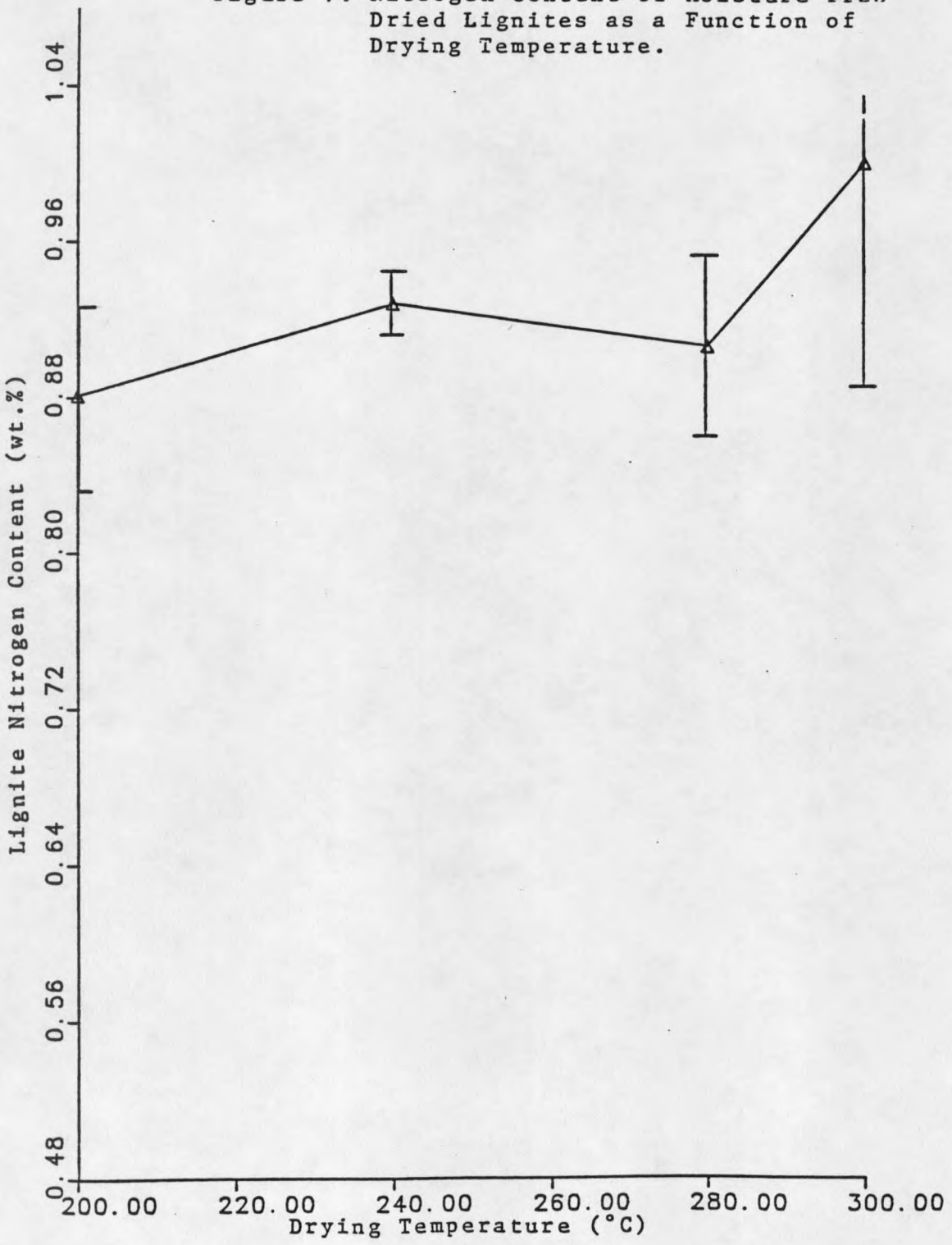


Figure 8. Hydrogen Content of Dried Lignites After Desication as a Function of Drying Temperature.

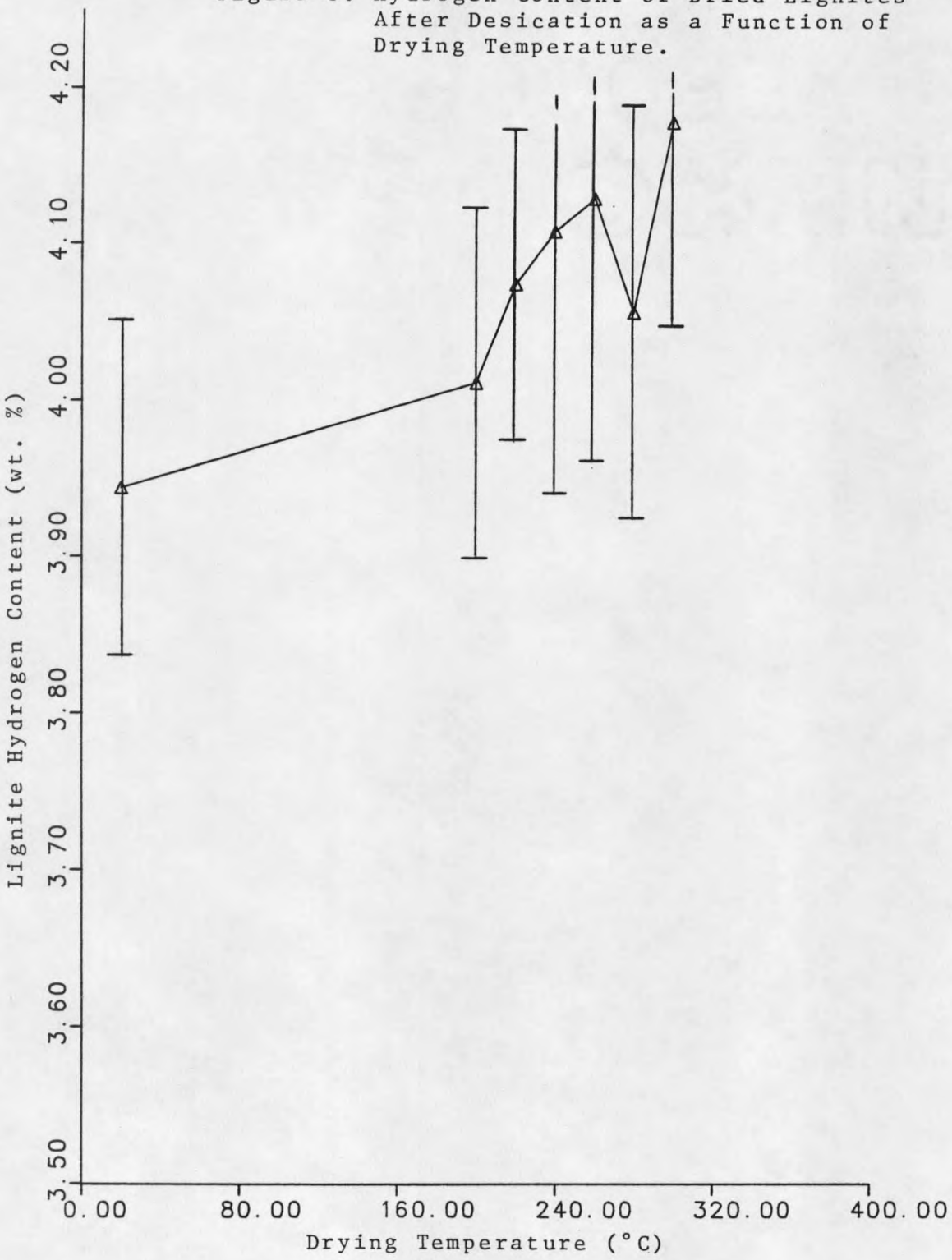
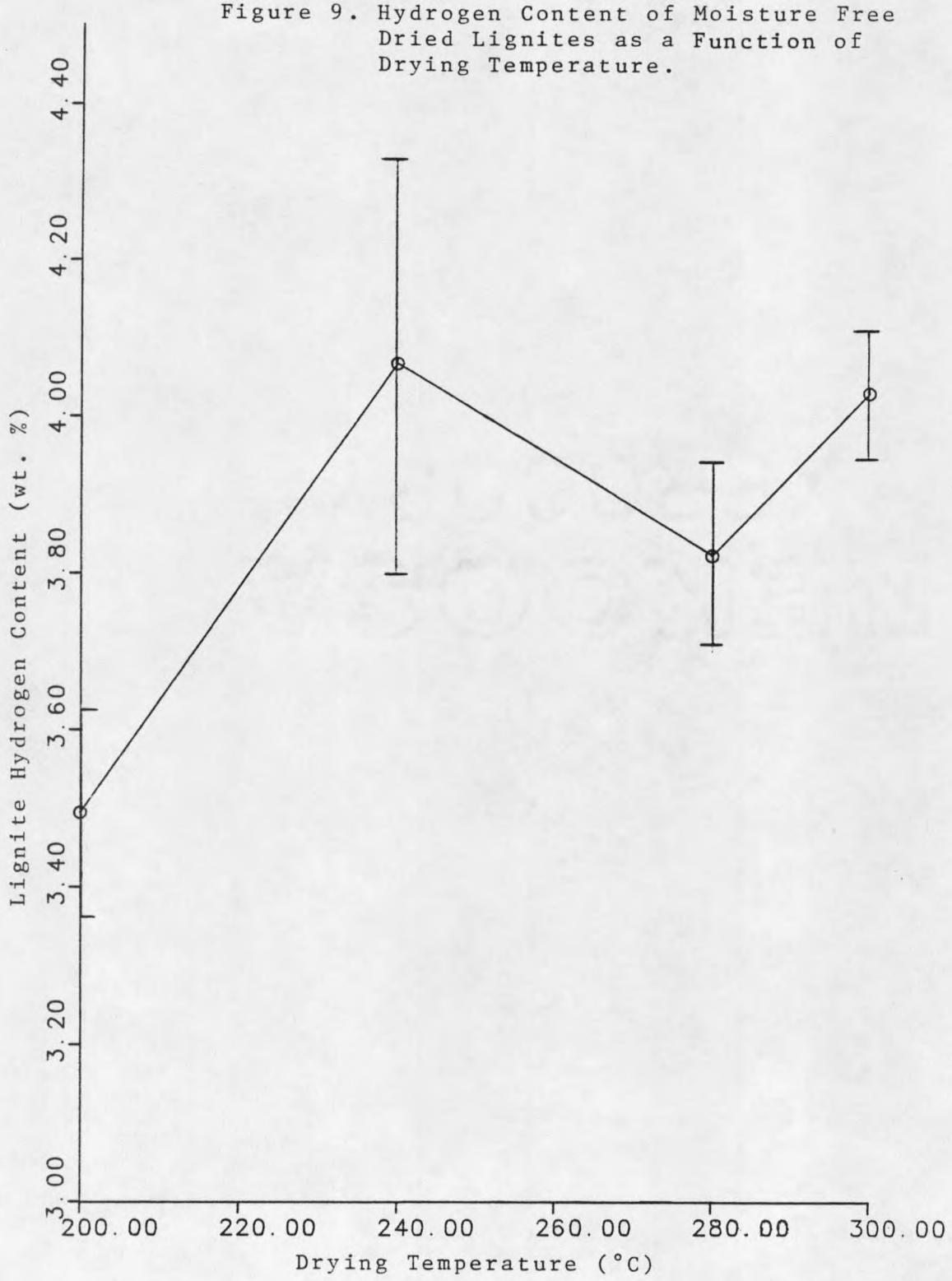


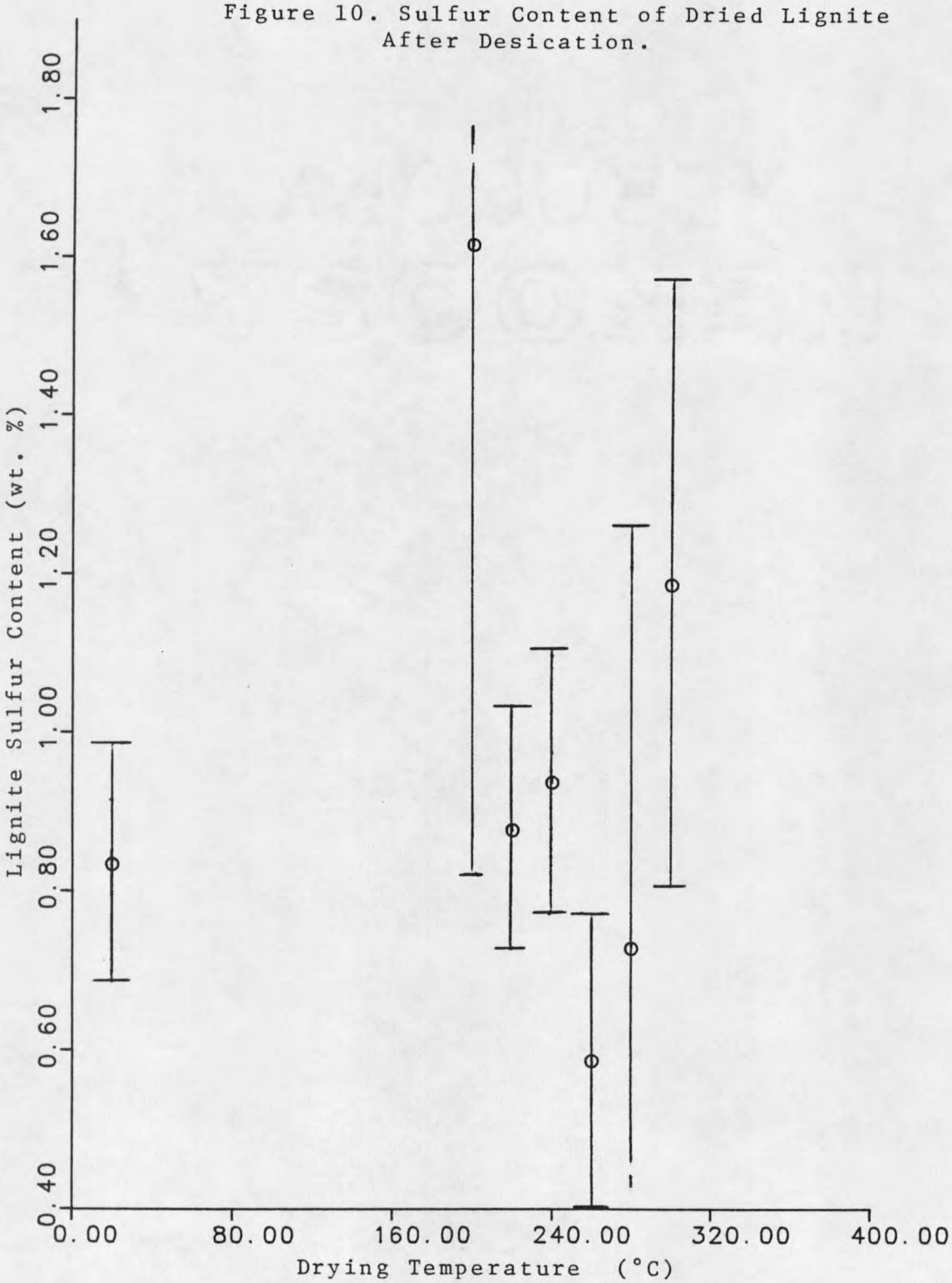
Figure 9. Hydrogen Content of Moisture Free Dried Lignites as a Function of Drying Temperature.



lignites. Generally, as the drying temperature increased the hydrogen content increased slightly. This would make sense, as the carboxyl groups decomposed to carbon dioxide the relative weight percent of the hydrogen would increase. Small amounts of methane and other hydrogen containing gases have been shown to be evolved by this process using other lignites (11). No hydrogen containing species were found in the off-gases of this system. It is believed that some were formed, but not enough to show in the gas chromatograph output or to significantly change the hydrogen content obtained in the ultimate analyses of the hot water dried lignite.

Sulfur determinations using the Carlo Erba ultimate analysis machine were erratic and unpredictable. The sulfur content varied from 0.58% to 1.61%. As illustrated in Figure 10, no correlation between sulfur content and drying temperature could be made using this data. The variation in sulfur content is not caused by the machine. This variation in sulfur content is believed to by a consequence of not making any distinction between the organic and the inorganic sulfur in the coal. With sample weights of approximately 1 milligram, a small amount of inorganic sulfur will result in a large jump in the sulfur detected. Other studies have found sulfur reductions of less than 2% over a similar drying temperature range, probably from SO_2 formation.(11)

Figure 10. Sulfur Content of Dried Lignite After Desication.



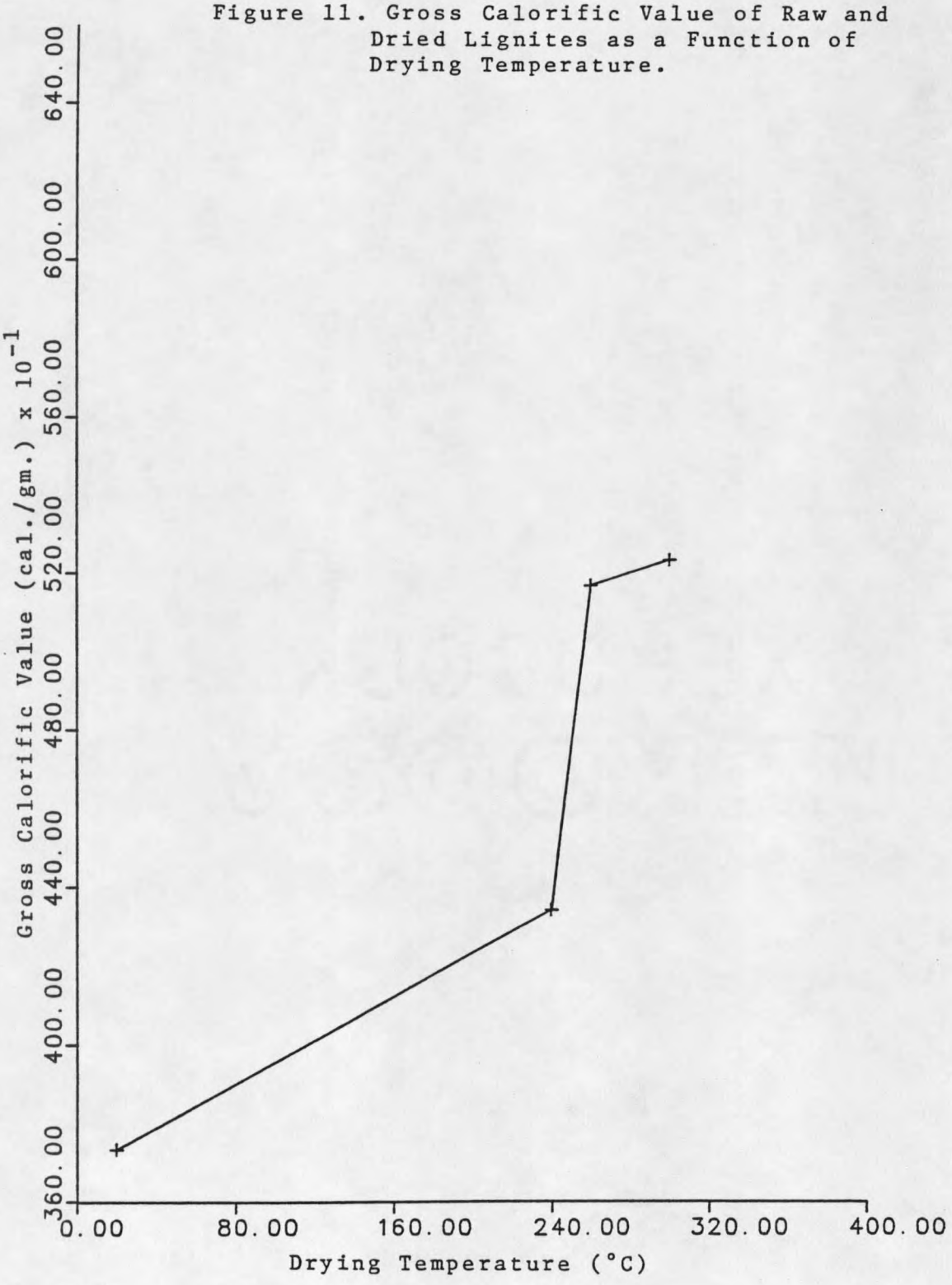
Heating Value

Figure 11 shows the effect of drying temperature on the gross heating value of the hot water dried lignite. The gross heating value increased from just 3735 calories per gram for the raw coal to 5234 calories per gram for the coal dried at 300°C. There is a jump in the calorific value between the 240°C run and the 260°C run. Again the jump from 4341 calories per gram to 5169 calories per gram occurs where the carboxylic group decomposition becomes significant.

Ash Content

The ash content was found to vary from sample to sample. However, the percentage ash does not appear to change significantly during the hot water drying process, regardless of temperature. Other studies have found varying degrees of ash removal. Maas(11) found no significant ash removal, while Potas et.al. (13) found significant ash loss during drying (25% and greater). Although no significant ash removal could be shown to take place, some ash is believed to have been removed. Sodium, a constituent of most coal ashes, was found in the process water by doing a flame test on the process water.

Figure 11. Gross Calorific Value of Raw and Dried Lignites as a Function of Drying Temperature.



Dried Lignite Briquet Strength

Various combinations of lignite, water, #6 fuel oil, corn starch, wheat paste, vinyl wallpaper paste, and concrete binder were used in the briquet making. Briquets were made using only one binder at a time. It was felt that using multiple combinations of different binders would increase the number of variables to the point where the interpretation of the results would become overly cumbersome. Additionally, the trial of too many binder combinations would exhaust the supply of hot-water-dried coals. As it was, the number of binder combinations made it necessary to restrict some combinations to briquets made with raw coal, and lignites dried at 240°C and 300°C. Table 4 shows the briquet binder schemes used in this study.

Briquets Made Without Water

Briquet compressive strength varied from almost zero to 6.4 pounds force. No briquets made without water and without a binder held together well enough to test for compressive strength. None of them were acceptable. This was also found to be true by Lin (18). The raw, undried coal, with the highest moisture content, came closest to producing a viable briquet.

Table 4. Briquet Mixture Combinations

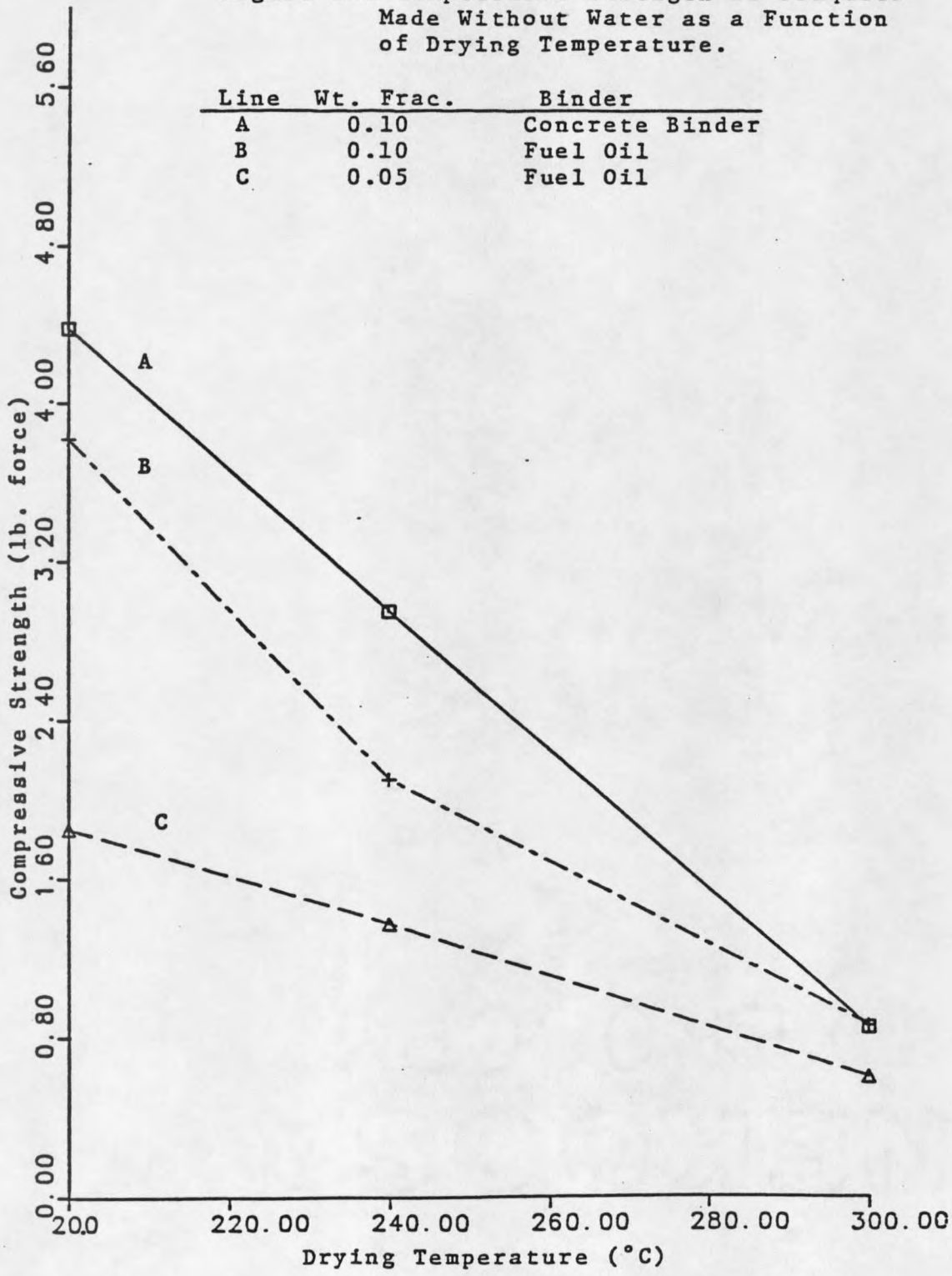
Mix #	Binder	Binder Wt.Frac.	coal/water ratio
1	fuel oil	0.10	---
2	fuel oil	0.05	---
3	fuel oil	0.02	---
4	corn starch	0.05	4/1
5	corn starch	0.10	2/1
6	corn starch	0.02	10/1
7	wheat paste	0.10	---
8	wheat paste	0.20	---
9	wheat paste	0.50	---
10	vinyl paste	0.10	---
11	vinyl paste	0.20	---
12	concrete binder	0.10	---
13	concrete binder	0.10	1/2
14	concrete binder	0.05	1/1
15	concrete binder	0.05	1/2
16	---------		1/2

The compressive strengths of briquets made with a binder, but no water, are illustrated versus drying temperature in Figure 12. All of the briquetting mixtures showed a fairly linear relationship between compressive strength and drying temperature. As the drying temperature increased the compressive strength decreased. While there was a wide variation in compressive strengths for various binders and raw lignite, the binder choice made little difference in the briquet strength for the coal dried at 300°C. Possibly the higher moisture content of the raw coal played a role by extending the natural cohesive forces of the coal.

The water soluble concrete binder produced the strongest briquets made without water. The concrete binder, being more water soluble than #6 fuel oil, may have been more able to replace water at sites on the surface of the coal. This would allow the concrete binder to adhere to the coal surface, producing a stronger briquet. A 0.05 weight fraction concrete binder briquet was attempted, but the small amount of binder did not wet the coal sufficiently well to produce a consistent briquetting mixture. The lignite hot water dried at 300°C had the lowest moisture content and was slightly hydrophobic. It would not have had water adsorbed on the surface of the coal for the concrete binder to replace. Therefore, the concrete binder would not

Figure 12. Compressive Strength of Briquets Made Without Water as a Function of Drying Temperature.

Line	Wt. Frac.	Binder
A	0.10	Concrete Binder
B	0.10	Fuel Oil
C	0.05	Fuel Oil



wet the coal any more than the other binders did, producing a briquet of similar compressive strength.

As expected, the briquets made with 10.0 weight percent fuel oil were stronger than the briquets made with 5.0 weight percent fuel oil. Both of them had a reduction in compressive strength as the drying temperature increased. This seems contrary to what one would expect. It would seem logical that as the moisture in the coal was reduced there would be less surface moisture in the coal to reduce the contact area between the binder and the coal. This moisture reduction would then produce a stronger briquet. Evidently, during the drying process the surface of the coal is changed such that no binder adheres as well to the coal, regardless of whether the binder is water soluble or not. This apparent change in the surface of the coal becomes more evident at higher drying temperatures. This surface change produces a briquet of similar compressive strength irrespective of binder choice or concentration.

Although #6 fuel oil makes a strong briquet and has a high gross heating value, 17000 BTU/Lb., it also has a high sulfur content. The Cenex #6 fuel oil used in these experiments contained 5 weight % sulfur(28). This amount of sulfur disallows the use of the fuel oil in a commercial application.

As the drying temperature increases the degree of comminution increases. Possibly at higher temperatures the particle size becomes small enough that the binder does not effectively cover the increased surface area of the smaller particles. However, when the binder concentration was increased the compressive strength did not increase significantly for the 300°C run. The degree of comminution thus did not seem to have an effect.

Briquets Made With Water

Compressive strengths of briquets made with the addition of water are presented in Figures 13 and 14. The vinyl paste and the wheat paste binders did not prove to be feasible. The binder concentration needed to produce a briquet was much higher than for the other binders, 30-40%. Therefore they were discarded and the briquetting data for them is not presented.

For the raw lignite, a mixture containing 5.0 weight percent concrete binder, 95.0 percent coal, added to a weight of water equal to the weight of coal produced the strongest briquet. For the dried coals a mixture containing 5.0 weight percent corn starch produced the strongest briquet. Corn starch is inexpensive and plentiful,making it an attractive binder. However, the preparation needed to use

Figure 13. Compressive Strength of Concrete Binder Briquets Made With Water.

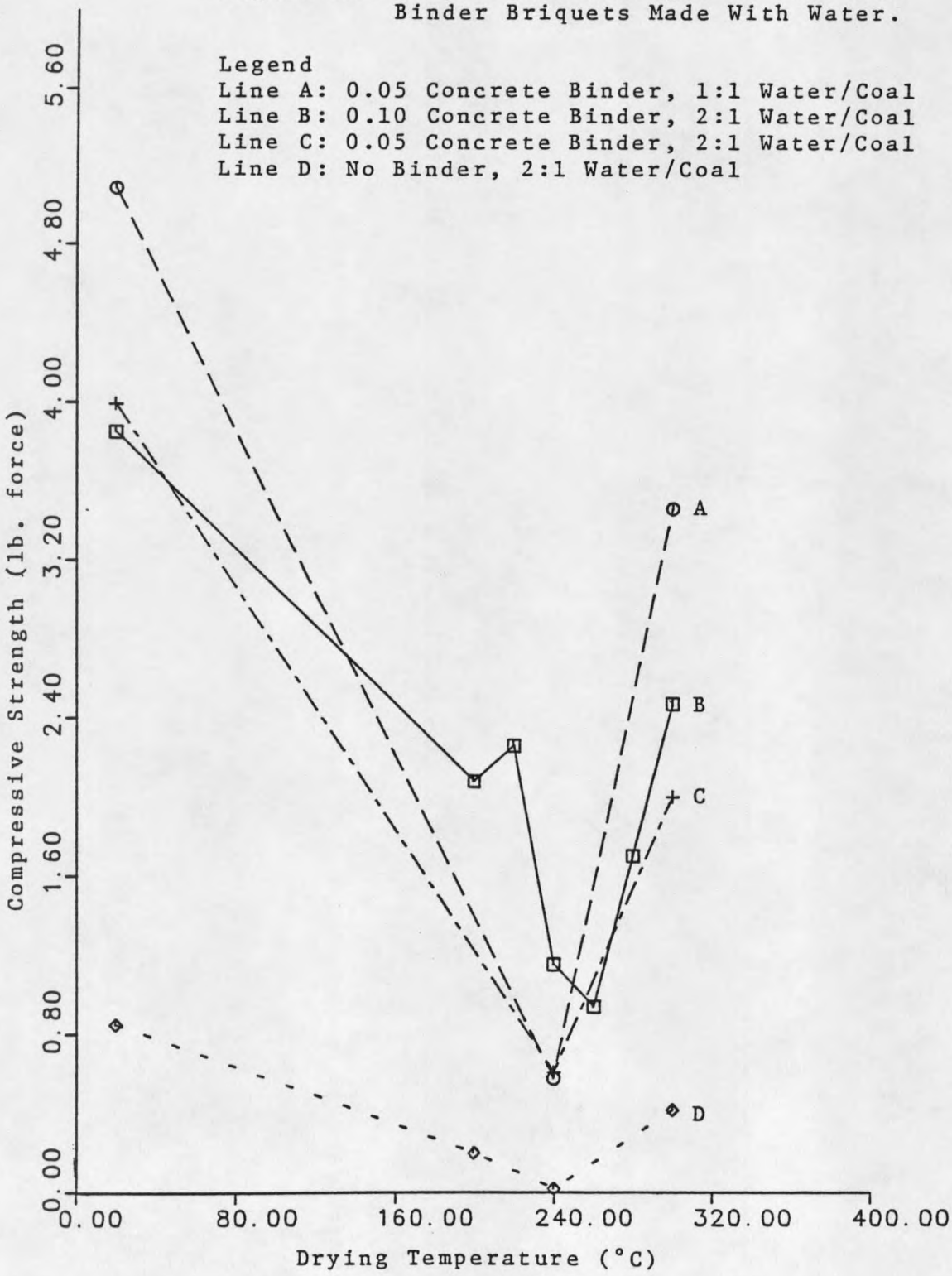
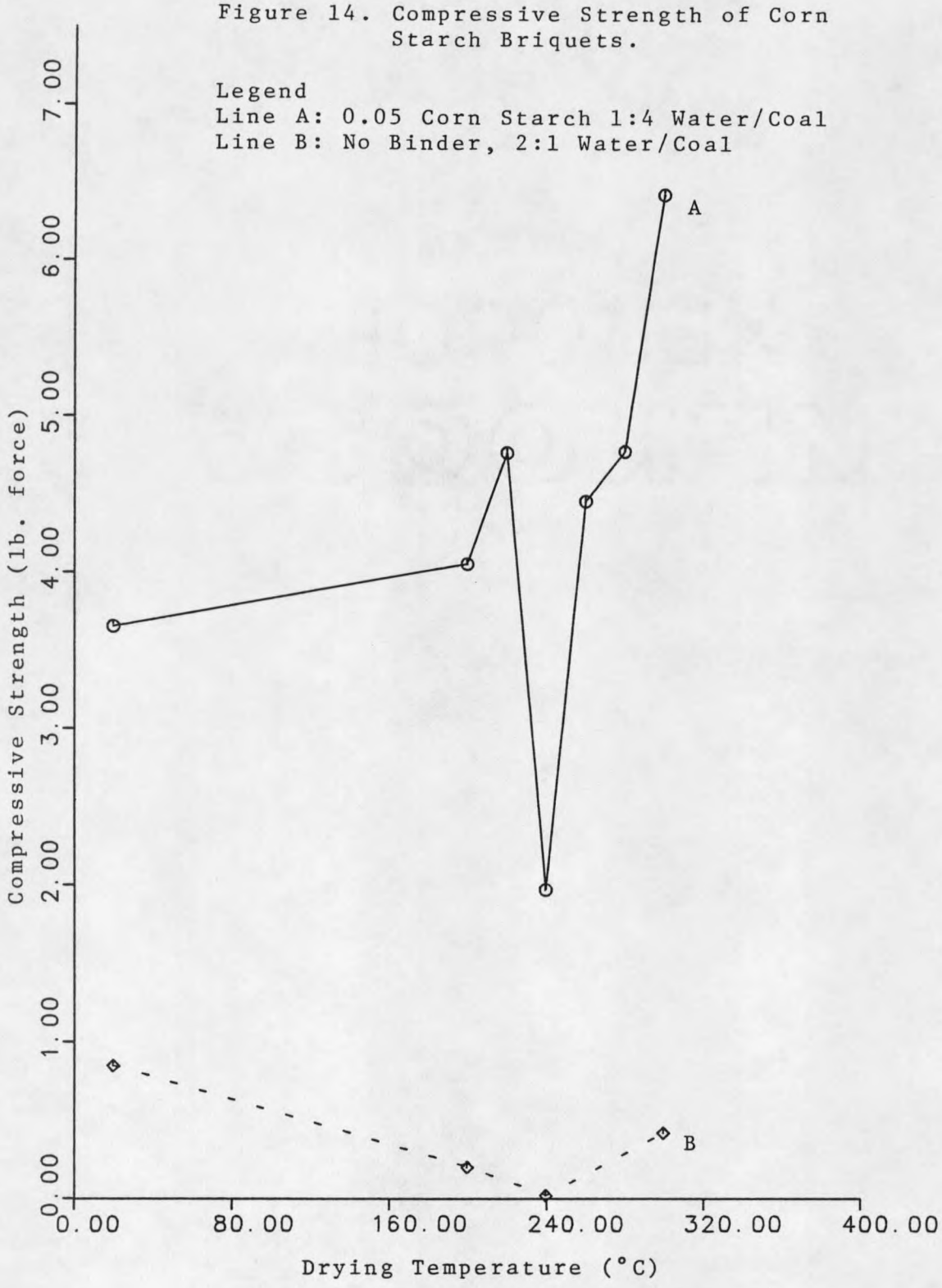


Figure 14. Compressive Strength of Corn Starch Briquets.



corn starch as a binder makes it less desirable in actual use.

What should be noted in Figures 13 and 14 is that in all cases a minimum in compressive strength occured at a drying temperature of 240°C or 260°C. The 5.0% concrete binder mixture with a coal-water ratio of 1:1 produced a stronger briquet than the 5.0% concrete binder mixture with a 1:2 coal-water ratio. This was expected as the binder concentration is higher in the former mixture. However, the former mixture was also stronger in most cases than briquets made with the 10.0% concrete binder mixture and coal water ratio of 1:2. This was not expected as the binder concentration in the 10% mixture was higher. Evidently the water does not act solely as a diluent. It should be noted that a plain coal-water mixture showed the same minimum in compressive strength as did the mixtures using a binder.

As the drying process takes place, the mean particle size and particle distribution become smaller. Possibly this size reduction causes changes in binder wetting angles and in the natural cohesive forces in the particles. This could result in the minimum in compressive strength.

As previously noted, during the drying process hydrophillic groups on the coal molecule may be converted to more hydrophobic groups. The increase in briquet strength above 240°C does not follow the notion that if the coal

molecule became very hydrophobic, water or a water soluble binder should not produce a stronger briquet. Briquets made at these higher drying temperatures would be expected to be weaker because the hydrophobic coal molecule would not allow the binder to adhere to the coal.

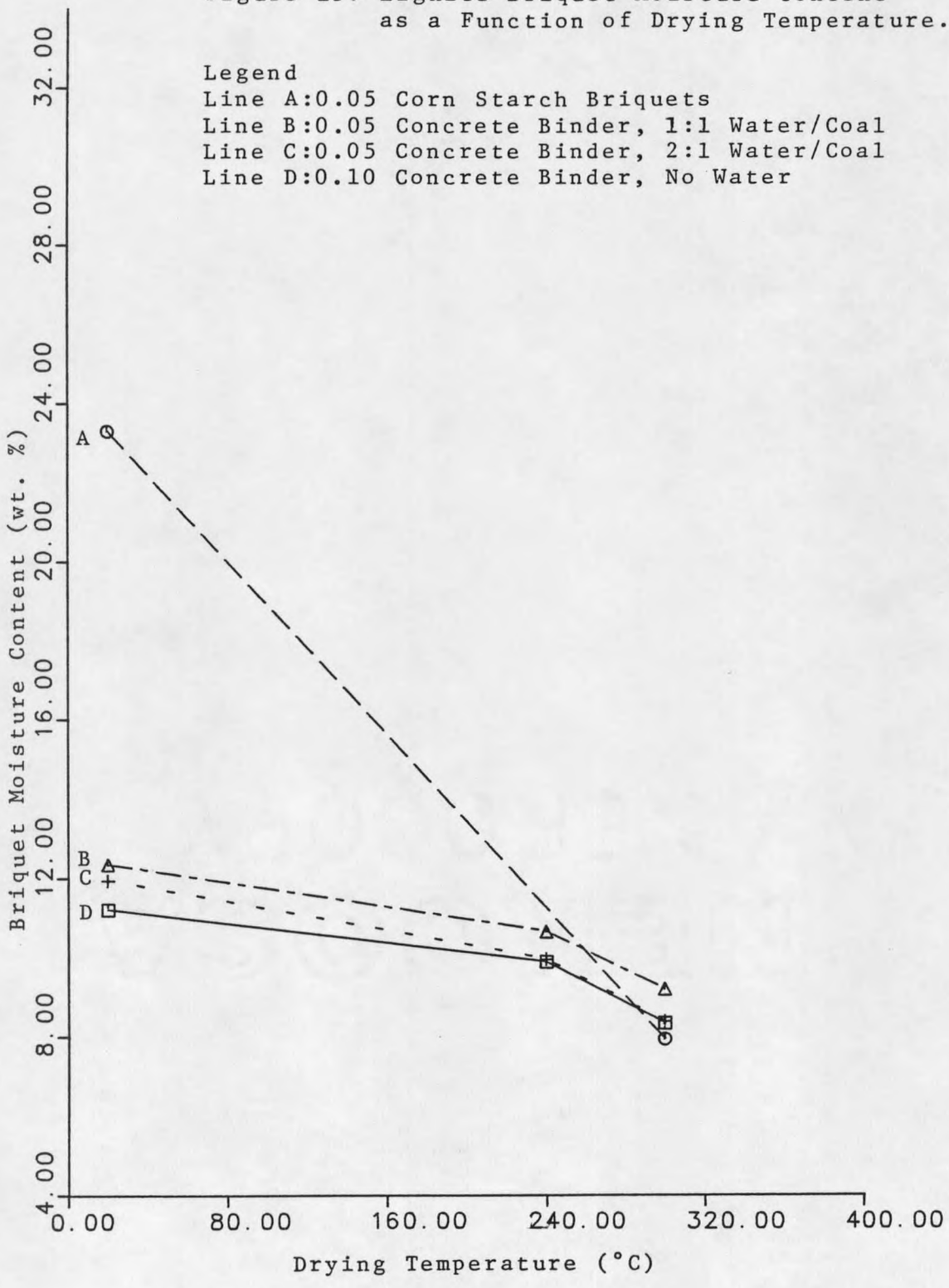
One possible scenario for the drying process is that, when dried at 240°C, the water that is chemically adsorbed to the surface of the microscopic pores of the coal is expelled to the macroscopic external surface where it acts as a barrier to good coal-binder contact. As the drying temperature increased, the water is completely eliminated from the coal. This would leave a clean surface to which the binder could easily attach, producing a stronger briquet.

Another possibility is that at 240°C a morphological change in the coal is just starting to take place. This change results in weak briquets. When the drying temperature is up to 300°C these morphological changes are more complete producing a coal better able to interact with the binder. It appears the lignite hot-water-dried at 300°C is slightly more hydrophobic than the raw coal, but not enough to make a difference in the briquet strength.

Briquet Moisture Content

The moisture content of the briquets made with water was checked and the results are presented in Figure 15. Although water was part of the briquetting mixture the moisture content of these briquets was equal to or less than the moisture content of the unbriquetted coals. The moisture content of the raw coal briquets varied, depending on the binder used. Binder choice did not seem to have an effect on the moisture content of hot-water-dried coal briquets. The moisture content of the raw coal briquets made with the concrete binder was much lower than expected. To eliminate the possibility that the concrete binder holds the moisture in the coal strongly enough that the 110°C temperatures used in moisture determination are not hot enough to drive away the moisture, the gross calorific value of two of the raw coal, concrete binder briquets was checked. The raw coal briquets made with a concrete binder concentration of 0.10 and no water had a gross heating value of 4755 calories per gram, while briquets with a concrete binder concentration of 0.05 and a 1:2 coal-water ratio had a heating value of 4822 calories per gram. These heating values corresponded very closely to the dried coals having a similar moisture content. The moisture content of the briquets is lower than the moisture content of the coals, possibly because the

Figure 15. Lignite Briquet Moisture Content as a Function of Drying Temperature.



binder replaces moisture at various sites on the coal molecule, allowing more of the water to be pressed out in the briquetting step. For the dried coals the moisture content depression occurred regardless of whether or not water was part of the briquetting mixture when the concrete binder was used.

The moisture content depression in briquets with water as part of the briquetting mixture became smaller as the drying temperature increased. The moisture content of briquets made with the coal dried at 300°C was very near to that of the unbriquetted dried coal.

In this investigation, and elsewhere(11), water has been shown to reabsorb onto the coal, especially coals dried at higher temperatures. This work seems to indicate that in hot-water drying the coal molecule does become more hydrophobic than undried coal, but it is not hydrophobic enough to drastically affect it's briquetting ability.

SUMMARY AND CONCLUSIONS

1. A high moisture content Savage lignite was hot water dried at temperatures between 200°C and 300°C. This produced a coal with a lower moisture content and an increased gross heating value.

2. The dried lignite had a higher carbon content and a lower oxygen content than did the raw lignite. The oxygen reduction is apparently from CO_2 formation during the drying process. Sodium has been shown to be lost to the process water on hot-water drying.

3. The dried coals regained part of the moisture lost during the drying process when kept in a 100% humidity chamber.

4. Briquetting of the dried coals was carried out on a hand press using Cenex #6 fuel oil, cornstarch, wheat paste, vinyl wallpaper paste, and a water soluble concrete binder as binders.

5. Cenex #6 fuel oil worked well as a binder but its high sulfur content probably precludes its use in commercial applications.

6. Corn starch, dried lignite and water showed good binding ability and is inexpensive, ample, and pollution free.

7. Concrete binder with water proved to be an easy, effective binder for dried coal. It produced strong, consistent briquets and may have good weather resistance.

8. Briquets made with water as part of the briquetting mixture showed a compressive strength minimum with drying temperature at 240°C to 260°C. This corresponds to temperatures where significant CO_2 production begins during the drying process; possibly the beginning stages of a morphological change which leads to a strength minimum according to a mechanism not yet completely determined.

9. Hot-water drying is an effective, efficient way to reduce the moisture content of coals. All coals are different and results with different coals will not be identical to those obtained in these experiments.

RECOMMENDATIONS

1. A study of the wetting ability of the dried coals would shed light on why a minimum in briquet compressive strength was obtained in briquets where water was added to the briquetting mixture.

2. Briquetting with the dried coals should be conducted at higher, more industrially accepted pressures of 5000 to 10,000 p.s.i.(3). This would show if the compressive strength minimum is a low pressure briquetting phenomena.

3. Briquetting should be carried out with other binders and with multiple combinations of binders to see if the compressive strength minimum for briquets made with water occurs with all binders or just the ones used in this investigation.

4. Moisture reabsorption tests should be conducted on the briquets to see if the binder or briquetting process changes the reabsorption characteristics of the coal.

5. The apparent unusually low moisture content of the concrete binder briquets made with raw coal should be investigated in depth. If actually present, this moisture reduction would be revolutionary to the low-rank coal industry.

REFERENCES CITED

REFERENCES CITED

1. Slatick, E.R., ed., Coal Data: A Reference, U.S. DOE, Energy Information Administration, Vol. 1, pg. 4 (1976).

2. Wilkinson, J. F., "Outlook 1986: Overcapacity Depresses Prices", Coal Age, Vol. 21, No. 2, (Feb., 1986).

3. Berg, L., Personal Communication, Montana State University, Bozeman, MT (1986).

4. Burger, J.R., ed., "Three New Approaches to the Problem of Dewatering Fine Coal", Coal Age, Vol. 21 No. 1,(Jan., 1986).

5. Fleissner, H., Drying Coal, U.S. Pat. 1,632,829 (1927).

6. Gronhovd, G.H., Sondreal, E.A., Kotowski, J., and Wiltsee, G., Low Rank Coal Technology Lignite and Subbituminous, Noyes Data Corp. Park Ridge, N.J. pp. 187-197, (1982).

7. Klein, H., "The Fleissner Method of Drying Lignites; It's Underlying Chemical and Physical Principles", Braun Kohle, 29, pp. 1-10,21-30 (1930).

8. Rao, P.D. and Wolff, E.N., "Steam Drying of Subbituminous Coals From The Nenena and Beluga Fields, A Laboratory Study", Mineral Industry Research Laboratory, University of Alaska, Fairbanks, AK (1981).

9. Rozgonyi, T.G. and Szigeti, L.Z., "Upgrading of High Moisture Content Lignite Using Saturated Steam", Fuel Processing Tech., Vol. 10, pp. 1-18 (1985).

10. Koppelman, E., U.S. Pat. 4,052,168 (1977).

11. Maas, D.J., "Hot-Water Drying of a Lignite Slurry in Water", Thesis, University of North Dakota, Grand Forks, ND (1983).

12. Baria, D.N., Maas, D.J., and Paulson L.E., "Steam/Hot-Water Drying of Lignite Part 1: Activities at the University of North Dakota. Hot Water Drying fo Lignite to Produce Slurries", Twelfth Biennial Lignite Symposium, Grand Forks, ND (May, 1983).

13. Potas, T.A., Sears, R.E., Maas, D.J., Baker, G.G., and Willson, W.G., "Preparation of Hydrothermally Treated LRC/Water Fuel Slurries", Chem. Eng. Communications, Vol. 44, pp. 133-151 (1986).

14. Lynch, L.J. and Webster, D.S., "Effect of Thermal Treatment on the Inteaction of Brown Coal and Water: A Nuclear Magnetic Resonance Study", Fuel, Vol. 61, No. 3, pp. 271-275 (1982).

15. Cole, E.L.,"Upgrading Low Rank Solid Fuel", U.S. Pat. 4,018,571 (1977).

16. Berkowitz, N., "Fundamental Aspects of Coal Briquetting", Proceeding of the Third Biennial Briquetting Conference, Natural Resources Research Institute, University of Wyoming, Laramie, WY, pp. 3-22 (1953).

17. Davies, J.T. and Rideal, E.K., Interfacial Phenomena, Acedemic Press, New York, pp. 36-41 (1961).

18. Lin, J.S., "Low Rank Coal Briquetting", Thesis Montana State University, Bozeman, MT (1984).

19. "Proximate Analysis of Coal and Coke", ASTM D 3172-73, Annual Book of ASTM Standards, Part 26, pp. 660 (1974).

20. "Carlo Erba Stumentazione Elemental Analyzer Mod. 1106 Instruction Manual", Montedison Group, Farmitalia Carlo Erba.

21. "Gross Calorific Value of Solid Fuel by the Adiabatic Bomb Calorimeter", ASTM D 2015-66, Annual Book of ASTM Standards, part 26, pp. 468-475 (1974).

22. "Operating Instuctions, Instron Universal Testing Instruments", Instron Corporation, Canton, MA.

23. Perry, R.H. and Chilton, C.H., Chemical Engineers Handbook, 5th ed., McGraw-Hill Book Co., pp. 9-3 (1973).

24. Moore, E.B., Coal, 2nd ed., John Wiley & Sons, Inc. pg. 35 (1940).

25. Kohl, A.L. and Riesenfeld, F.C., Gas Purification, 3rd ed., Gulf Pub. Co., Houston, pp. 228 (1979).

26. Houghton, G., McLean, A.M., and Ritchie, P.D., "Compressibility, Fugacity, and Water-Solubility of Carbon Dioxide", Chem. Eng. Science, Vol. 6, pp. 132-137(1957).

27. Volk, W., Applied Statistics for Engineers, McGraw-Hill Book Co., pp. 98-120 (1958).

28. Berg, J., Personal Communication, Cenex Inc., Laurel, MT (1986).

APPENDIX

Table 5. Temperature History of Coal-Water Contacting Vessel to 255°C.

Time(min)	Temp.(°C)
0	21
5	25
7	30
11	40
13	46
16	57
19	64
28	91
35	118
46	150
51	161
59	177
65	188
69	195
73	202
78	211
82	218
89	232
93	239
96	244
99	248
103	255

Run temperature set at 260°C. It was held at a nominal 260°C for 15 minutes after achieving this temperature in approximately 2 additional minutes. It than began to cool.

MONTANA STATE UNIVERSITY LIBRARIES
3 1762 10014815 2

AMERICAN BINDERIES