Low-rank coal briquetting
by Ji-Shing Lin

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering
Montana State University
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Abstract:
The proximate analyses, thermal dewatering characteristics, and heat contents of four low-rank coals (Dominy lignite, Savage lignite, Colstrip subbituminous, and Gillette subbituminous) from Montana and Wyoming mines were examined. Dewatering and briquetting as means of upgrading these coals were studied with three materials (no. 6 fuel oil, kraft sulfate liquor, and corn starch) as possible binders by different combinations and percentages to find the appropriate binder and operational procedures.

Comparing the amounts and binding ability of the binders used and accompanying pollution, corn starch was determined to be the most appropriate binder among these three materials. The best briquet contained 95 wt.% dried coal and 5 wt.% corn starch binder. The increased percentages of calorific values between briquets and raw coals (as-received) ranged from 14.7% to 52.8%. The higher the moisture content of the raw coal, the more its calorific value increased. The costs of raw coals ranged from $0.80 to $1.0 per million Btu and those of briquets ranged from $1.44 to $1.89 per million Btu.

In conclusion it appears that the benefit of dewatering and briquetting is fuel of higher calorific value, less material loss, and easier handling.

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This thesis has been read by each member of the thesis
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ABSTRACT

The proximate analyses, thermal dewatering characteristics, and heat contents of four low-rank coals (Dominy lignite, Savage lignite, Colstrip subbituminous, and Gillette subbituminous) from Montana and Wyoming mines were examined. Dewatering and briquetting as means of upgrading these coals were studied with three materials (no. 6 fuel oil, kraft sulfate liquor, and corn starch) as possible binders by different combinations and percentages to find the appropriate binder and operational procedures.

Comparing the amounts and binding ability of the binders used and accompanying pollution, corn starch was determined to be the most appropriate binder among these three materials. The best briquet contained 95 wt.% dried coal and 5 wt.% corn starch binder. The increased percentages of calorific values between briquets and raw coals (as-received) ranged from 14.7% to 52.8%. The higher the moisture content of the raw coal, the more its calorific value increased. The costs of raw coals ranged from $0.80 to $1.0 per million Btu and those of briquets ranged from $1.44 to $1.89 per million Btu.

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INTRODUCTION

Low-rank coals (lignite and subbituminous) are those which have been subjected to the least amount of metamorphic change during the coal-forming process. They retain a greater fraction of moisture (20 to 30 wt.% in subbituminous and 35 to 40 wt.% in lignite) and volatile matter from the original peat material and contain less fixed carbon than the high-rank coals (bituminous and anthracite).

The primary measure used to classify the lower ranks of coal is calorific value. Lignite is defined (in America by ASTM--the American Society for Testing and Materials) as coal with a calorific value less than 8,300 Btu/lb, on a moist, mineral-matter-free basis (m,mmf). Subbituminous coal ranges from 8,300 to 11,500 Btu/lb (m,mmf) [1].

According to the U. S. Geological Survey, about half of the reserves of coal in the United States are low-rank coals which represent a major and largely untapped energy resource.

Since the late 1960's, low-rank coals began to be used increasingly through technological, regulatory, and other developments that changed their relative economics:

1. Large quantities of economically recoverable reserves made coal one of the few indigenous energy sources capable of relieving U. S. overdependence on imported oil.

2. The price and long-term supply uncertainty of OPEC oil and domestic gas rose rapidly.

3. Very large pulverized-coal boilers and strip mining machines were adapted for low-rank coals. These allowed the industry to realize the economics of scale required to make low-rank-coal utilization competitive.

4. Limits were placed on emission of sulfur dioxide. This created a huge demand for the low-sulfur western low-rank coals (low sulfur content means the percentage of sulfur is lower than 1.0 wt.%).

Prior to 1970, low-rank coals accounted for 1 to 2% of the total annual U. S. coal production. In 1980, they accounted for 24%. By 1990, they may account for 40 to 50% of a greatly expanded total [1].

Briquetting

The high moisture contents of low-rank coals yield reduced utilization efficiencies. Because the moisture content is largely inherent, the coals actually appear dry and dusty during handling, transportation, and use. As

moisture evaporates from low-rank coal particles, the surface becomes brittle and particles spall off. This process is termed slacking [1]. This dusty appearance causes material (and accompanying cost) loss as well as hygienic and environmental problems.

Means of upgrading utilization of these low-rank coals include dewatering and briquetting, gasification, liquefaction, etc.

Briquetting [2] is the conversion of a pulverized material into coherent artifacts by either directly compressing the powder itself or by compressing an intimate mixture of the powder and an appropriate binding agent(s).

The purposes of coal briquetting are:

1. To increase the calorific value.

2. To convert a low-grade solid fuel into a more easily handled and attractive fuel.

3. To reduce powder loss.

4. To produce cokes from normally non-coking coals [2].

It follows that the briquetted product should satisfy four conditions:

1. It should have satisfactory combustion properties.

2. It should be hard and resistant to mechanical stresses that cause abrasion and fracture.

3. It should be of uniform quality.

4. It should be more economical than the original raw material.

In practice, therefore, sound operation demands, first, careful control over the composition of the feed material and, secondly, a briquetting process in which adequate cohesion of the briquetted material is ensured by careful selection of binder(s) and of the conditions under which the mixture is compressed.

The briquetting technique consists essentially of:

1. Pretreatment of the raw material.

2. Introduction of a suitable binder(s).

3. Intimate mixing (fluxing) of the resultant mass.

4. Briquetting under proper temperature and pressure.

5. After-treatment.

Research Objectives

The objectives of this research were to investigate four low-rank coals (Dominy lignite, Savage lignite, Colstrip subbituminous and Gillette subbituminous) and upgrade their utilization through dewatering and briquetting. The intrinsic physical properties (moisture, volatile matter, fixed carbon, and ash contents in proximate analysis, thermal dewatering, and heat content) of these coals were to be determined. Three possible binders were chosen from many industrial binding agents. The most appropriate one was to be determined and the briquetting procedures were to be developed.

Calorimetric results of raw coals (as-received) and their briquets were to be compared to show the benefit of upgrading these low-rank coals through dewatering and briquetting.

THEORETICAL ASPECTS

Briquet strength of coal with an extraneous binding agent(s) depends on three factors:

1. The nature of the coal.

2. The distribution of binding agent(s) in the coal.

3. The strength of the bond between the individual coal particle and the binding agent(s).

Environmental factors (e.g., temperature and pressure) and inherent properties (e.g., the moisture content of the coal) play important roles in briquet strength because they influence the above factors 2 and 3. Also, since factor 3 is necessarily as much dependent upon surface characteristics of the coal as upon the binding agent(s), the nature of the coal is certainly important.

There are six variables (pressure, temperature, time, degree of comminution, film-forming material, and the nature of the binder) that influence the briquetted products.

Pressure

The pressure factor plays an important role in the briquetting process. Agglomeration occurs when force is applied to a particulate system in a confined space.

Huffine and Stewart [3] showed the following briquetting equation for non-metallic powders:

$$\log P = m * (V/Vs) + b$$

where P is pressure applied to compact,

V is compact volume at pressure P,

Vs is solid material volume (void-free), and

m and b are constants.

The mechanisms of compaction were discussed by Cooper and Eaton [3]:

1. Filling of large holes with particles from the original size distribution.

2. Filling of holes smaller than the original particles by plastic flow or fragmentation.

Increasing pressure leads to progressively denser compactness and more extensive plastic deformation of a solid, and is always beneficial.

Temperature

Heat will generally reduce the modulus of elasticity of a solid [2] and the viscosity of a fluid. Provided that briquetting is carried out under conditions that will not cause thermal degradation of the briquetted material, an increase in temperature will be beneficial.

Time

Any process involving deformation of a solid is a rate
process, i.e., the deformation requires a finite
displacement of structure units in space and time. The
degree of compaction that can be imparted to a given solid
under fixed conditions of pressure and temperature will be
significantly affected by the compaction period. Since the
rate of deformation of a solid under constant external
pressure approaches zero asymptotically, the strength-time
relationship generally is expressed as a logarithmic form
of this type [2]:

$$\log S = K * \log t + B$$

where S is the briquet strength,

K and B are constants, and

t is time.

Degree of Comminution

The beneficial effect of fine grinding is not solely
due to the fact that small particles will allow denser
packing in the briquet. Mutual adhesion of solid particles
increases as the particle size is reduced. Since the
elastic constants of a solid are substantially independent
of size, surface forces emanating from particles can extend
interparticulate contacts if the particles are small.
However, excessively small particle size will make the

shortcoming of floating dust significant, and it will need
more binding agent to agglomerate the larger surface area
of finely separate powders.

Film-forming Material

Adsorbed film (irrespective of the nature of the
film-forming material) can influence the ease and degree of
compactness of a granular assemblage in three ways [2]:

1. It reduces the free energy (or surface tension) of
   the solid and consequently increases its
   deformability under external constraint.
2. An absorbed film can act as boundary lubricant and
   therefore enables the particles to rearrange
   themselves more quickly and efficiently into a
   dense and stable packing.
3. It reinforces solid-solid cohesion forces in a
   artifact by capillary forces which tend to extend
   the field of interaction.

Many fluid binding agents play the role of
film-forming material in briquets.

Nature of Binder

An adequate binder might be considered as one which,
apart from possessing satisfactory adhesive properties,
possesses an internal cohesion not very much inferior to

that of the coal particles and a marked affinity for the
coal surfaces to which it is to adhere. The first part of
this composite requirement is equivalent to saying that the
binder had better be ductile at ordinary temperature. For
the most part, external stresses acting on a bonded briquet
are those producing fracture and abrasion, and such
stresses are best counteracted, not by a hard and brittle
binder, but by a binder that (while hard) possesses an
element of ductility [2].

EXPERIMENTAL

Materials

Four low-rank coals (Dominy lignite of Western Energy Co., Savage lignite of Montana Dakota Utilities Co., Colstrip subbituminous coal of N. W. Improv. Co., and Gillette subbituminous coal of Carter Mining Co.) were studied. These coals had been sampled by the coal companies.

Many materials such as glue, gelatin, gum, resin, wax, and petroleum pitch [3] have been used as binding agents in many applications. Here, three local products were chosen as possible binders for the low-rank coals:

1. No. 6 fuel oil

   This petroleum fuel came from a local refinery (Farmers Union Central Exchange--Cenex Inc. at Laurel, Montana). It consisted primarily of paraffins, isoparaffins, aromatics, and naphthenes plus related derivatives of sulfur, oxygen, and nitrogen [3]. Its kinematic viscosity at 50°C was about 300 centistokes [3], calorific value was 17,000 Btu/lb and the sulfur content was 5 wt.% [4]. This viscous fuel oil was preferred for its high heat content and binding ability [1, 2, 3].

2. Kraft sulfate liquor (Tall oil)

This sulfate liquor came from a local pulp company
(Champion International Co. at Missoula, Montana).
It consisted of 15.8 wt.% unsaponifiables, 45.5
wt.% fatty acids, and 38.7 wt.% resin acids [5].
It contained no sulfur [5]. Pulp sulfate liquor
has been used as the binder of coal briquets [2, 3,
6, 7, 8].

3. Corn starch

Corn starch consists of 29 wt.% amylose and 71 wt.%
amylopectin [9] (polymers of glucose units). Its
calorific value is 7,522 Btu/lb [10]. It has been
used as a binder in the paste form [8, 9, 11, 12].
Usually, the starch paste is obtained by cooking
the aqueous solution at the gelatinization
temperature [9, 13]. Its viscous and pasty
character results from the presence of enormously
swollen elastic starch granules, and its viscosity
is imparted by the high polymeric carbohydrate
substance [9]. Among the common starches of corn,
wheat, sago, potato, sorghum, and tapioca, corn
starch shows comparatively good paste properties
[9]. It is also relatively cheap and easily
obtainable from a market of ample supply (corn is
the greatest single source of commercial starch in
the United States [9]). In this research, only

corn starch was used as the binder. Three

different corn starches purchased from a market

(two were labeled thick solutions and the third one

was a powder type) were investigated.

Preparation of Coal Samples

Mortar and pestle were used to grind coals into two

different sizes. The first size of pulverized powders,

which passed U. S. Standard No. 60 mesh (0.25 mm) sieve,

was for proximate analysis [14]. The second one, which

passed U. S. Standard No. 8 mesh (2.38 mm) sieve, was for

briquetting [1, 7, 8, 15, 16]. These two kinds of coal

powders were kept in tightly closed bottles. Their

moisture contents were checked every month.

Proximate Analysis

The proximate analysis of coal is the determination of

moisture, volatile matter, fixed carbon, and ash contents.

Volatile matter is the portion of the coal, which when

heated in the absence of air, is liberated as gases and

vapors. Ash is the inorganic residue that remains after

the coal has been burned. Fixed carbon is the carbonaceous

residue left after the volatile matter is driven off, and

its amount is calculated by subtracting from 100% the

percentages of moisture, volatile matter, and ash contents

[3].

According to ASTM, the proximate analysis of coals is
determined as follows [14, 17, 18, 19, 20]:

1. Moisture

   About 1 gram sample in a crucible is put in an oven
   at 104 to 110°C for 1 hour. The change of weight
   before and after heating is the moisture content.

2. Volatile matter

   The dehydrated coal in the crucible is covered with
   a lid and heated at 930 to 970°C for 7 minutes.

3. Ash

   The sample from item 2 is heated without a lid at
   700 to 750°C until constant weight is achieved.

4. Fixed carbon

   Fixed carbon wt.% = 100% - moisture wt.% - ash wt.%
   - volatile matter wt.%

Thermal Dewatering

The high moisture contents of low-rank coals translate
into higher feed throughput requirements for given energy
production rates. Thermal dewatering has several
advantages [1, 21, 22]:

1. Improved transport economics resulting from
   improved heating values and reduced likelihood of
   freezing problems during adverse weather

conditions.

2. Improved utilization economics due to increased boiler efficiency, lower throughput, and pulverizer capacity.

The moisture content in a coal sample is a parameter typical for the coal, and the less metamorphized coals possess higher adsorptivity and wettability of moisture [23]. The elimination of moisture proceeds differently in different ranks of coals, and is a characteristic parameter of the coals [23].

It would be helpful to know the thermal dewatering characteristics of these four low-rank coals concerning their utilization. These coal samples of 0.25 mm size were heated at 104 to 110°C to check their moisture contents decreasing with time [17, 18].

Preparation of Binders

All of the binders investigated were pretreated before they were introduced into the coal powders.

No. 6 fuel oil was preheated to 150°C to melt it. Kraft sulfate liquor was preheated to 80°C. At these elevated temperatures, they became easier to mix with coal powders.

Two corn starch solutions (Niagara Liquid Starch of CPC International Co. and Staley Liquid Starch of A. E.

Staley Co.) were checked and their water contents were found to be 92.2 and 87.38 wt.% respectively. It would be very uneconomic to use these starch solutions as binders, because lots of energy is needed to evaporate so much water to get dried briquets. The third corn starch was a dried powder type.

Three assay methods, which were proposed by TAPPI (Technical Association of the Pulp and Paper Industry), could be used to check the moisture content of starch [9]:

1. Dry a 2-gram sample 1 hour at 130 to 135°C.

2. Dry a 2-gram sample 20 minutes at 150°C.

3. Dry an 1-gram sample 15 minutes at 150°C.

These three methods were examined and compared to check (by statistical F-test [24, 25, 26]) if their results were consistent.

Corn starch was cooked with water (1 part starch and 10 parts water) at about 80°C for 10 to 12 minutes to form paste. During cooking, constant agitation was necessary to get good quality of starch paste [13, 27].

Briquetting

Generally speaking, the briquetting pressure for making coal briquets is at least sevsral thousand psi pressure [1, 2, 3, 12, 16] which is produced by briquetting machines. In this research, no machine was available. Two

hand presses were used. The first one, which could be used to produce about 100 psi pressure, and a cylindrical container (6-cm diameter) were used to make briquets. The second one, which could be used to produce several hundred psi pressure, and a new cylindrical container (1.5-cm diameter) were then devised to be used to make briquets because of the more powerful pressure.

The briquetting scheme for these four low-rank coals with different binders is shown in Table 1. Totally there are eight possible choices which form a complete combination out of three binders.

For every binder choice, except Choice 1 (blank contrast), different percentages of binders were tried. Every treatment was repeated five times (i. e., five replications) to check its repeatability. Every resultant mixture was heated to at least 80°C during mixing to facilitate good mixing, then it was quickly briquetted. Preheated coal powders prevented the hot starch paste from setting into a gel and quick solidification of fuel oil as they were added to coal powders.

In Binder Choice 1 of Table 1, no binder was used. This was the basis for checking the effect of binder. The pulverized coal was heated at 107°C to get rid of the water before briquetting. The briquets were cooled down to room temperature naturally.

For Binder Choice 2 (fuel oil as the binder), 3

Table 1. Briquetting Scheme of Binder Combinations
and Percentages

Binder choice

	1	2	3	4	5	6	7	8
	B	F	S	C	F-S	F-C	S-C	F-S-C
Binder percentage		20	20	20	15-5	15-5	15-5	10-6-4
		15	15	15	5-15	5-15	5-15	4-6-6
		10	10	10	12-8	12-8	12-8	6-6-4
		8	8	8	8-12	8-12	8-12	6-4-4
		5	5	5	10-10	10-10	10-10	4-4-4
		2	2	2	8-6	8-6	8-6	4-2-4
					6-8	6-8	6-8	2-4-4
					5-5	5-5	5-5	4-4-2
					2-2	2-2	2-2	2-2-2

B: Blank (no binder)
F: Fuel Oil (No. 6)
S: Sulfate Liquor (Kraft)
C: Corn Starch

For example: F-S-C 6-4-4 means Fuel Oil 6 wt % plus
Sulfate Liquor 4 wt % plus
Corn Starch 4 wt % as a
combined binder.

(sulfate liquor as the binder), and 5 (combined fuel oil and sulfate liquor as the binder), the coal powders were dried before the binder was introduced. The products were cooled down to room temperature naturally.

In Binder Choice 4 (corn starch as the binder), the coal powders were preheated to 80°C and then the starch was mixed in. After briquetting, the products were heated to 104 to 110°C for drying.

In Binder Choice 6 (combined fuel oil and corn starch as the binder), 7 (combined sulfate liquor and corn starch as the binder), and 8 (combined fuel oil, sulfate liquor, and corn starch as the binder), the corn starch paste was first added to the preheated coal powders, mixed and the mass air dried. Then the sulfate liquor and fuel oil were introduced, mixed and briquetted. The briquets were cooled down to room temperature naturally.

Briquet Evaluation

So far, there is no generally accepted standard for testing the quality of coal briquets [2, 6, 7, 12, 16]. Several test methods (e. g., loss and compression tests) have been suggested [7, 20]. They are imitations of the quality test of coals in ASTM [28, 29]. In ASTM tests, the sizes of coal samples are as large as several inches. Opposing opinions against these suggested tests have also

been proposed [2, 6, 7, 12]. In this research, no testing
(e. g., shatter or tumbler test) machines were available.
Detailed inspection of the surface and squeezing (pinching
with fingers) were adopted to check the quality of the
briquets. The acceptable briquet should be a smooth
agglomerate (no crevices or powdery dust) and be
compression-resistant. Here, in every treatment, there
were five replications. Unless all these five passed the
checkings, this treatment would be regarded as unacceptable.

Calorimetry Method

Calorimetry is a generally accepted standard method to
obtain the calorific values of samples [30]. The apparatus
used is a calorimeter. The essential components of a bomb
calorimeter as shown in Figure 1 are:

1. A bomb which contains the sample in a crucible and
   oxygen.

2. A electrical ignition system which includes two
   platinum electrodes and a piece of iron fuse.

3. A calorimeter in which a known weight of water
   surrounds the bomb.

4. A precision thermometer graduated to $0.01^{\circ}C$, and a
   magnifying lens.

5. A stirrer connected with a motor.

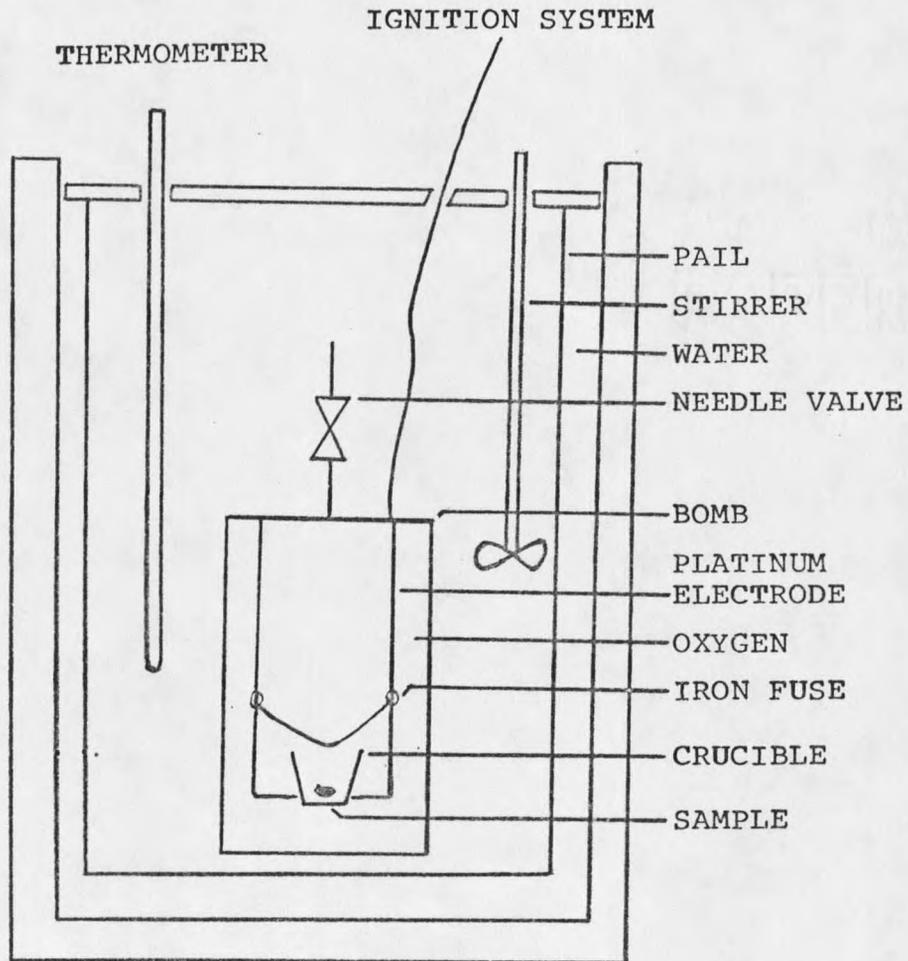6. An insulating wall (adiabatic jacket) surrounding

Figure 1. Calorimeter

the calorimeter.

In the calorimetry method, first, the heat capacity (energy equivalent factor) of the calorimeter was determined with the aid of a known calorific-value material (e. g., naphthalene or benzoic acid). This is used in standardizing the calorimeter [30].

The experimental procedures were:

1. One gram (weighed to 0.0001 gram) naphthalene (17,303 Btu/lb heat content [31]), or benzoic acid (11,372 Btu/lb heat content [31]) was pressed into a pellet in a die by a hydrauic press.

2. The sample was placed in the crucible. The two platinum electrodes inside the bomb calorimeter were connected to a piece of special iron wire of about 0.005 mm in diameter (its calorific value was 2.3 cal/cm).

3. The bomb was assembled and tightened after inspection (to make sure that it was dry and clean).

4. Atmospheric nitrogen was removed from the bomb by first flushing with oxygen. Then the bomb was slowly filled with oxygen to 20-30 atm pressure. The ignition wires were connected.

5. The bomb was placed in the pail of the calorimeter. The pail was filled with exactly 2000 ml water. The stirrer and thermometer were positioned.

6. The stirrer was started. Temperature changes were

observed for several minutes to attain thermal equilibrium (because of the heat generated by the action of stirrer).

7. Then temperature readings were taken every 1 minute. Both time and temperature (estimated to $0.001^{\circ}C$) were recorded. After the steady temperature rise was recorded for about 5 minutes (for the purpose of radiation correction [32]), the ignition button was pressed and the bomb was fired.

8. Time-temperature readings were continued and recorded every 1 minute. The temperature would start to rise about 15 to 20 seconds after ignition. This might continue for 10 to 20 minutes, after which the temperature would level off and become steady. Another 5 minutes were monitored (for the purpose of radiation correction [32]).

9. After the pressure was slowly released by turning the needle valve, the bomb was opened. The unburned parts of the iron wire fuse were removed and their combined length was measured.

10. The interior of the bomb was examined for the soot or other evidence of incomplete combustion. If any was found, the test was discarded.

The thermometer in the calorimeter was a very precise one with a movable magnifying lens on it. The actual temperature should be corrected according to the newest

Thermometer Test Certificate furnished by the thermometer maker.

Samples for the calorimetric method were these four low-rank coals (on the as-received and dry bases) and their briquets (95 wt.% dried coals and 5 wt.% corn starch). All the samples were ground to pass the U. S. Standard No. 60 mesh (0.25 mm) sieve before checking their calorific values [32].

The particle size of samples for calorimetry method is important, because the combustion reaction proceeds to completion within a few seconds, and if any of the individual particles are too large, they will not burn completely. A sample that is too finely pulverized may also be difficult to burn completely, because extremely small particles can be swept out of the combustion capsule by the turbulent filling and purging gases. If they fall to the bottom of the bomb without being ignited, the test will be rejected.

RESULTS AND DISCUSSION

Proximate Analysis

Table 2 shows the proximate analysis results of these four low-rank coals on the as-received and dry bases. From these results, it was clear that the moisture content of lignite was higher than that of subbituminous. These two kinds of lignites had as high as 35 wt.% moisture content, which would be detrimental to their calorific values because of the magnitude of the heat of vaporization of water (1050 Btu/lb). Fixed carbon contents (from 28.6 to 40.5 wt.%) of these low-rank coals were far less than those of high-rank coals (e. g. from 86 to 98 wt.% in anthracite [3, 33]), and their volatile matter contents (from 24.0 to 36.1 wt.%) were more than the high-rank coals (e. g., from 2 to 14 wt.% in anthracite [3, 33]).

Thermal Dewatering

Table 3 and Figure 2 show the results of thermal dewatering. The moisture contents decreased rapidly during the first quarter hour, and then leveled off gradually. The moisture-loss curves were similar to those from drying theory [34, 35, 36] (e. g., an initial constant rate period

Table 2. Proximate Analysis of Various
Low-rank Coals*

	Moisture	Volatile matter	Fixed carbon	Ash	Sulfur**	Total
Dominy lignite						
As-received	35.4	24.0	32.0	8.6	0.7	100
Dry	–	37.2	49.5	13.3	1.1	100
Savage lignite						
As-received	35.3	31.4	28.6	4.7	0.5	100
Dry	–	48.5	44.2	7.3	0.8	100
Colstrip subbituminous						
As-received	14.2	36.1	40.5	9.2	0.5	100
Dry	–	42.1	47.2	10.7	0.6	100
Gillette subbituminous						
As-received	27.5	33.1	32.8	6.6	0.5	100
Dry	–	45.7	45.2	10.1	0.7	100

*: All were expressed in wt.%.

**: Sulfur content values were given by the owners of
the mines.

Table 3. Thermal Dewatering of Various
Low-rank Coals*

	Heating time (min)	Moisture content (g)	Moisture evaporated (g)	Moisture evaporated (%)
Dominy	0	0.352	0.000	0
	15	0.028	0.324	92
	30	0.011	0.341	97
lignite	45	0.004	0.348	99
	60	0.000	0.352	100
Savage	0	0.350	0.000	0
	15	0.035	0.315	90
	30	0.017	0.333	95
lignite	45	0.009	0.341	98
	60	0.000	0.450	100
Colstrip	0	0.140	0.000	0
	15	0.023	0.117	84
	30	0.013	0.127	91
subbituminous	45	0.006	0.134	96
	60	0.000	0.140	100
Gillette	0	0.279	0.000	0
	15	0.033	0.246	88
	30	0.017	0.262	94
subbituminous	45	0.008	0.271	97
	60	0.000	0.279	100

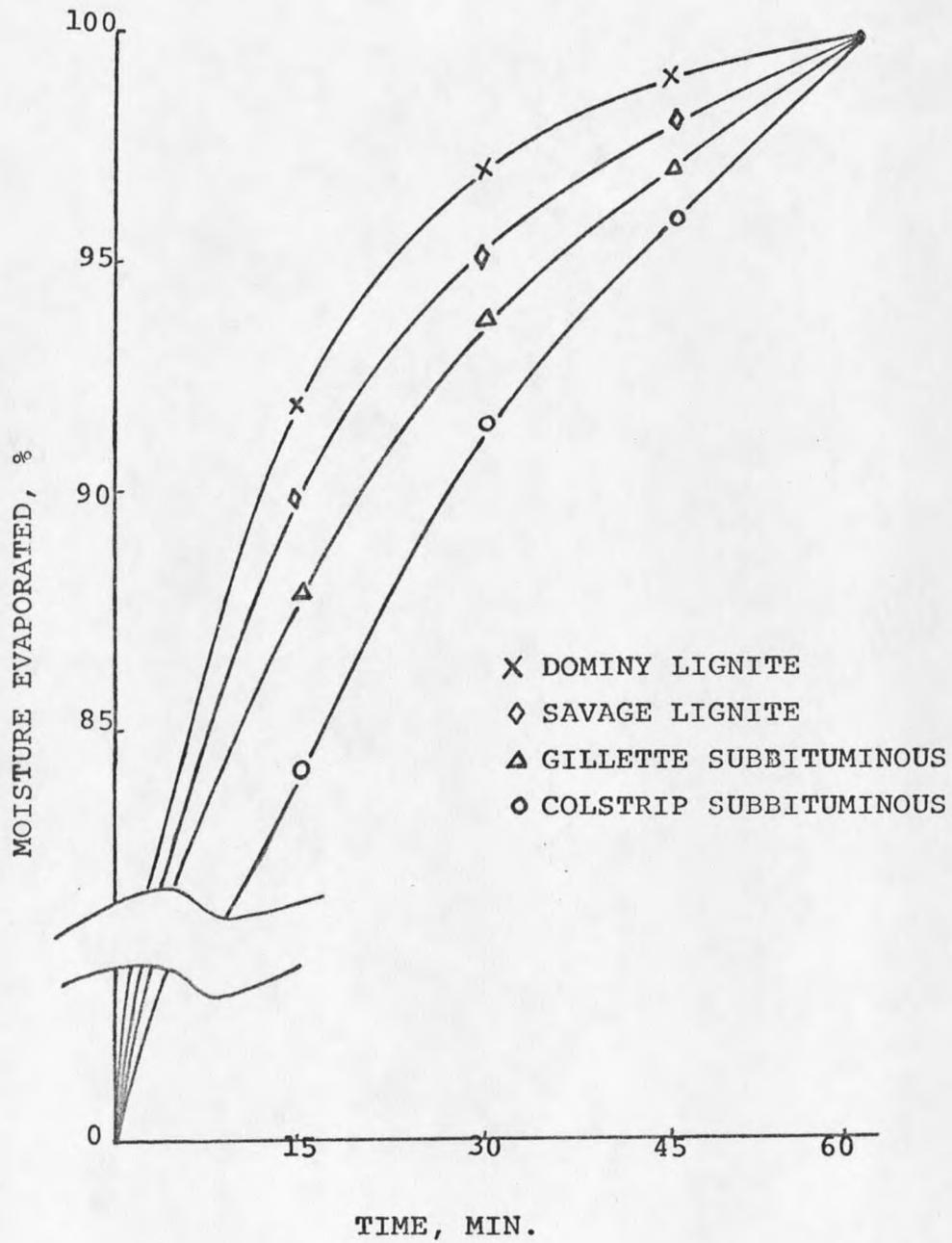*: On the basis of 1 gram sample (at 104 to 110°C)

Figure 2. Thermal Dewatering of Various Low-rank Coals

and then a falling rate period). These coal samples were all very small particles with large surface areas. So, the dewatering rate was greatly enhanced during the initial period. Then the drying rate decreased as a result of the decreasing wetted evaporation surface area. The nature of the coal substance and its characteristic release of moisture [1] became the major factors in the falling rate period of drying.

From his experiments, Agroskin [23] concluded that:

1. The coefficient of thermal conductivity of coals increased at higher moisture content.

2. The coefficient of thermal diffusivity of coals increased with moisture content, due to the simultaneous increase in the thermal conductivity and specific volume.

3. The coefficient of thermal conductivity of coals was appreciably affected by the ash content. Because the thermal conductivity of the organic matter was considerably lower than that of the ash, the coefficient of thermal conductivity increased with the ash content.

His conclusions could be applied to explain the experimental results of the thermal dewatering in this research:

1. Lignites showed faster dewatering rates than subbituminous coals due to higher moisture content.

2. Dominy lignite showed a faster dewatering rate than Savage lignite due to higher ash content.

Moisture Content of Corn Starch

The analysis results of moisture content of the corn starch powder are shown in Table 4. The statistical F-test in Table 5 confirmed the consistency of the results obtained by the three TAPPI analytical methods. So, any of these three methods could be used to check the moisture contents of corn starches purchased from a market.

Briquetted Products

The results of briquetted products are shown in Table 6. Unacceptable briquets are indicated in brackets. Sample data of drop tests of coal briquets are shown in Appendix A, which shows that the appropriate amount of corn starch binder is 5 wt.% but not 2 wt.%.

For the blank test (no binder was used), all the briquets were relatively brittle and unacceptable. So, briquetting of these low-rank coals without binder seemed to be improper. The shortcoming of briquetting without binder was also indicated by Gregory and other researchers [37]. The benefit of briquetting with binder was studied by Berkowitz [2], whose experiment is shown in Appendix B.

No. 6 fuel oil was a suitable binder, especially for

Table 4. Moisture Content of Corn Starch

Samples 1-5 by method 1: Dry a 2-gram sample 1 hour
at 130-135 C
Samples 6-10 by method 2: Dry a 2-gram sample 20
minutes at 150 C
Samples 11-15 by method 3: Dry an 1-gram sample 15
minutes at 150 C

Sample no.	Sample weight	Water weight	Water wt.%	Average wt.%	Standard deviation
1	2.0037	0.1703	18.5		
2	1.9960	0.1751	18.8		
3	1.9966	0.1796	19.0	18.6	0.0032
4	1.9911	0.1676	18.4		
5	2.0006	0.1646	18.2		
6	2.0000	0.1794	19.0		
7	2.0005	0.1702	18.5		
8	2.0001	0.1763	18.8	18.6	0.0031
9	2.0003	0.1693	18.5		
10	2.0000	0.1693	18.5		
11	1.0001	0.0824	18.2		
12	1.0001	0.0871	18.7		
13	0.9997	0.082	18.3	18.3	0.0025
14	0.9978	0.0801	18.1		
15	1.0000	0.0812	18.1		

Table 5. Statistical Analysis (F-test) for Moisture
Content of Corn Starch

Source	DF	SS	MS	F
Treatment	2	0.001	0.00005	0.156
Error	12	0.0038	0.000317	
Total	14	0.0039		

DF: Degree of Freedom

SS: Sum of Squares, MS: Mean of Sum of Squares

F: F-value = MSTr/MSE

MSTr: MS of Treatment, MSE: MS of Error

M1, M2, M3: Means of the three groups
(each with 5 treatments)

Test HO: M1 = M2 = M3 vs Ha: not all equal

For 95% confidence: F(0.95; 2,12) = 3.89

Rejection region: F > 3.89

Calculated F = 0.156 < 3.89

Do not reject H0

So, M1 = M2 = M3

The moisture contents obtained by these 3 methods
were the same.

Table 6. Briquetting Results of Different Binder Combinations and percentages*

Binder choice

	1	2	3	4	5	6	7	8
	B	F	S	C	F-S	F-C	S-C	F-S-C
		20	{20}	20	15-5	15-5	15-5	10-6-4
Binder		15	{15}	15	5-15	5-15	5-15	4-6-6
percentage		10	{10}	10	12-8	12-8	12-8	6-6-4
		8	{8}	8	8-12	8-12	8-12	6-4-4
		5	{5}	5	10-10	10-10	10-10	4-4-4
		{2}	{2}	{2}	8-6	8-6	8-6	4-2-4
					6-8	6-8	6-8	2-4-4
					5-5	5-5	5-5	4-4-2
					{2-2}	{2-2}	{2-2}	{2-2-2}

B: Blank (no binder)
F: Fuel Oil (No. 6)
S: Sulfate Liquor (Kraft)
C: Corn Starch

For example: F-S-C 6-4-4 means Fuel Oil 6 wt % plus
                              Sulfate Liquor 4 wt % plus
                              Corn Starch 4 wt % as a
                              combined binder.
* The {} sign indicates unsatisfactory results.

its strong binding ability [1, 2, 3]. In this research,
the weight percentage of fuel oil binder could be reduced
to 5 wt.%. An amount of 2 wt% was not sufficient to make
an acceptable briquet. This amount was too little to
agglomerate the coal powders. However, this Cenex no. 6
fuel oil contained 5 wt.% sulfur [4]. In consideration of
the accompanying environmental pollution due to the
addition of sulfur, this Cenex no. 6 fuel oil was not
appropriate to be used as a binder. If some other no. 6
fuel oil with no sulfur content was available, then, it
would be a very excellent binder.

The briquets made by kraft sulfate liquor binder were
powdery and fragile no matter how much of it was used. Its
binding ability was not effective for these low-rank coals.

Corn starch showed strong binding ability as a
briquetting agent. Corn starch used as a binder had some
obvious advantanges:

1. The operational procedures were relatively easy.

2. It did not contain any sulfur (no accompanying
   pollution).

3. It had strong binding ability [8, 11, 12].

4. It produced neither stinking odor nor fume.

Starch used as a coal briquet binder was reported [11, 14,
17], but no detailed procedures were described.

If the briquets made by the combined binder (e. g.,
fuel oil plus corn starch) had almost the same quality as

those made by the single binder, usually the single binder would be preferred because of the economic and operational considerations:

    1. Economic consideration

        The more ingredients the process used, the more managing (e. g., purchasing, stocking, distributing, maintaining, and supply-source diversities) problems would arise.

    2. Operational consideration

        The preparation of these three binders were different due to their different intrinsic properties. For example, no. 6 fuel oil was heated to at least 150°C (about 7 centistokes) [3] to let it become easily mixed with coal powders and corn starch paste was obtained by cooking starch aqueous solution at 80°C. If these two binders were used together, the complexity of operation was increased.

From the above discussion, corn starch was concluded to be the most suitable binder of the eight binder choices in Table 6, and 5 wt.% was the most proper binder amount.

In this research, no briquetting machine was available. The briquetting pressure from the hand press used was less powerful and might influence the quality of the briquets. In mechanics, the change in momentum in any finite interval is equal to the time integral of the force acting (i. e., impulse) [38]. Since no high pressure from briquetting