



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
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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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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.

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:

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

where P is pressure applied to compact,

V is compact volume at pressure P,

V_s 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 several 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°C , and a magnifying lens.
5. A stirrer connected with a motor.
6. An insulating wall (adiabatic jacket) surrounding

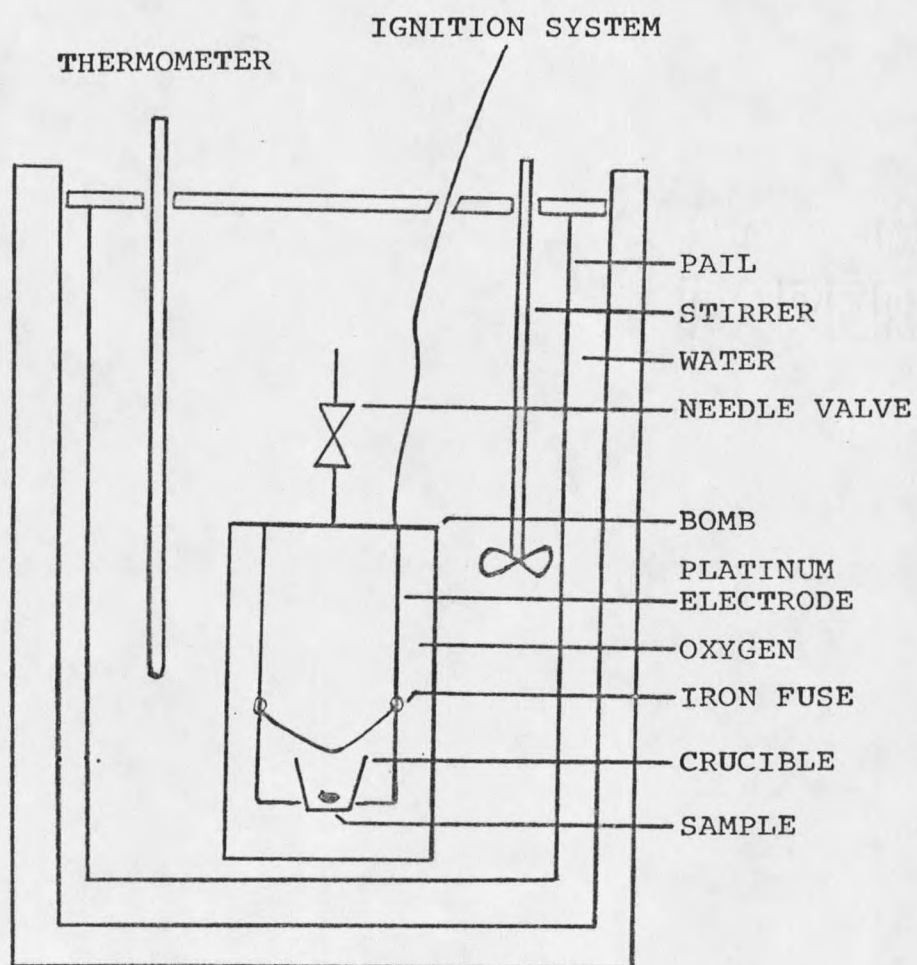


Figure 1. Calorimeter

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 hydraulic 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°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 lignite	0	0.352	0.000	0
	15	0.028	0.324	92
	30	0.011	0.341	97
	45	0.004	0.348	99
	60	0.000	0.352	100
Savage lignite	0	0.350	0.000	0
	15	0.035	0.315	90
	30	0.017	0.333	95
	45	0.009	0.341	98
	60	0.000	0.450	100
Colstrip subbituminous	0	0.140	0.000	0
	15	0.023	0.117	84
	30	0.013	0.127	91
	45	0.006	0.134	96
	60	0.000	0.140	100
Gillette subbituminous	0	0.279	0.000	0
	15	0.033	0.246	88
	30	0.017	0.262	94
	45	0.008	0.271	97
	60	0.000	0.279	100

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

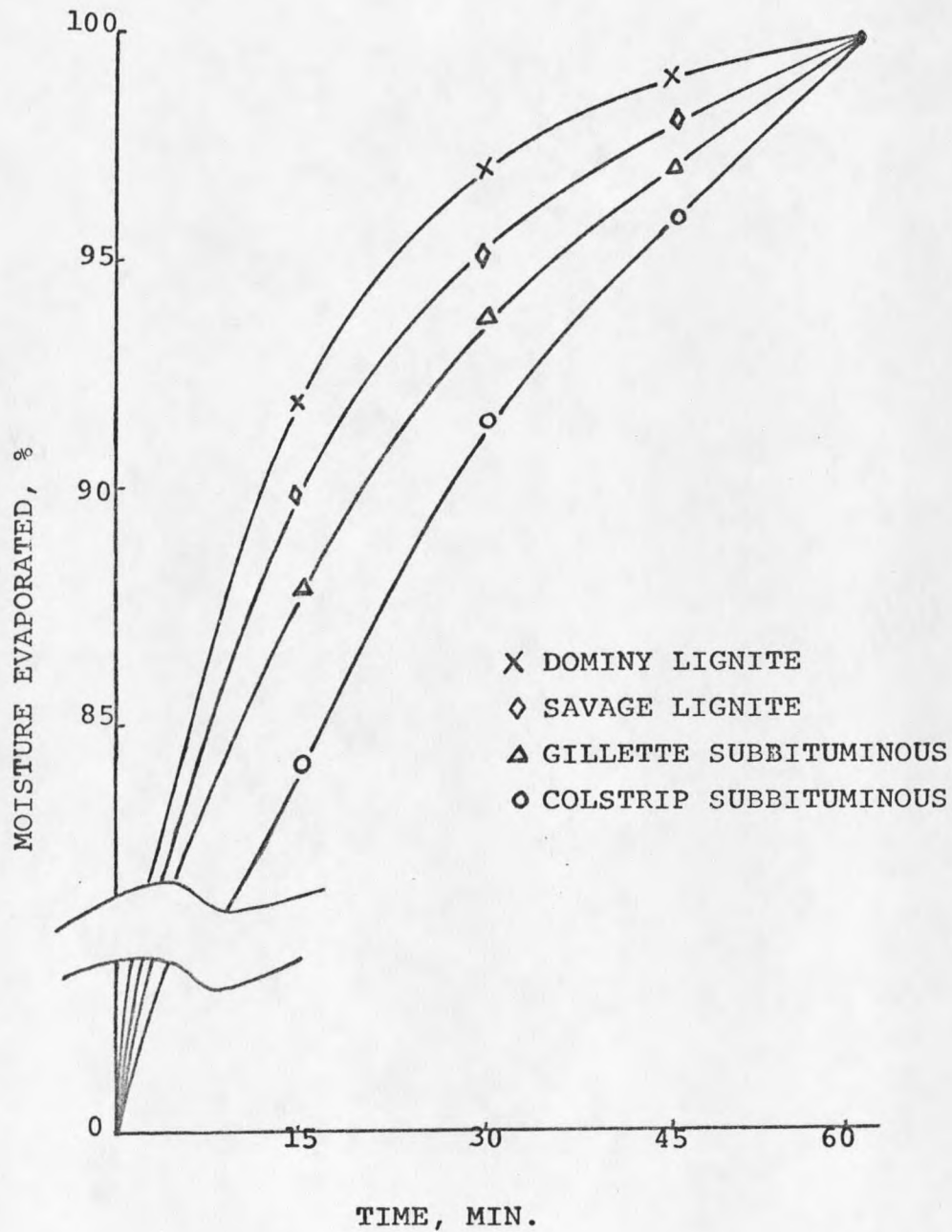


Figure 2. Thermal Dewatering of Various Low-rank Coals

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 $H_0: M1 = M2 = M3$ vs H_a : 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 H_0

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
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.

* 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 advantages:

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

machines was available, a longer briquetting period was necessary to compensate the smaller pressure produced by the hand press. This was consistent with the time factor in the briquetting theory.

Degree of comminution affected the quality of the briquetted products because of the packing density, mutual adhesion, and interparticulate contacts [2]. In this research, the size of pulverized coal powders was that which passed U. S. Standard No. 8 mesh (2.38 mm) sieve (generally used as the briquet size [1, 6, 7, 8, 15, 16]). Another size of coal powders, which passed U. S. Standard No. 60 mesh (0.25 mm) sieve, was also briquetted to compare the effect of degree of comminution. All these four low-rank coals of 0.25 mm size powders were briquetted with corn starch (95 wt.% dried coal and 5 wt.% corn starch). The briquets were subjected to the same quality checkings as those made of 2.38 mm size coal powders. All briquets of this contrasting size (0.25 mm) were found to be unsatisfactory. Berkowitz [2] mentioned this briquetting problem of too fine powders as extensive arching (elastic interlocking) of particles and unsatisfactory compactness would happen.

The temperature factor was important in the briquetting process. Coal powders should be heated to at least 80°C to prevent hot starch paste from setting into a gel and solidification of fuel oil before thorough mixing. Bennett

and other researchers [37] found that high temperature (above 360°C) would cause gas evolution of volatile content in coals. In this research, the maximum temperature used was 150°C .

Absorbed film influenced the quality of briquets. In consideration of the briquetting results obtained with corn starch, the chemical structures and biochemical phases [9, 24, 39, 40, 41] of coal and starch (e. g., hydrogen bonding, polymeric and hygroscopic properties), the ductility and wettability (bonding affinity) factors of the briquetting theory might be justified.

Calorific Values

Table 7 shows the energy equivalent factor of the calorimeter by benzoic acid and naphthalene. From this factor, the calorific values of samples could be calculated.

The calorific values and the descriptive statistics of these four low-rank coals on the as-received and dry bases are shown in Tables 8 and 9. Sample calculations are shown in Appendix C, which include the calorific values of coals and cost estimation of briquets (95 wt.% dried coal and 5 wt.% corn starch binder). For Dominy lignite, the cost of briquets would be cheaper than that of raw coal when the shipping cost was higher than \$38/Ton (\$37/Ton for Savage lignite, \$103/Ton for Colstrip subbituminous, and \$39/Ton

Table 7. Energy Equivalent Factor of the Calorimeter
and Descriptive Statistics

Calorific value of benzoic acid = 6318 cal/g [31]

Calorific value of naphthalene = 9613 cal/g [31]

	By benzoic acid	By naphthalene
1	1366	1371
2	1368	1375
3	1375	1363
4	1372	1360
Average	1370	1367
Range*	9	15
Standard deviation	4.0	6.9
Coefficient of variation**	0.3%	0.5%

*: Range = Maximum - Minimum

**: Coefficient of variation = Standard deviation/Average

Coefficient of variation is a measurement of
reliability in statistics.

Table 8. Calorimetric Results* of Various Low-rank Coals on the As-received and Dry bases

	1	2	3	4	Average
	(Btu/lb)				
Dominy lignite					
As-received	6750	6765	6780	6748	6761
Dry	10482	10445	10464	10437	10457
Savage lignite					
As-received	7085	7064	7062	7108	7080
Dry	10932	10973	10941	10956	10950
Colstrip subbituminous					
As-received	10071	10064	10050	10025	10052
Dry	11703	11733	11705	11740	11720
Gillette subbituminous					
As-received	8279	8313	8275	8311	8295
Dry	11411	11438	11453	11410	11428

*: By calorimetry method

Table 9. Descriptive Statistics of Calorimetric Results in Table 8

	Average (Btu/lb)	Range* (Btu/lb)	Standard deviation (Btu/lb)	Coefficient of variation (%)**
Dominy lignite				
As-received	6761	32	14.9	0.22
Dry	10457	45	20.1	0.19
Savage lignite				
As-received	7080	46	21.5	0.30
Dry	10950	41	18.0	0.16
Colstrip subbituminous				
As-received	10052	49	20.3	0.20
Dry	11720	37	19.0	0.16
Gillette subbituminous				
As-received	8295	38	20.2	0.24
Dry	11428	43	21.1	0.18

*: Range = Maximum - Minimum

According to ASTM D240, the acceptability of measurement results obtained with a bomb calorimeter (95% probability), i. e., the repeatability, is that duplicate results should be less than 55 btu/lb apart.

** : Coefficient of variation = Standard deviation/Average

Coefficient of variation is a measurement of reliability in statistics.

for Gillette subbituminous). A significant benefit of briquetting was its fulfillment for the industrial processes of higher calorific value requirements. Processes such as cement, elemental phosphorus, lead smelting, and iron reduction require a fuel of sufficient calorific value to attain the higher operating temperatures.

The calorific value of coal depends on the variation of moisture and ash contents. Coals are characterized by their heat contents referred to the combustible matter [23]. For low-rank coals, as the organic mass becomes higher in carbon, its calorific value goes up [23]. Referring to Tables 2 and 8, the magnitude of calorific values of coals was related to the amount of combustible matter. The calorific value of lignite was lower than that of subbituminous coal due to less carbon in organic mass and more moisture content.

Comparing the calorific values of coals on the as-received basis and dry basis in Table 8, the increases of calorific values after drying were obvious. In order to obtain high heat-content coals, dewatering and grinding (for efficient drying) were necessary. Then the problems of dusty powders (material loss and pollution) emerged. Dewatering and briquetting as means of upgrading coals were commonly adopted. For the industrial processes of higher calorific value requirements (e. g., steel mill), dewatered and briquetted coals became attractive fuels.

The calorific values and descriptive statistics of briquets (5 wt.% corn starch binder) are shown in Tables 10 and 11. Table 12 shows the comparison of the calorific values of coals (as-received basis) and those of briquets. Increases in calorific values are obvious. The higher the moisture content of coal, the more the increased percentage of the calorific value. In this research, the briquetted products (about 1.5-cm diameter and 0.5 cm height cylindrical shape) were put in an oven (at 104 to 110°C) about 5 hours in order to get dried briquets. Table 13 shows the calorific values of these briquets by calculation (i. e., the calorific value of dried coal multiplied by 0.95 plus the calorific value of corn starch multiplied by 0.05) and by calorimetry method (one gram sample in a calorimeter). In consideration of experimental errors, these briquets might be considered as dried.

In conclusion, the benefits of dewatering and briquetting of coals were:

1. Higher calorific value.
2. More easily handled fuel.
3. Less powder loss and non-dusty dried fuel.

Table 10. Calorimetric Results* of Low-rank-coal
Briquets**

	1	2	3	4
	(Btu/lb)			
Dominy lignite briquet	10324	10342	10318	10352
Savage lignite briquet	10789	10815	10794	10819
Colstrip subbituminous briquet	11514	11538	11543	11556
Gillette subbituminous briquet	11265	11246	11240	11276

*: All are by calorimetry method.

** : Every briquets contains 95 wt.% dried coal and
5 wt.% corn starch binder.

Table 11. Descriptive Statistics of Calorimetric Results in Table 10

	Average (Btu/lb)	Range* (Btu/lb)	Standard deviation (Btu/lb)	Coefficient** of variation (%)
Dominy lignite briquet	10,334	34	15.7	1.5%
Savage lignite briquet	10,804	30	14.9	1.4%
Colstrip subbituminous briquet	11,533	42	17.6	1.5%
Gillette subbituminous briquet	11,257	36	16.7	1.5%

*: Range = Maximum - Minimum

According to ASTM D240, the acceptability of measurement results obtained with a bomb calorimeter (95% probability), i. e., the repeatability, is that duplicate results should be less than 55 Btu/lb apart.

** : Coefficient of Variation = Standard deviation/Average

The coefficient of variation is a measurement of reliability in statistics.

Table 12. Increase Percentages of Calorific Values* after Briquetting

	Coal as- received (Btu/lb)	Briquet (95 wt.% dried coal & 5 wt.% corn Starch) (Btu/lb)	Calorific value increase (Btu/lb)	Calorific value increase percentage (%)**
Dominy lignite	6,761	10,334	3,573	52.8
Savage lignite	7,080	10,804	3,724	52.6
Colstrip subbituminous	10,052	11,533	1,481	14.7
Gillette subbituminous	8,295	11,257	2,961	35.7

*: All are obtained by calorimetry method.

**: The increase percentage is based on the calorific value of coal as-received.

Table 13. Comparison of Calorific Values of Briquets by Calculation* and by Calorimetry Method

Dried coal	95 wt. % dry coal	5 wt. % corn starch	Briquet by calculation	Briquet by calorimetry	% Difference**
(Btu/lb)					
Dominy lignite					
10457	9934	376	10310	10334	0.23
Savage lignite					
10950	10403	376	10779	10804	0.23
Colstrip subbituminous					
11720	11134	376	11510	11533	0.19
Gillette subbituminous					
11428	10857	376	11233	11257	0.21

*: Calorific value of starch = 7552 Btu/lb [10]
 Calorific value of briquet (by calculation)
 $= 0.95 * (\text{calorific value of dried coal})$
 $+ 0.05 * (\text{calorific value of corn starch})$

** : The percentage difference between the calorific values of briquet by calculation and by calorimetry method is based on the calorific value of briquet by calorimetry method.

SUMMARY AND CONCLUSIONS

1. Four local low-rank coals (Dominy lignite, Savage lignite, Colstrip subbituminous, and Gillette subbituminous) from Montana and Wyoming mines were studied. Proximate analyses showed high moisture content of these coals, especially lignites (up to 35 wt.%). These low-rank coals had lower fixed carbon contents than high-rank coals due to less metamorphic changes.
2. Thermal dewatering characteristics of these four coals were examined. The results were consistent with the drying theory and the thermal coefficients of coals obtained by Agroskin [23].
3. Three materials (Cenex no. 6 fuel oil, Champion kraft sulfate liquor, and corn starch) were examined as possible binders for these coals. Eight binder combinations, fifty-five treatments (different percentages), and five replications in each treatment were the experimental scheme to determine the best binder, briquet composition, and operational procedures.
4. Cenex no. 6 fuel oil showed good binding ability, but it was rejected due to its sulfur content and

accompanying environmental pollution.

5. Champion kraft sulfate liquor was rejected due to its weak binding ability.
6. Corn starch was found to be an appropriate binder for these coals. It had the advantages of strong binding ability, sulfur-free, ample supply, and cheap price.
7. Three analysis methods proposed by TAPPI to check the moisture content of corn starch were performed and their consistency was confirmed by statistical ANOVA F-test.
8. Briquetting procedures with corn starch were fairly easy. Corn starch aqueous solution (1 part starch and 10 parts water) was cooked at 80°C with constant agitation for 10 to 12 minutes to form starch paste. After thorough mixing, the resultant mass was briquetted and dried. The best briquet contained 95 wt.% dried coal and 5 wt.% corn starch.
9. Briquetting variables of pressure, temperature, time, degree of comminution, film-forming material, and nature of binder influenced the quality of briquets.
10. The calorimetry method was used to determine the calorific value of coals (on the as-received and dry bases) and briquets.
11. The calorific value of coal was influenced by its

moisture content (detrimental factor) and
combustible matter content (favorable factor).

12. Dewatering and briquetting as means of upgrading of coals resulted from the higher heat content of dried coals and the dust reduction.
13. The increase percentage of calorific value through dewatering and briquetting increased with the moisture content of the raw coal. The increase percentages ranged from 14.7% to 52.8%.
14. The benefits of dewatering and briquetting of coals were the higher calorific values, easier handling, less loss and non-dusty fuels.

RECOMMENDATIONS FOR FUTURE RESEARCH

1. For physical testing of coal briquets, there are no generally accepted standards [2, 6, 7, 12, 42]. The compression strength test with Komarek-Greaves tester is used widely. It would seem to be desirable to have this apparatus to do the test.
2. One shortcoming of the briquet made by corn starch binder is its weak weather resistance. One solution to overcome this is the coating of a weather resistant material on the briquet. This needs further study.

APPENDICES

APPENDIX A

DROP TEST OF COAL BRIQUETS

DROP TEST OF COAL BRIQUETS

Drop tests of Colstrip subbituminous briquets were performed (smooth concrete floor) with 5 briquets dropped 3 times each. W and W' are briquet weights before and after dropping. L is the amount of loss after dropping.

1. Briquets are 95 wt.% dried coal and 5 wt.% corn starch shown in Table 14:

Table 14. Drop Test of Coal Briquets

24-inch height					36-inch height			
Sample	W(g)	W'(g)	L(g)	L(%)	W(g)	W'(g)	L(g)	L(%)
1	1.80	1.78	0.02	1.0	1.78	1.76	0.02	1.0
2	1.57	1.56	0.01	0.6	1.56	1.55	0.01	0.6
3	1.07	1.06	0.01	0.9	1.06	1.05	0.01	0.9
4	1.45	1.45	0.00	0.0	1.45	1.44	0.01	0.7
5	1.67	1.66	0.01	0.6	1.66	1.64	0.02	1.0
6	1.35	1.33	0.02	1.5	1.33	1.31	0.02	1.5
7	1.39	1.39	0.00	0.0	1.39	1.37	0.02	1.0
8	1.55	1.54	0.01	0.6	1.54	1.53	0.01	0.6
9	1.17	1.17	0.00	0.0	1.17	1.16	0.01	0.8
10	1.33	1.32	0.01	0.8	1.32	1.31	0.01	0.8
Loss average			:	0.6%	0.9%			

The briquets tested above were considered to be acceptable.

2. Briquets are 98 wt.% dried coal and 2 wt.% corn starch:

All these briquets broke into shattered pieces and failed the drop test.

APPENDIX B

BENEFIT OF BRIQUETTING
WITH BINDER

BENEFIT OF BRIQUETTING WITH BINDER

Berkowitz [2] did experiments and showed that even a very small amount of suitable binder would be capable of increasing the strength and stability of briquets as shown in Table 15:

Table 15. Benefit of Briquetting with Binder

Briquet	Briquet strength (psi)	Strength increase (%)
Blank	2,000	-
0.2 wt.% Pyridine	7,900	300
0.5 wt.% Fuel oil	7,020	250

APPENDIX C

SAMPLE CALCULATIONS

SAMPLE CALCULATIONS

The sample calculations are based on Dominy lignite and include the calorific value of coal as-received in a calorimeter and cost estimation of raw coal and briquet (95 wt.% dried coal and 5 wt.% corn starch binder).

All the calorific values are obtained by the calorimetry method. The costs of coals at mine (\$/T) are given by the coal companies.

1. Calorific Value of Dominy Lignite (As-received)

Calculated from Table 16:

a = time of firing
= 0.0 (min.)

b = time (to the nearest 0.1 min.) when the temperature reaches 60% of the total rise**
= 6.8 - 5.0 = 1.8 (min.)

c = time at beginning of period (after the temperature rise) in which the rate of temperature change has become constant
= 13.0 - 5.0 = 8.0 (min.)

Ta = temperature at time of firing (corrected for thermometer scale error)
= 72.377 (°F)

Tc = temperature at time c (corrected)
= 75.109 (°F)

R1 = rate (temperature units per minute) at which temperature is rising during the 5-min. period before firing
= 0.0 (°F)

Table 16. Temperature Change in a Calorimeter
for Dominy Lignite (As-received)

Time (min.)	Calorimeter temperature (°F)	+ Temperature correction (°F)	= Actual temperature (°F)
1	72.351	0.026	72.377
2	72.351	0.026	72.377
3	72.351	0.026	72.377
4	72.351	0.026	72.377
5	72.351	0.026	72.377
6	73.300	0.029	73.329
7	74.400	0.032	74.432
8	74.840	0.033	74.873
9	74.980	0.034	75.014
10	75.050	0.034	75.084
11	75.070	0.034	75.104
12	75.076	0.034	75.110
13	75.076	0.034	75.110
14	75.076	0.034	75.110
15	75.076	0.034	75.110
16	75.076	0.034	75.110

R2 = rate (temperature units per minute) at which
temperature is falling during the 5-min. period
after time c
= 0.00025 (°F)

w = energy equivalent of the calorimeter
= 1367 (cal/°F)

m = sample weight

$$= 0.9915 \text{ (gram)}$$

$$\begin{aligned} L &= \text{length of iron fuse consumed in firing} \\ &= 5.0 \text{ (cm)} \end{aligned}$$

$$\begin{aligned} e &= \text{heat of combustion of iron fuse} \\ &= 2.3 \text{ cal/cm} \end{aligned}$$

Net temperature rise:

$$\begin{aligned} t &= T_c - T_a - R_1(b - a) + R_2(c - a) \\ &= 2.733 \text{ (}^\circ\text{F)} \end{aligned}$$

Gross heat of combustion:

$$\begin{aligned} H_g &= (t * w - 2.3 * L) / m \\ &= 3750 \text{ (cal/g)} \\ &= 6750 \text{ (Btu/lb)} \end{aligned}$$

**: This is the radiation correction which comes from ASTM D240 and D3286 [29, 31]. For calculation of the heat gain or loss from calorimeter, the point of transition from the period of heat gain to the point of heat loss occurs at a point of time when the temperature rise has reached 60% of its total amount. During the time period in which six-tenths of the temperature rise occurs, the calorimeter is being heated by its surroundings at a rate equivalent to that determined by observations made during the 5-min. preliminary period. But during the time in which the remaining four-tenths of the temperature rise occurs, the calorimeter is being cooled at a rate equal to that determined in the final 5-min. period.

2. Cost Estimation of Briquet (95 wt.% Dried Dominy Lignite and 5 wt.% Corn Starch)

Drier calculation:

$$2000 \text{ lb/T} \times 65\% \text{ dried} = 1300 \text{ lb/T}$$

$$2000 \text{ lb/T} - 1300 \text{ lb/T} = 700 \text{ lb/T}$$

$$700 \text{ lb/T} \times 1050 \text{ Btu/lb} = 735000 \text{ Btu/T}$$

$$\begin{aligned} \text{Heating value of lignite} &= 6761 \text{ Btu/lb} \\ &= 13522000 \text{ Btu/T} \end{aligned}$$

At heating efficiency of 75%, the amount of
lignite required for drying =

$$735000 / (13522000 \times 75\%) = 7.2\% \text{ lignite}$$

Total cost (\$/T):

$$\text{Lignite, 1 ton @ \$12.0} \text{ ----- } \$12.00$$

$$\text{Lignite burned in drier: } \$12.0 \times 7.2\% \text{ --- } \$0.86$$

$$\text{Corn starch @ \$100/T, 5\% required} \text{ ----- } \$3.42$$

$$\text{Processing cost, \$10/T [43]} \text{ ----- } \$10.00$$

$$\text{Total} \text{ ----- } \$26.28$$

Cost of the briquet at mine:

$$\begin{aligned} &\$26.28 \times 2000 / (1300 + 64) / 10334 / 2000 \\ &= \$1.86 \text{ per million Btu} \end{aligned}$$

Cost of coal at mine:

$$\begin{aligned} &\$12.0 / (6761 \times 2000) / 1000000 \\ &= \$0.89 \text{ per million Btu} \end{aligned}$$

A. When the shipping cost = \$30/T:

$$\begin{aligned} \text{cost of raw coal} &= \$30 / 6.761 / 2 + 0.89 \\ &= \$3.11 \text{ per million Btu} \end{aligned}$$

$$\begin{aligned} \text{cost of briquet} &= \$30 / 10.334 / 2 + 1.86 \\ &= \$3.31 \text{ per million Btu} \end{aligned}$$

B. When the shipping cost = \$40/T:

$$\text{cost of raw coal} = \$40 / 6.761 / 2 + 0.89$$

= \$3.85 per million Btu

cost of briquet = $\$40/10.334/2 + 1.86$
= \$3.79 per million Btu

C. When the shipping cost = \$38/T:

cost of raw coal = $\$38/6.761/2 + 0.89$
= \$3.70 per million Btu

cost of briquet = $\$38/10.334/2 + 1.86$
= \$3.70 per million Btu

The delivered cost of the briquet would be cheaper than raw coal when the shipping cost is higher than \$38/T.

Table 17 shows the summary results:

Table 17. Cost of Briquets (Including Shipping)

	Dominy lignite	Savage lignite	Colstrip subbitu- minous	Gillette subbitu- minous
Cost of coal at mine (\$/T)	12.0	14.13	16.0	13.54
Cost of coal at mine (\$ per million Btu)	0.89	1.0	0.80	0.82
Cost of briquet (\$ per million Btu)	1.86	1.89	1.45	1.44
Shipping cost to give the same cost of raw coal and briquet	\$38/T	\$37/T	\$103/T	\$39/T

All these four kinds of briquets of raw-rank coals (at the mine) are cheaper than the current price of natural gas (\$5 per million Btu).

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