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URBANA

BULLETIN NO. 72

BRIQUETTING ILLINOIS COALS WITHOUT BINDER

BY

R. J. PIERSOL

AUG. 26TH 1818

PRINTED BY AUTHORITY OF THE STATE OF ILLINOIS

URBANA, ILLINOIS

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Topographic Mapping in Cooperation with the United States Geological Survey.
This report is a contribution of the Physics Division.

August 31, 1947

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PREFACE

A PROGRAM of research into the making of smokeless briquets from Illinois coal was initiated by the Illinois State Geological Survey in 1931, and this pioneering investigation has been in continuous progress since that time. These briquetting studies have advanced through two phases of development, the laboratory-scale stage from 1931 to 1939 and the pilot-plant stage from 1939 to 1946. A number of reports upon the former have been issued, as follows.

Piersol, R. J., Briquetting Illinois coals without a binder by compression and impact: Illinois Geol. Survey Rept. Inv. 31, 1933.

———, Briquetting Illinois coals without a binder—second report of laboratory investigation: Illinois Geol. Survey Rept. Inv. 37, 1935.

———, Smoke index: a quantitative measurement of smoke: Illinois Geol. Survey Rept. Inv. 41, 1936; reprinted in Fuel in Science and Practice, vol. 15, nos. 9, 10, 11, 12, 1936.

———, Smokeless briquets: impacted without binder from partially prevolatilized Illinois coals: Illinois Geol. Survey Rept. Inv. 41, 1936.

———, Smoke index: Proc. 34th Ann. Convention of Smoke Prevention Assn. of America Inc., p. 20, 1940.

———, New data in regard to burning Illinois coal in hand-fired furnace: Proc. 35th Ann. Convention of Smoke Prevention Assn. of America Inc., p. 33, 1941.

———, New information on coal in the field of physics: Illinois Geol. Survey Bull. 68, pp. 50-57, 1944.

———, Theoretical physics and pioneering research in Illinois Minerals: Trans. Illinois Acad. Sci., vol. 38, pp. 88-94, 1945.

In this report the term "smokeless," when applied to the combustion of coal or coal products, is used according to its commercial definition. A natural smokeless coal may be defined as a coal which contains 23 percent or less of volatile matter, or as a coal which produces a smoke density of Ringlemann No. 2 or less when burned in a conventional hand-fired furnace. It follows that a commercially smokeless briquet is a briquet which burns with no greater liberation of smoke than that of natural smokeless coal.

The laboratory-scale investigations led to the discovery that firm smokeless briquets can be made, at least on such a scale, from Illinois coal, without the addition of binder, by the impact method. There was also developed an original smoke-index laboratory method for precise quantitative determination of the smoke produced by a fuel, followed by three significant discoveries: (1) Briquets made without binder were found to possess a lower smoke-index than the coal from which they were made; (2) the smoke producing component in coal was known from work by Parr to be the low-temperature fraction of the volatile matter, and it was found that partial prevolatilization prior to briquetting gave a relatively high-volatile briquet with a smoke-index lower than that of Pocahontas coal; and (3) a fine size of coal with a concentration of approximately 15 percent fusain was found to produce a briquet which without volatilization had a lower smoke-index than that of Pocahontas coals, provided it was made without binder or with a smokeless binder.

These discoveries of product, process and equipment for making smokeless briquets have been protected by patents for the benefit of the people of the State of Illinois, as follows.

U. S. Patent No. 2-021-020, Method of briquetting coal, granted Nov. 12, 1935, and corresponding Canadian Patent No. 358-755, June 13, 1936.

U. S. Patent No. 2-119-243, Briquetting presses, granted May 31, 1937, and corresponding Canadian Patent No. 384-362, granted Oct. 3, 1939.

U. S. Patent No. 2-321-238, Smokeless briquets, granted June 8, 1943.

Mathematical deductions, supported by laboratory tests, established certain necessary conditions that must be met in the design of the new unconventional type of press especially constructed, along with a preheater, for briquetting without binder on a commercial scale. Search was made for a conventional type of press which most nearly met the requirements of making a binderless briquet. The conventional roll presses for briquetting coal with binder lack a tightly confined die. The conventional mechanical and hydraulic presses, for forming cold-pressed ceramic bricks and various types of plastics, possess the necessary tightly confined die and the necessary pressure but lack the production capacity per unit cost. Impact presses of the steam-hammer or falling-weight type provide satisfactory briquetting operations but the operating life of the dies is unsatisfactory due to the violent impact. The type of press which seemed most nearly to meet the condition was the rotary type with eccentrically placed rolls. This basic type was therefore selected as offering the most promise of successful adaptation to the special requirements.

The need of a pilot-plant demonstration of the production of smokeless briquets from Illinois coal became urgent in 1939 because of impending smoke legislation against the use of high volatile coal for hand-fired domestic heating in St. Louis. The effect of such legislation would be to greatly curtail the use of high volatile Illinois coal in that city. As a result, the Sixty-First General Assembly of Illinois made a special appropriation, under House Bill No. 577, of $95,000 for the construction of an Applied Research Laboratory, $60,000 for the briquetting machine, preheater, and accessory equipment, and $25,000 for salaries and travel for two years.

Starting in July 1939, the pilot-scale briquetting equipment was designed and detailed shop drawings were made by the Survey, and the equipment was built by the J. P. Devine Manufacturing Company, Inc., of Mt. Vernon, Illinois. The press was delivered and installed in December 1940 in the Survey Laboratory. The preheater was completed, delivered, and installed in December 1941.

This report consists of eight sections. For convenience, the final results are given in the first section and various aspects of the research problem are taken up in the later articles.

BRIQUETTING ILLINOIS COALS WITHOUT BINDER

BY

R. J. PIERSOL

ARTICLE 1—DESIGN AND OPERATION OF COMMERCIAL-SCALE EQUIPMENT

Construction of the commercial-scale equipment for briquetting Illinois coal without a binder followed experimentation with small-scale equipment which extended over a period of eight years. As happens commonly during transition from laboratory-scale to production-scale equipment, new problems presented themselves having to do with automatic operation of the equipment. As it will be seen later in this article, many of these development problems have been solved in the first large-scale briquetting press described here. However, certain remaining problems are recognized and their solutions are suggested in the proposed improved briquetting press.

The first article describes the demonstration press and the procedures and development of the briquetting process, and also briefly outlines the steps in the exploratory development of the briquetting process using the commercial-scale equipment. The discussion includes (a) a brief summary of the design requirements for a press to briquet Illinois coal without use of a binder; (b) an evaluation of the various standard types of briquetting devices used in briquetting coal without a binder; (c) a description of the Piersol press as finally constructed; (d) an account of experiences in operating the machine using preheated coal; (e) an account of experiences in operating the machine using coal at room temperatures; and (f) proposed desirable changes in the Piersol press for use with preheated or unheated coal, or with only preheated coal.

The physical and mathematical considerations that influenced the design and construction of the commercial-scale machine are set forth in following articles.

DESIGN REQUIREMENTS

The requirements of a briquetting press are determined by the findings of laboratory-scale research and by mathematical analysis of the physical laws governing the relationship between quality of the briquet, the briquetting pressure, temperature, and time of application of pressure. These requirements, briefly stated, are as follows:

(1) A tightly confining system of dies. This is necessary in order to prevent extrusion of the fluid coal between the die walls.

(2) Exclusive primary pressure. This is important because secondary pressures following the application of the maximum pressure (while the briquet is still in the die) tend to shear or shatter the briquets.

(3) A uniform feeding device. Irregular feeding causes variation in density and hardness of the briquets.

(4) A pressure system that permits gradual uniform increase in pressure. This permits the essential close tolerance in the die material which probably could not be maintained under conditions of repeated impact, each of which is equivalent to steady pressure of 30,000 lbs. per sq. in. at a temperature of 400°C.

(5) Rapid production. This is best accomplished by a rotary type of press, because of the waste action involved in the operation of any press of the reciprocating type.

CONVENTIONAL BRIQUETTING PRESSES

The final choice of a press for briquetting Illinois coal without additional binder was preceded by thorough canvassing of the field representing equipment that has been used for briquetting bituminous coal and lignite without the use of a binder. However, so far as known none of these devices has been successful in the large-scale briquetting of bituminous coal.

These types include: the conventional roll press; the eccentric rotary press; the rotary press with two rings inclined at an angle; the hay-baler type of press; and the extrusion press.

Conventional Roll Press

A conventional roll press[1] is being used on small-scale operation to briquet, without binder, fuel pellets from Canadian bituminous coal. The press has a capacity of 4 tons per hour. It consists of two rolls, 23.5 inches in diameter and 13 inches wide, operating at from 5 to 8 r.p.m. The pellets are about ¾ inch in size.

The conventional roll press fails to confine the coal. At higher pressures, the coal tends to extrude forward and backward from the position of least spacing between the two rolls and thus limits the pressure to which coal may be subjected. The effective pressure may be increased either by making very small briquets or by using rolls of very large diameter. For economic operation, it is not desirable to go to large rolls (e.g. 20 feet in diameter) or very small pellets (e.g. less than an inch in size). Thus the conventional roll press does not provide sufficient pressure for making commercial size briquets (2 inches or over) without binder from bituminous coal.

Eccentric Rotary Press

Presses of the eccentric rotary type have been made by Jenkins[2] (1921), Apfelbeck[3] (1927), and Hasing[4] (1933). So far as is known, the Apfelbeck press is the only one that has been put into commercial operation and this only for making briquets without binder from brown coal. The outer ring of the Apfelbeck press consists of two parts which form a trough that becomes wider after passing the position of maximum compression; and the eccentric inner ring acts as a circular plunger, forming a ribbon briquet 1.5 inches wide and 1.2 inches thick, the ribbon being notched at 2.5 inch intervals in order to facilitate breaking the ribbon into individual briquets. Prior to the war, samples of Illinois coal were sent to Apfelbeck in Germany for briquetting tests; he reported that he found it necessary to add two percent asphalt binder in order to briquet these samples of coal in his press.

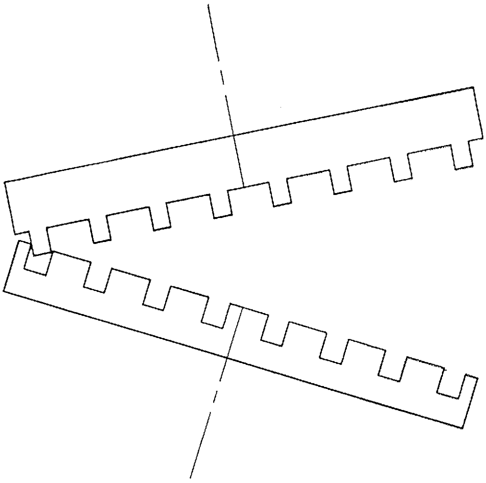

Fig. 1.—Laring briquetting press.

Although the Apfelbeck design of the eccentric rotary press is not satisfactory for briquetting Illinois coals without a binder, the basic principle of an eccentric press may be used in the design of a satisfactory press. The Apfelbeck design does not work on Illinois coal because the diameter of the inner roll is too small as compared with the outer roll, so that the coal is not confined, and because the cavities prevent the backward and forward extrusion of individual briquets.

Rotary Press with Two Rings Inclined at an Angle

A rotary press with two rings inclined at an angle (fig. 1 shows schematic view) was designed by Laring,[5] but so far as known it was never put into operation. Later on, and doubtless independently, an

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[1] High pressure coal briquetting machine. Engineering (British) February 25, 1944.

[2] Jenkins, C. D., Briquetting press: U. S. Patent No. 1-376-096, April 26, 1921.

[3] Apfelbeck, H., Presses for making briquets: U. S. Patent No. 1-620-621, March 15, 1927.

[4] Hasing, F. W., Briquetting machine: U. S. Patent No. 1-931-759, October 24, 1933.

[5] Laring, H. G., Coal briquet machine: U. S. Patent No. 1-752-644, April 1, 1930.

experimental press of this type was built by the J. I. Case Company and placed in operation at the Pugh Coal Company at Racine, Wisconsin. The press consists of a lower circular plate which has a series of 3-inch circular die cavities and an upper circular plate, inclined at an angle, which has a series of 3-inch circular plungers that enter into the cavities as the two plates rotate synchronously with each other. The press makes briquets without binder from Pocahontas screenings ground to minus 8-mesh and heated to slightly more than 100° C. to expel the moisture. The press has a capacity of 1.5 tons per hour; the briquets weigh about ¼ pound each. Their mechanical strength is sufficient for local delivery.

The Laring type of press does not provide positive confinement of the coal owing to the fact that the diameter of its cylindrical plungers is, of necessity, considerably less than that of the cylindrical die cavities.

HAY-BALER TYPE OF PRESS

The hay-baler type of press, which is the most commonly used in Germany for briquetting brown coal without binder, is usually referred to as a knuckle or elbow press. A charge of coal is rammed into a die, rectangular in cross-section, about 2 inches by 6 inches in size, at a pressure of about 30,000 pounds per sq. in. The die is slightly tapered to produce a resisting pressure as successive charges of coal are rammed forward in the die; the briquets have parting planes between the individual charges and therefore break apart as they emerge from the tapered open end of the die. The briquets usually are about 2 inches thick and weigh about 1.5 pounds each.

This type of press has proved to be commercially suitable for briquetting German brown coal without an added binder owing to the fact that such coal has a more or less fibrous texture similar to that of peat which contributes to the formation of strong briquets. However, the higher rank coals, such as bituminous coals, lack this fibrous texture and therefore this type of press has not proved satisfactory for their briquetting without an added binder.

EXTRUSION TYPE OF PRESS

A large amount of experimental work has been done on various extrusion types of presses for making coal briquets without binder. The coal is forced through a tapered orifice by means of an auger in a manner similar to that of a continuous press for making bricks from clay. As yet, this type of press has not been altogether successful for use in making coal briquets, and perhaps its intrinsic limitations will prohibit its ultimate success for use either with or without binder.

Attempt to briquet Illinois coal without binder in the Survey laboratories by the extrusion method showed lack of promise owing to the instability of the process. The pressure of extrusion for a ¼-inch diameter orifice would build up to more than 100,000 pounds per sq. in. without forward motion of the material through the tapered nozzles until a point of instability was reached at which the material jetted outward through the nozzle, reducing the pressure of extrusion to values as low as 30,000 pounds per sq. in., and then the cycle would be repeated. Attempts failed to secure either a uniform rate of flow of extruded coal or a uniform extrusion pressure. It appears that this instability is due to the nonhomogeneous texture of coal as contrasted to the homogeneous texture of true plastics. Furthermore, the dynamic friction of coal against the inner surface of the nozzle is doubtless much less than that of the static friction, thereby furthering the instability of extrusion. This condition of instability may well be an intrinsic limitation to commercially briquetting coal without binder, and perhaps with binder, by means of an extrusion method.

PIERSOL PRESS[6]

After consideration of the characteristics and results obtained by the various types of presses used in briquetting coal and lignite without a binder, and after reaching the decision that none would meet the requirements of a successful press for making briquets from Illinois coal without use of a

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[6] Piersol, R. J., Briquetting press: U. S. Patent No. 2-119-243, May 31, 1938.

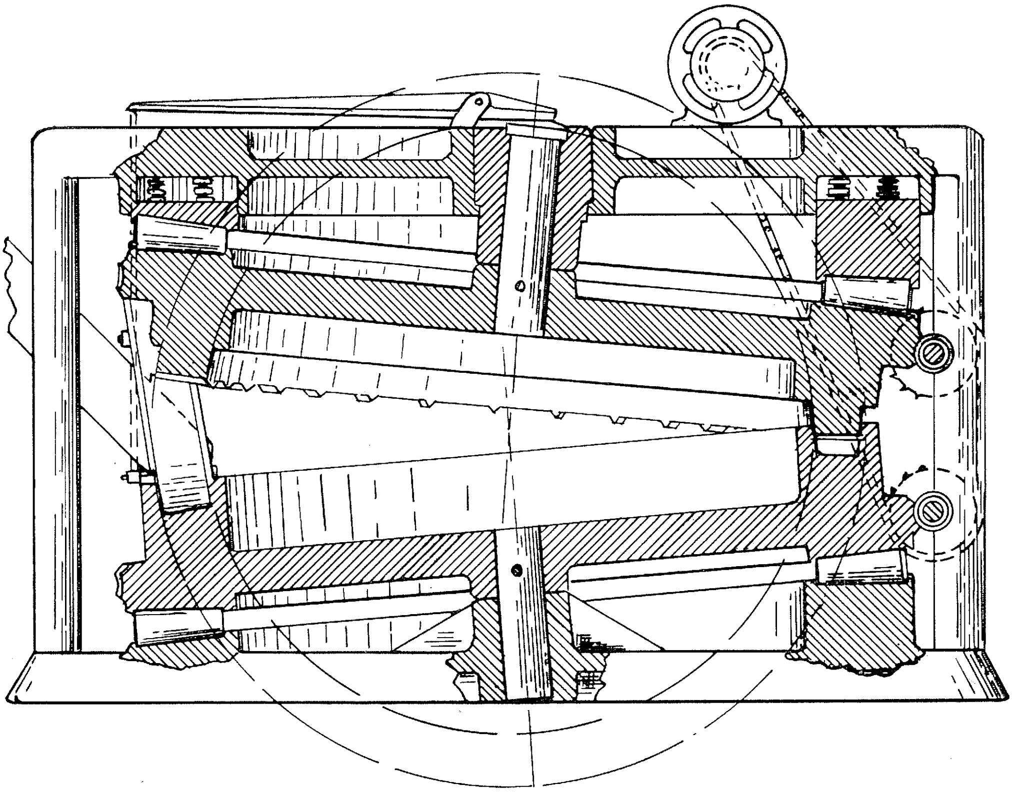

FIG. 2.—Early design of the Piersol briquetting press.

binder for reasons that have been given, it became necessary to design a special form of press or to make a special adaptation of one of the standard types to meet these requirements.

DESCRIPTION OF PRESS

The Piersol briquetting press is still in the process of development. The design passed through an early preliminary stage before it reached its general present form in which the experimental work has been done. As a result of experiences with the press, concepts have developed upon the basis of which it is believed that a still more satisfactory design can be worked out.

The general requirements of a successful briquetting press were believed to have been met in the initial design (fig. 2) but incidental, although important, mechanical requirements made necessary radical modification of that design, which was never constructed in its initial form. The early exploration of designs were fruitful mainly in establishing the necessity of using standard sizes of rolling-mill bearings in the construction of the press, inasmuch as pressures up to a million pounds would be required.

The critical and essential feature of the Piersol press (figs. 3, 4, and 5) as finally constructed and installed is the use of a heavy outer ring or roll, a heavy inner ring or roll set eccentrically, and backed up by a heavy backing roll through which the pressure is applied. The ring containing the outer die is set inside the outer roll, and the ring containing the inner die is set on the outside of the inner roll. The inside diameter of the outer die and the outside diameter of the inner die are 45 and 37 inches, respectively, with centers 3 inches apart. In order to obtain a more positive confinement of coal in the Piersol press than that obtained in the Apfelbeck press, the eccentricity of the former (fig. 6) is very much less than that of the latter (fig. 7).

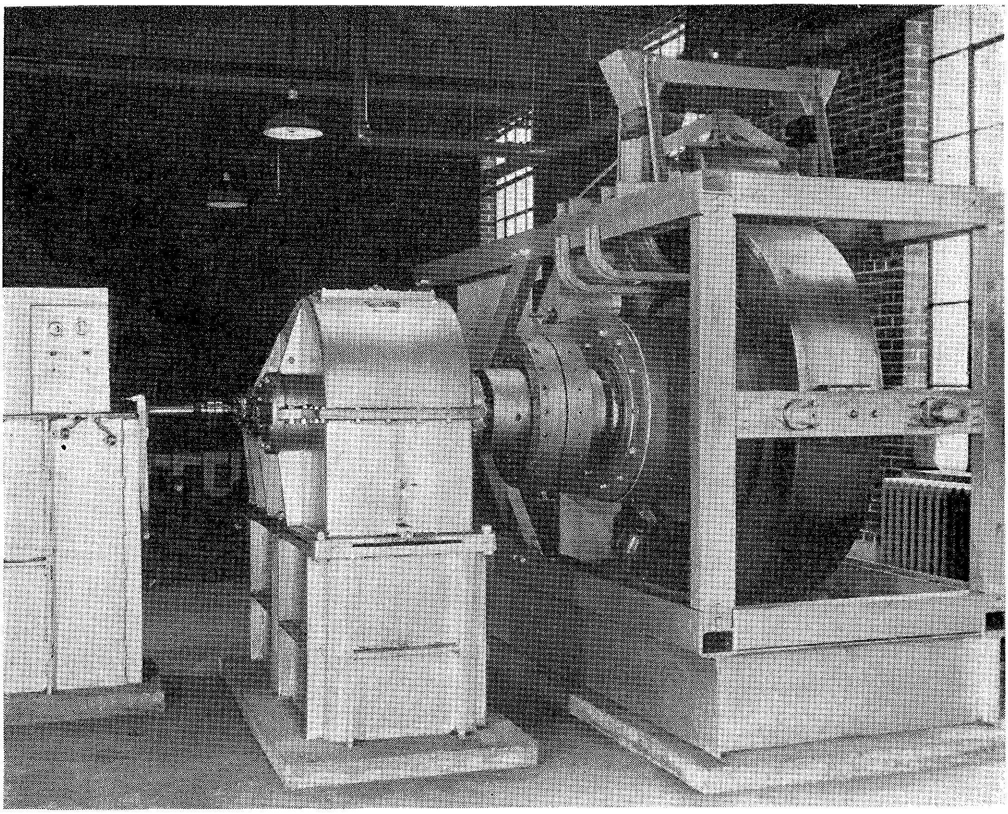

FIG. 3.—Piersol briquetting press.

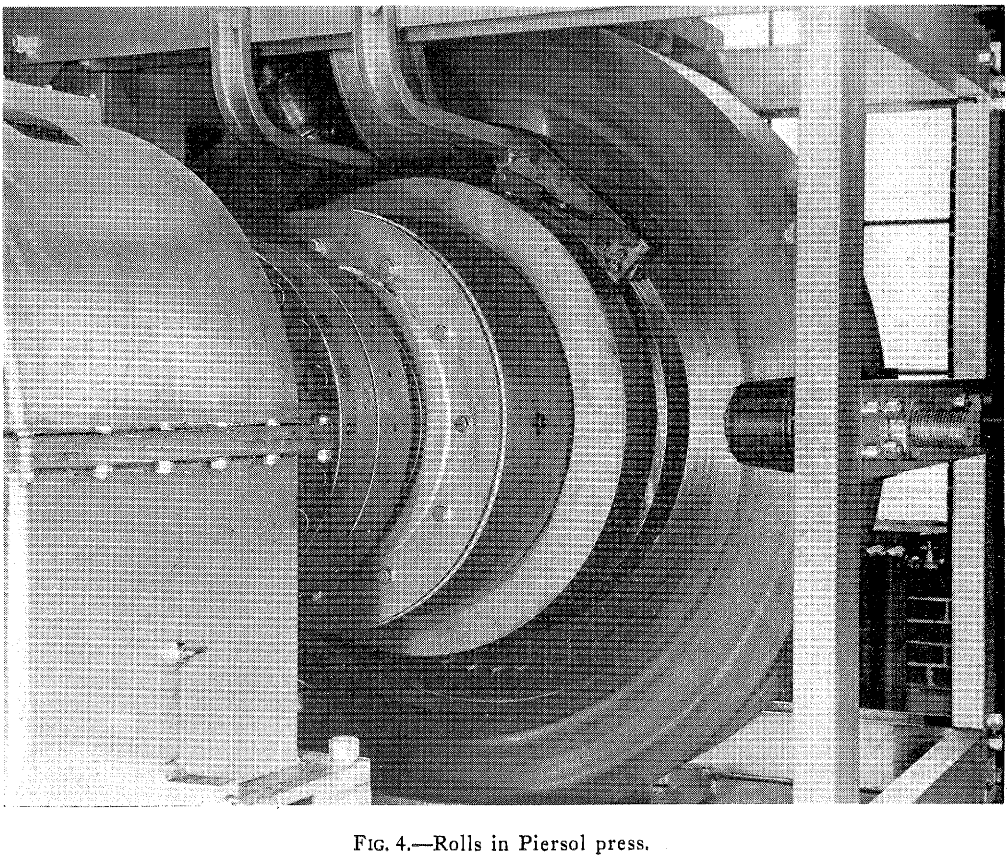

FIG. 4.—Rolls in Piersol press.

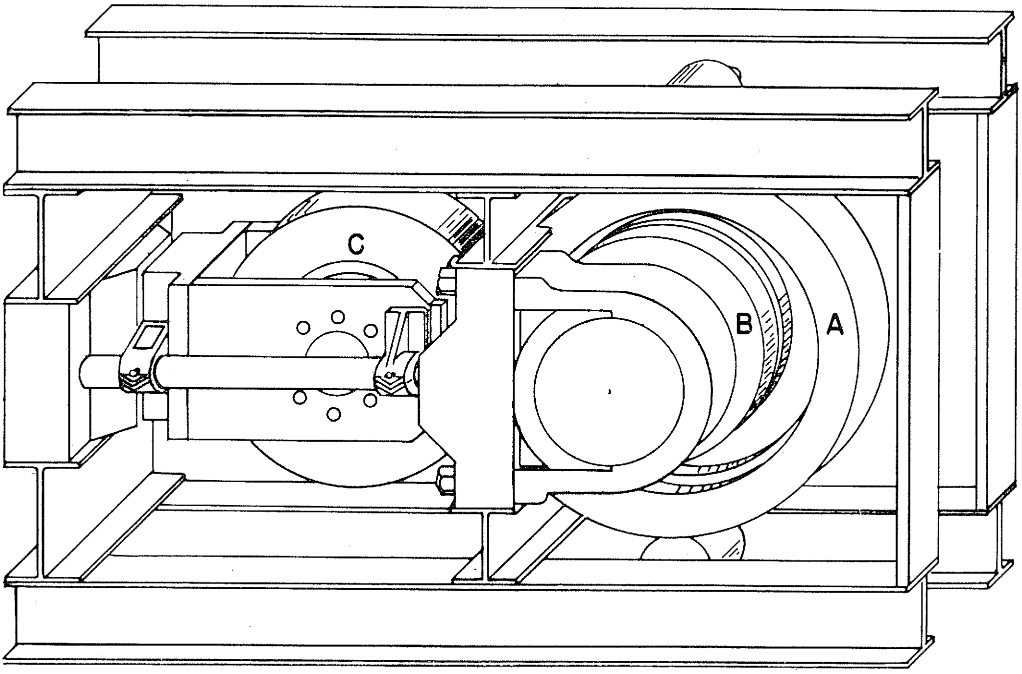

FIG. 5.—Present design of Piersol briquetting press. A—Outer roll; B—Inner roll; C—Backing roll.

At the position of maximum compression, the outer roll (A, fig. 5) contacts the backing roll (C, fig. 5) in order to secure pressure on the coal within the dies. The inner roll (B, fig. 5) is fixed to a 16-inch diameter shaft, supported by a double tapered roller bearing on each side of the roll and is motor driven by a 125-horsepower Zepher-Lincoln automobile engine through a 208 to 1 herringbone speed reducer. The outer roll is floating and is held in alignment with the inner roll by means of three rollers on each of its sides. The backing roll rotates on four tapered roller bearings about a fixed 16-inch diameter shaft. Detailed shop drawings of the briquetting press, which are kept in the Survey files, are available for inspection.

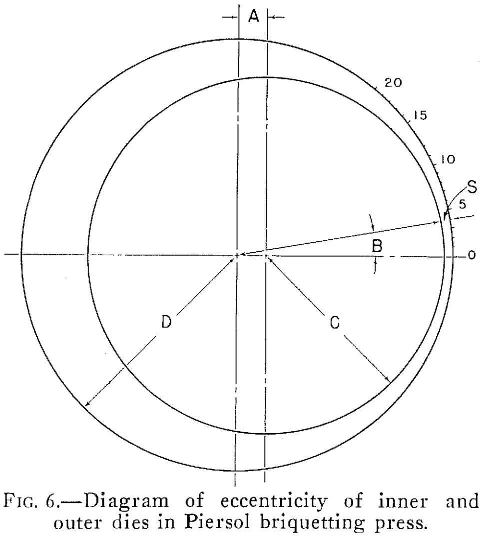

FIG. 6.—Diagram of eccentricity of inner and outer dies in Piersol briquetting press.

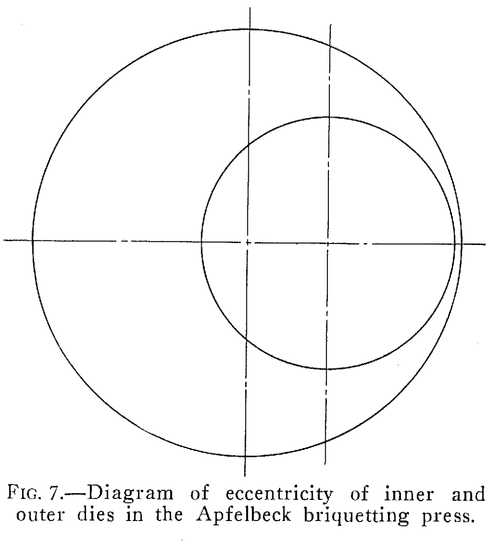

FIG. 7.—Diagram of eccentricity of inner and outer dies in the Apfelbeck briquetting press.

DIES

DIE CONTOURS AND BRIQUET SHAPES

The rings containing the briquetting dies were detachable and interchangeable so that it was possible to use a variety of die shapes and sizes in early experiments exploring the effect of variations in these factors on the quality of the briquets produced. Dies of four different contours have been tried in making briquets: (1) a double row of 1.5-inch by 1.2-inch dies making a ribbon briquet; (2) a double row of 2-inch dies making a rope briquet; (3) a double row of 2-inch dies making semi-biscuit briquets; and (4) a single row of 3-inch dies making semi-biscuit briquets. Also a set of dies, which had cavities in both the inner and outer ring, was built for making a double row of 1.5-inch full biscuit briquets. These did not prove satisfactoy owing to the thin side wall of the die cavities in the outer die which tended to break because the side wall of the outer die was not supported by backing metal. Because of this difficulty, this type of outer die was immediately discontinued and for it was substituted an outer die of rectangular cross-section, thereby eliminating thin side walls.

(1) *Ribbon briquet.*—The ribbon briquet weighs 20 pounds per revolution of the inner die, which is 116 inches in circumference. The ribbon may be broken readily by a mechanical breaker at its notched position, 2.5 inches apart.

(2) *Rope briquet.*—The rope briquet has an oval cross-section and it weighs 18 pounds per revolution of the inner die. It may be broken into any desired length by a mechanical breaker. Both the rope and the ribbon briquets break with a ragged surface which is less pleasing in appearance than that of individually formed briquets.

(3) *Biscuit briquet* (2-inch size).—This size of semi-biscuit briquet weighs 0.1 pound each; 120 briquets are made each revolution and therefore weigh 12 pounds.

(4) *Biscuit briquet* (3-inch size).—This size weighs ¼ pound each; 40 briquets are made each revolution and therefore weigh 10 pounds.

DIE MATERIAL

Die rings made from soft iron lacked the necessary mechanical strength; those made from chromium steel castings, with or without heat hardening, eventually broke due to brittleness which resulted from work-hardening at the high pressures involved; those made from manganese steel performed better than those made from chromium steel, but eventually the manganese steel dies showed cracks. However, the problem of a suitable metallurgical composition of dies has been solved by the use of Evansteel made by the Chicago Steel Foundry Company.

ACCESSORY BRIQUETTING EQUIPMENT

The accessory briquetting equipment consists of: (1) stoker and furnace to supply hot gases for preheating the coal; (2) a continuous preheater; (3) a press feeder; and (4) a batch preheater.

STOKER AND FURNACE

An industrial size stoker with a capacity of 200 pounds of coal an hour is used in connection with a furnace built of brick with inside dimensions of 4 feet wide, 6 feet long, and 5 feet high, which serves as a combustion chamber.

CONTINUOUS PREHEATER

The continuous preheater (fig. 8) consists of two parallel rows of 6-inch diameter conveyor screws on three levels, the length of each level is 10 feet and therefore the coal passes a total distance of 30 feet in the three levels of the preheater. Each screw operates in a sealed U-shaped trough, with hot air ducts on each side of the trough; the coal is heated by indirect heat from the exhaust gases from the furnace. The coal is fed by gravity from a hopper above the preheater at a constant rate by means of two rotary vane type feeders to each of two parallel screws on the top level; when conveyed to the opposite end of the preheater, the coal drops by gravity to the middle level where it is conveyed back to the entrance end of the preheater; then the coal drops to the lower level and is conveyed again to the opposite end and drops into an inclined

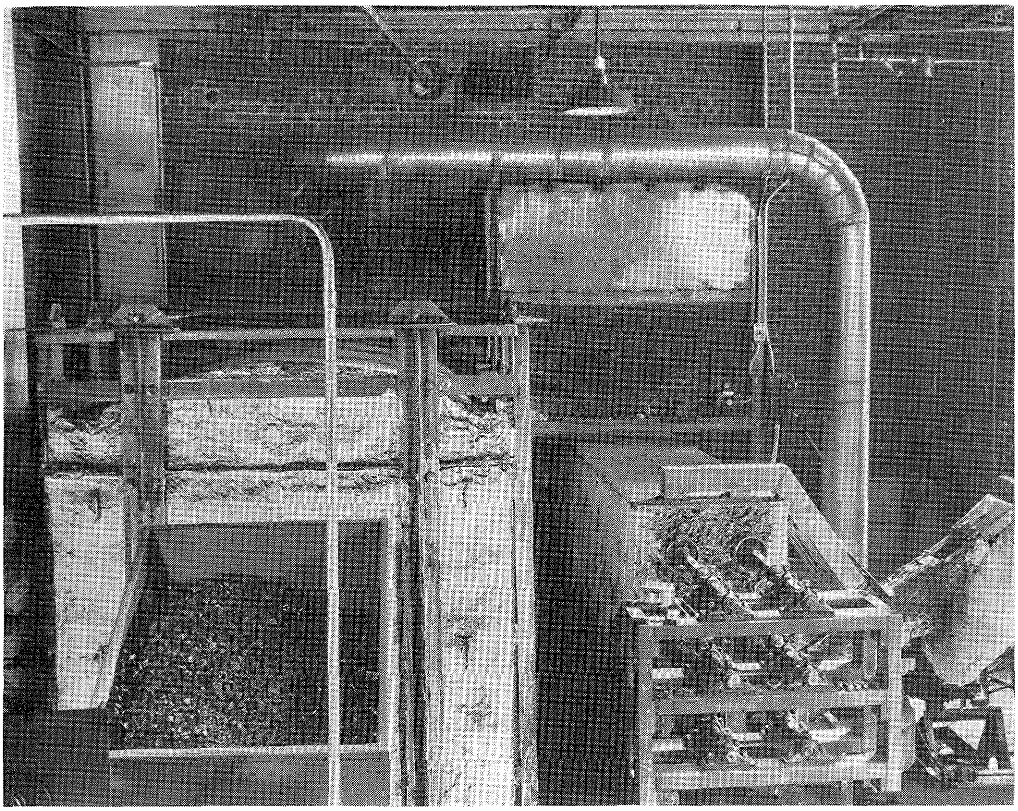

FIG. 8.—Preheater.

screw which conveys the heated coal into a hopper located above the briquetting press.

PRESS FEEDER

The press as originally designed was constructed to feed the coal into the dies by means of an auger which led from a supply bin filled from the preheater. However, the attempts to do this showed that the rate of feed was far from uniform. The problem of uniform feed was eventually satisfactorily solved by the use of an electromagnetic vibrator feeder attached to a small supply bin at the top of the press. The rate of feed was controlled by an adjustable shoe which maintained the desired thickness of the stream of coal.

BATCH PREHEATER

Operational difficulties that developed in the early stages of the large-scale tests made it evident that the use of 100 pound lots of coal would be advantageous rather than the 1000 pound lots required when the large preheater and furnace were used. A continuous preheater is essential for operation on a commercial scale, but because of its large heat capacity it requires 24 hours to bring it up to the desired equilibrium temperature and hence is not suitable for preparing small lots of coal. A small-batch preheater was therefore built in which a drum of coal (250 pounds or less) can be rotated above a large gas burner, the unit being enclosed in an insulated housing with draft connections with the chimney.

BRIQUETS FROM PREHEATED COAL

The briquetting press was first used for a considerable time in exploring the procedure for making briquets from coal preheated in the large preheater, later with coal heated in small batches in the small preheater, and finally in the production of briquets at room temperature which were

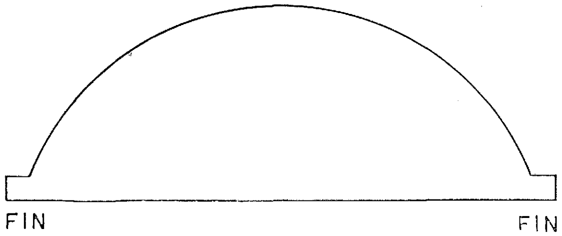

FIG. 9.—Cross-section of semi-biscuit briquet with fins.

subsequently heat-treated to harden them and partially or completely volatilize or carbonize the coal. It is the writer's conviction that the latter procedure lends itself to practice with greater economy than the former, hence in this article this phase of the operational experiences and results is emphasized.

With certain exceptions, which have been suggested, the briquetting press has operated without difficulty. The press was somewhat over-engineered with respect to mechanical strength, and no weakness has developed in any part. The difficulties which were encountered in the feeder and in the dies have been discussed (pp. 23 and 24). A third major difficulty was encountered in releasing the briquets from the die when preheated coal was used.

The problem of releasing the briquets made from preheated coal has not been satisfactorily solved for the present design of the briquetting machine and dies. The semi-biscuit-shaped briquets finally found to be most satisfactory have fins which press against the two side walls of the die (fig. 9). Mechanical fin breakers were installed to break the fins, but results were not satisfactory because many of the briquets were also broken.

BRIQUETS MADE AT ROOM TEMPERATURE

PRODUCTION

It has been found that briquets which are made in the Piersol press at room temperature do not stick in the press, as contrasted to the briquets made from hot preheated coal. The briquets roll out from the cavities by gravity, due to an action which the briquetting press operators refer to as a "rocking chair" motion. As each individual briquet passes beyond the line of maximum compression the briquet rotates (rocks) in the die through an angle of about 5 degrees owing to the greater spacing between dies for the forward part of the briquet. This rotation of the briquet frees it from the inner surface of the die cavity and also frees its fins from the side walls of the die.

The mechanical breakage is less than 0.5 percent by weight, and this may be salvaged by simply returning the broken briquets to the feed and running them through the press until all the coal is briquetted to the extent necessary for heat treatment. When preheated coal is used this simple method of recovery of breakage might not be possible.

SUBSEQUENT HEAT-TREATMENT

Swelling of heat-treated briquets.—The effect of heat-treating briquets made from St. Clair County coal is shown in the accompanying photographs (fig. 10). The upper row shows untreated briquets, the second row the same briquets heat-treated for 6 hours at 530° C., with a volatile matter reduction to 31 percent from an original 39 percent; the third row represents the lump coal from which the briquets were made, after it had been heat-treated in the same manner as the briquets, and the fourth row is an untreated piece of lump coal cut from the same block as the heat-treated lump.

The photographs indicate the complete absence of swelling of the heat-treated St. Clair County coal used in these tests. This is in sharp contrast with the obvious swelling of the lump coal subjected to the same heat treatment. It is apparent that in the lump coal, swelling is very largely restricted to the vitrain bands and the microvitrain bands in the clarain, the amount of swelling apparently amounting to as much as

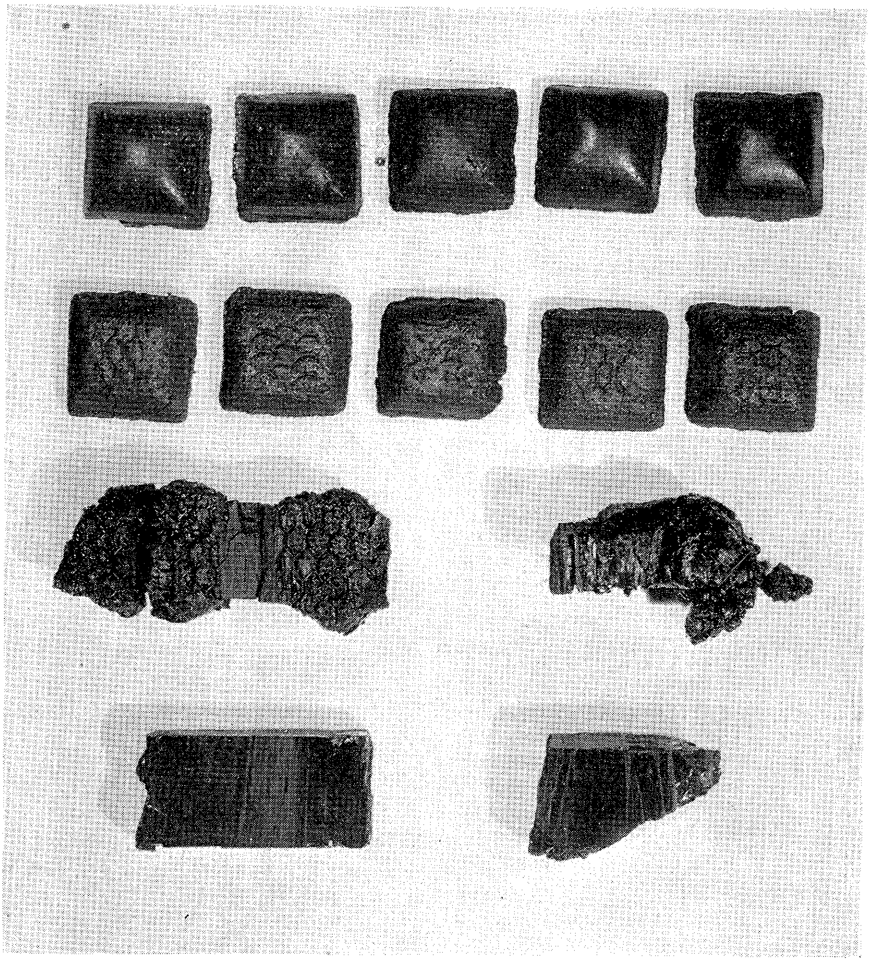

FIG. 10.—Briquets and coal heated to plastic stage.

three-fold for some bands. This lack of swelling shown in the case of the briquets made from St. Clair County coal is characteristic of all Illinois coals that have been investigated and of a few coals of similar rank and character from adjacent regions. It has been found also in the case of the briquets that the temperature of the heater may be increased to as much as 800°C. for a period as much as 6 hours without producing swelling, but with the beneficial effect of increasing the hardness of the briquets and decreasing their volatile content to a considerable extent (see article 2).

Loss of volatile matter.—The amount of loss of volatile matter, as suggested above, depends both on the temperature and the time of heat treatment. The results of proximate analysis of the coal and of the briquets after heat-treating indicate that for the material analyzed the experimental volatile matter agrees very closely with the weight loss on a dry basis, and it is accordingly assumed that this loss mainly represents loss in volatile matter.

To illustrate, according to proximate analyses raw St. Clair County briquets contain 39.0 percent volatile matter (dry basis); the experimental weight loss from heat treating was 10.8 percent by weight; the calculated volatile matter of the treated briquets should be 31.6 percent

$$\frac{(39.0 - 10.8)}{(100.0 - 10.8)} \times 100 = 31.6$$

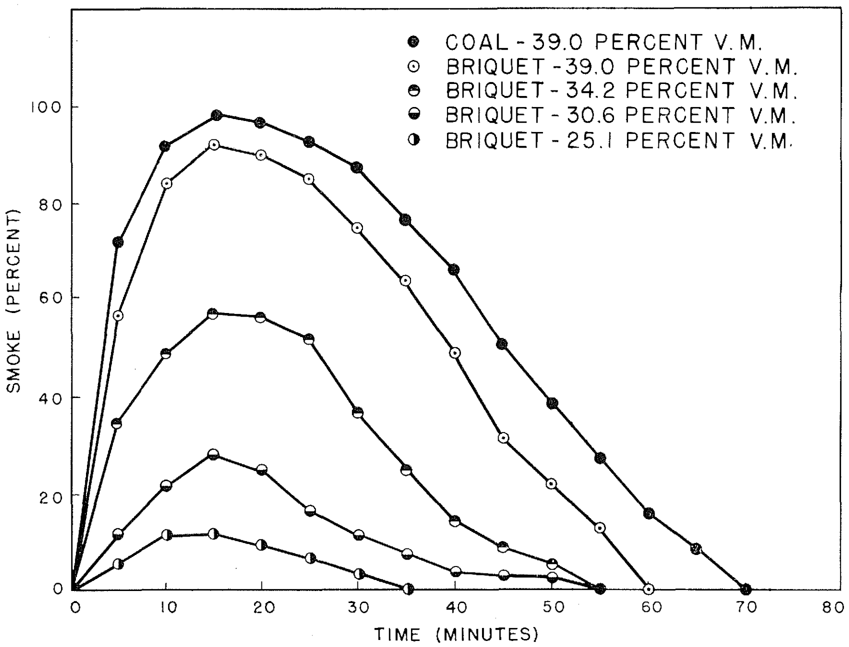

FIG. 11.—Influence of degree of volatilization on smoke-index of St. Clair County coal and St. Clair County briquets. (Data from table 1)

and according to proximate analyses the treated briquets actually contain 31.5 percent volatile matter. There seems to be no good reason for believing that this relationship does not hold true for all Illinois coals even when the temperature is raised to 530°C., the usual temperature at which heat-treating is carried on.

Reduction in smokiness.—The extent to which heat-treating of briquetted coal and the resulting decrease in volatile matter reduces the tendency of the briquets to smoke is indicated by tests that have been made (table 1 and fig. 11) on St. Clair County coal and St. Clair County briquets untreated and heat-treated to various degrees

TABLE 1.—INFLUENCE OF DEGREE OF VOLATILIZATION ON SMOKE-INDEX OF ST. CLAIR COAL AND ST. CLAIR COUNTY BRIQUETS
(Data for Fig. 11)

Time (Minutes)	Coal 39.0% V. M.	Briquet			
		39.0% V.M.	34.2% V.M.	30.6% V.M.	25.1% V.M.
5	72	57	34	12	5
10	92	84	49	21	11
15	98	92	57	28	11
20	97	90	56	25	9
25	93	85	52	16	6
30	87	75	37	11	3
35	77	64	24	8	0
40	66	49	14	4	0
45	51	32	9	3	0
50	38	22	6	3	0
55	27	13	0	0	0
60	15	0	0	0	0
65	8	0	0	0	0
70	0	0	0	0	0
Smoke-index	205	166	85	33	11

of volatile matter. The data reveal that the change ~~in volatile matter~~ caused by briquetting reduces the smoke-index from 205 to 165 points but the change in volatilization produced by heat treatment reduces the smoke-index to 11 points.

It is believed that briquets made from raw Illinois coal at room temperature and heat treated at 530°C. for 6 hours will yield a fuel that is essentially smokeless (article 5).

Hardness of briquets.—The hardness of a briquet made at room temperature without a binder is increased more or less in proportion to the amount of heat applied. When heated at a temperature sufficient to produce softening, that is to about 530° C., the briquet is partly carbonized to the extent that its crushing strength is increased from about 200 pounds to more than 500 pounds.

Such a briquet will withstand a 6-foot drop on an iron plate, whereas the untreated briquet will disrupt when similarly dropped a distance of only 3 feet.

Weathering characteristics.—Briquets made from raw Illinois coal at room temperature lack weather resistant properties similar to those possessed by the experimental cylindrical briquets, upon which many tests have been made. When the briquets made at room temperature are heat-treated the additional hardness imparts some degree of weather resistant properties. A few accelerated weathering tests and the general character of these briquets are believed to justify the opinion that weathering will cause little deterioration of the briquets heat-treated to the softening temperature (approximately 530°C.). Heating to lower temperatures will produce briquets with less resistance to weathering but the exact extent to which heat-treatment affects weathering has not been investigated. No systematic investigation has been possible of the effect of prolonged weathering upon these heat-treated briquets.

Conclusions.—Data at hand provide a basis for estimating the cost of producing the briquet at room temperature without a binder using the Piersol machine. This amounts to approximately $0.75 a ton. The cost of subsequent heat treatment of the briquets has not been thoroughly explored and involves engineering problems which also have not been explored. It is believed that the experimental operations that have been carried on at Urbana have successfully demonstrated a method of producing marketable briquets that will be a satisfactory domestic fuel under conditions of the most strict smoke limitations. The solution of the engineering problems involved in the heat treatment of the briquets appears to be a minor aspect of the whole problem which should offer no great difficulty.

Suggested Improvements in Piersol Press

FOR BRIQUETTING PREHEATED COAL OR COAL AT ROOM TEMPERATURE

In the design of the present press all adjustments and changes have been made that were required for its successful operation. Thus provisions were made in the original design and construction to maintain a constant pressure of the backing roll against the outer roll by the installation of large helical springs. These were found to be unnecessary and even undesirable. Various other features included in the present machine have also been found unnecessary as can be seen by comparing the drawings of the two machines (fig. 2 and figs. 3, 4, and 5). The omission of these parts will simplify the construction of future presses.

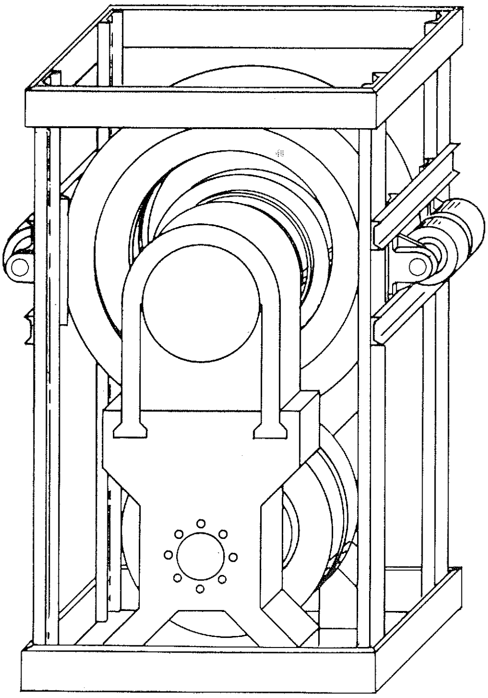

FIG. 12.—Proposed design of Piersol press.

The substitution of an electromagnetic vibrator type of feeder for an auger type makes it desirable to turn the press 90 degrees, thereby placing the backing roll beneath the die rolls (fig. 12) instead of having the rolls in the same horizontal plane.

FOR BRIQUETTING PREHEATED COAL

If the die cavity is placed in the outer rather than the inner ring or roll, a poppet value type of plunger can be installed in each die cavity (fig. 12) for knocking out the briquets made from heated coal.

ARTICLE 2—FACTORS AFFECTING CHARACTERISTICS OF BRIQUETS

The tests described in this article were made on small-scale laboratory briquets, the work having been completed prior to the building of the large-scale laboratory equipment. Characteristics of briquets made by large-scale equipment are affected similarly by the same factors.

In pioneering a new field, such as making smokeless briquets from Illinois coals without binder, attention in the early phases must be concentrated on the laboratory development of a process which actually will make such a product. Once this objective has been accomplished, laboratory study must be centered on the experimental determination of the various factors which influence the quality of the briquet and then these findings must be analyzed and correlated in order to discover the physical laws which govern the formation of briquets having no binder.

This article brings together the fundamental characteristics of briquets made without adding binder, as contrasted to those of natural coal and, also, of the conventional commercial coal briquet which is made with binder added. Comparative data are given regarding mechanical properties, chemical properties, and burning characteristics. Some of the results have been previously published but most of the findings are here reported for the first time.

PHYSICAL PROPERTIES

Crushing Strengths

One of the more important characteristics of a briquet is its crushing strength as determined by the pressure necessary to shatter the briquets. Briquets must be resistant to crushing if they are to be handled without excessive degradation. As expected, the crushing strength of a binderless briquet was found to be closely related to its density, and the density was found to depend upon the pressure used in briquetting, the temperature to which the coal was heated at the time of briquetting and, to a lesser degree, the length of time the pressure was applied (article 8). The density of a briquet controls its degree of porosity, which in turn is the chief factor in the resistance of a briquet to weathering.

EQUIPMENT AND PROCEDURE

The equipment used for testing the crushing strength on laboratory briquets consisted of a hydraulic press that has two horizontal parallel plates, the lower of which (the platen plate) is raised by the hydraulic ram. The applied pressure may be read from a gauge which is calibrated in units of total pounds pressure.

In testing crushing strength the sample briquet was placed centrally on the platen plate. For cylindrical briquets (the common form of laboratory briquets), the briquet was set with one flat end on the platen plate. Its other parallel flat end contacted the upper plate as the platen plate was raised slowly in order to permit an accurate reading of the pressure gauge at the instant prior to the crushing of the briquet.

Proximate analyses of laboratory type briquets used for crushing strength tests.—Proximate analyses of the briquets made from the Chicago, Wilmington and Franklin Coal Company Orient No. 2 minus 20-mesh deduster dust is as follows: moisture, 0.8 percent; volatile matter, 28.1 percent; fixed carbon, 59.6 percent; ash, 11.5 percent; total sulfur, 1.55 percent; calorific value, 12,580 B.t.u.; and the ash fusion softening temperature, 2224°F.

Proximate analyses of the briquets made from the Franklin County Coal Corporation Buckhorn Mine minus 20-mesh deduster dust is as follows: moisture, 1.7 percent; volatile matter, 28.3 percent; fixed carbon, 60.3 percent; ash, 9.7 percent; total sulfur, 0.74 percent; calorific value, 12,900 B.t.u.; and ash fusion softening temperature, 2145°F.

The proximate analyses of the briquets are identical in both cases to that of the deduster dust from which the briquets were

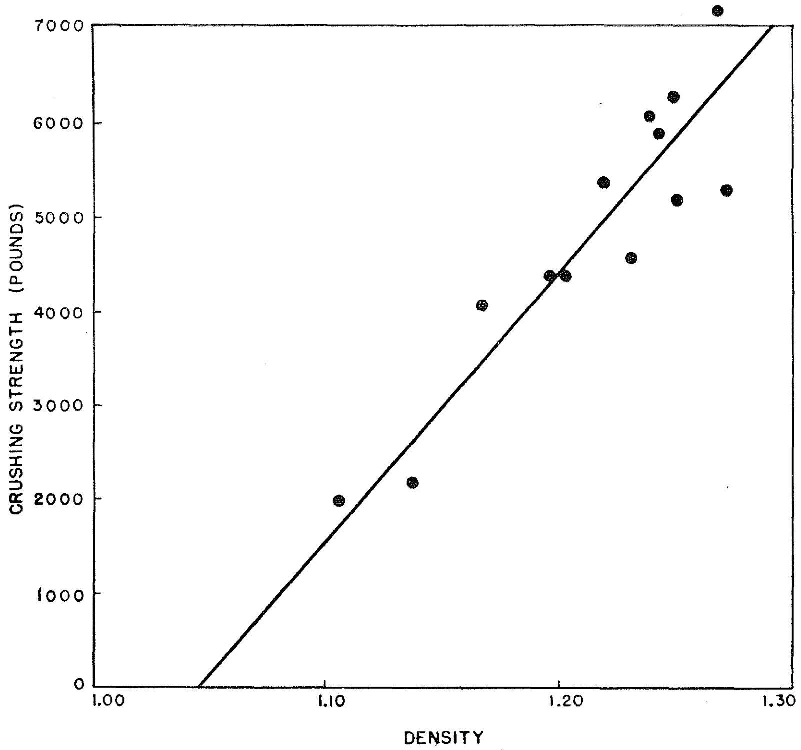

FIG. 13.—Effect of density on crushing strength of deduster dust briquets made from coal from Orient Mine No. 2. (Data from table 2)

made and are included as a matter of information.

Effect of variation in temperature and pressure on the density and crushing strength.—Table 2 shows the effect of temperature, 350° and 400°C., and of a briqueting pressure range from 2500 pounds to 30,000 pounds per sq. in. on the density and the crushing strength of briquets made from Orient No. 2 minus 20-mesh deduster dust. Figure 13, which is a graph of the crushing strength versus the density of these briquets, reveals a straight-line increase of crushing strength with increasing density. The strength ranges from 2,000 lbs. to more than 7,000 lbs.

TABLE 2.—EFFECT OF TEMPERATURE AND PRESSURE ON THE DENSITY AND CRUSHING STRENGTH OF ORIENT NO. 2 CYLINDRICAL BRIQUETS

(Data for Fig. 13)

Briquetting pressure in lbs.	Temperature					
	350°C.			400°C.		
	Lab. No.	Density	Strength lbs.	Lab. No.	Density	Strength lbs.
2500	—	—	—	49	1.105	2000
5000	71	1.137	2200	47	1.167	4100
10000	69	1.194	4600	51	1.231	4600
15000	67	1.219	5300	53	1.249	6300
20000	65	1.203	4400	55	1.243	5900
25000	63	1.239	6100	57	1.269	7200
30000	61	1.251	5200	59	1.274	5300

TABLE 3.—EFFECT OF TEMPERATURE AND PRESSURE ON THE DENSITY AND CRUSHING STRENGTH OF BUCKHORN CYLINDRICAL BRIQUETS
(Data for Fig. 14)

Briquetting pressure lbs.	Crushing strength at various temperatures of briquetting											
	325°C.			350°C.			375°C.			400°C.		
	Lab. No.	Sp. gr.	Strength	Lab. No.	Sp. gr.	Strength	Lab. No.	Sp. gr.	Strength	Lab. No.	Sp. gr.	Strength
2,500	—	—	—	—	—	—	26	1.176	2100	36	1.233	3300
5,000	11	1.132	1100	18	1.125	1100	25	1.294	6000	35	1.287	4400
10,000	10	1.174	1500	17	1.210	2300	24	1.302	5700	38	1.322	4500
15,000	9	1.178	1800	16	1.225	2700	23	1.288	4500	33	1.310	6100
20,000	8	1.225	2400	15	1.289	4000	22	1.320	7000	32	1.342	7000
25,000	7	1.236	2500	14	1.278	4100	21	1.319	6100	31	1.338	7100
30,000	6	1.234	2000	13	1.282	3600	20	1.307	6200	30	1.346	5700

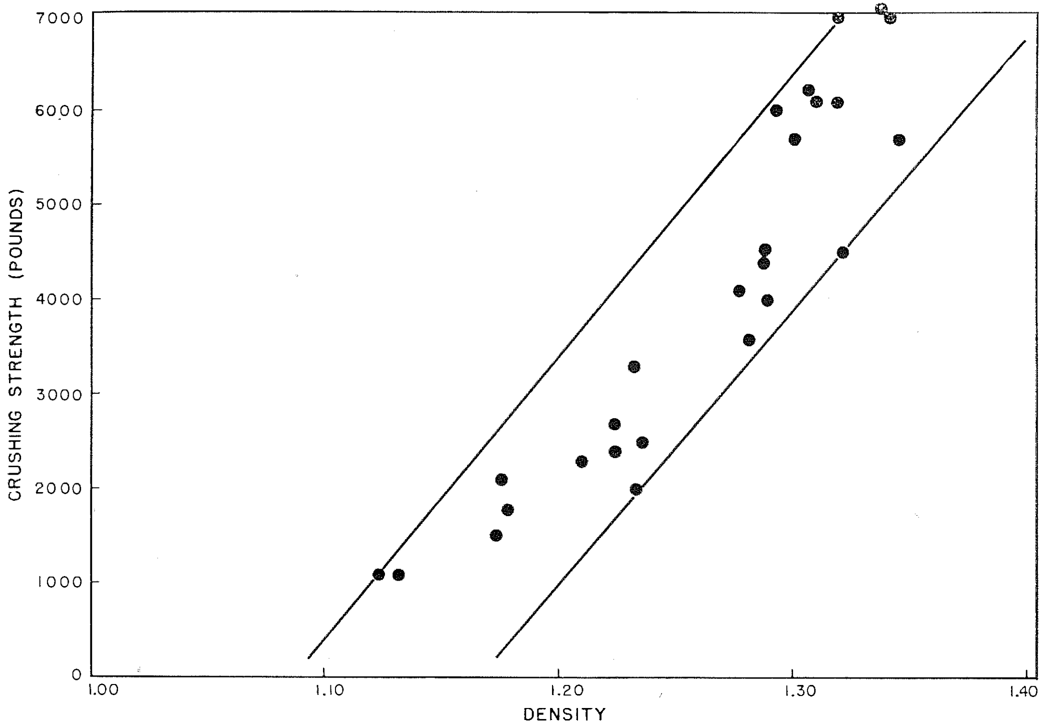

FIG. 14.—Effect of density on crushing strength of deduster dust briquets made from coal from the Franklin County Coal Company. (Data from table 3)

TABLE 4.—CRUSHING STRENGTH OF VARIOUS BRIQUETS[a]

Type of briquet	Fuel	Binder used	Binder (percent)	Strength[b] (lb.)
Ford	Charcoal	Starch	7	130
Ambricol	Anthracite and coking coal	"Hite"	8–10	130
Berwind	Semi-bituminous	Oil pitch and coal tar pitch	8	230
Sunglo Koalets	Sub-bituminous	Petroleum asphalt	6	125
Canmore	"	" "	8	175
Welscot	Anthracite	" "	—	175
Burnrite No. 2	Pocahontas	" "	—	210
Burnrite No. 3	Pocahontas and coke	" "	—	150

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[a] Fuel Briquetting: Canadian Bur. Mines, p. 56, 1937.

[b] "Briquets which break at less than 130 pounds are not considered sufficiently strong to withstand normal handling."

Table 3 shows similar data for briquets made from Buckhorn Mine minus 20-mesh deduster dust, except that the temperature range is from 325° to 400°C. Likewise, figure 14, which is a corresponding graph of the crushing strength versus the density of the Buckhorn briquets, reveals that there is an increase of crushing strength with increasing density; the spread of values, which is shown between the two parallel lines, may be due partially to the wider temperature range.

Crushing strength of various commercial briquets.—Comparison of the strength of the laboratory made cylindrical briquets and that of commercial briquets made with a binder is possible by reference to table 4 (reprinted from table 3, page 56, Fuel Briquetting by Canadian Bureau of Mines, 1937). In this Canadian report it is stated that briquets which break at less than 130 pounds are not considered sufficiently strong to withstand normal handling.

Comparative crushing strength of Survey binderless briquets and commercial briquets.—A comparison of the data shown in tables 2 and 3 with those shown in table 4 reveals that the crushing strength of the Survey cylindrical laboratory briquets is several fold greater than the average of the commercial briquets (166 pounds for the 8 types of briquets shown). This difference in crushing strength is due primarily to the greater density of the Survey briquets but also partly to the cylindrical shape of the Survey briquet which resists crushing better than the pillow shaped commercial briquets. This is shown by the fact that the crushing strength of a cylindrical briquet is less (usually about one half) for side pressure than for end pressure.

The published results (Reports of Investigations Nos. 31, 37, and 41) on extensive tumbling tests on cylindrical laboratory briquets are not included here because comparative results are not available for commercial briquets made with binder.

POROSITY

The strength of briquets made without a binder is believed to be explained by the essential elimination of both internal and interstitial pore space. The compacting force, when it attains what is here called the critical pressure (article 8) produces a briquet having a pore-free density. The attainment of such a condition is believed essential to the production of a stable, hard binderless briquet of relatively low volatile content and having the characteristics of smokeless fuel.

In order to arrive at a clear understanding of the porosity of a binderless briquet made from fine sizes of bituminous coal it is desirable to consider both the nature of the internal porosity of the coal and of the interstitial porosity between the coal particles and also the effect of the briquetting operation upon the two kinds of porosity of the coal particles.

DETERMINATION OF POROSITY

The porosity of a sample of coal may be determined by at least two different methods. One method consists in the experimental determination of the percent porosity by obtaining the volume of a liquid necessary to fill the pore space of a known volume of dry coal. Another method is based on the comparison of densities of dry coal before and after the pore space is removed completely by compaction at very high compression, that is, what is here called the pore-free density.

POROSITY BY DETERMINATION OF LIQUID REQUIRED TO SATURATE PORE SPACE

There are two common devices that can be used for the experimental determination of the porosity of a sample of broken coal by the filling of the pore space. These are the Jolly balance and the pycnometer. By definition, the percentage porosity is numerically equal to the ratio of the volume of the pore space to that of the sample (expressed in percent).

In both methods, the volume of the pore space is determined by measuring the weight of the water which is required to saturate the pore space. The sample is dried to zero moisture, weighed, saturated with moisture (placed in a flask, having a separatory funnel, which is evacuated and water added to cover the sample and if necessary the water is boiled), and the saturated sample is removed, dried sufficiently to remove surface moisture, and weighed. The weight of the saturated sample less the weight of the dry sample is the weight of the water which saturates the pore space; and this weight (gr.) of water is the volume of the pore space (cc.).

In the Jolly balance method the volume of the sample is determined by the difference in weight of the saturated sample weighed in air and weighed submerged in water.

In the pycnometer (specific gravity bottle) method the volume of the sample is determined by the amount of water which the saturated sample displaces.

And finally, in both methods, the percent porosity is calculated as the percent ratio of the volume of the pore space to that of the sample.

CALCULATION OF PERCENT POROSITY FROM PORE-FREE DENSITY OF COAL

The percent porosity of briquetted coal (or coal itself) may also be calculated from its apparent density and its pore-free density as follows:

Consider a sample of coal of unit volume (1 cc.) of any apparent density D of which the pore-free density D_c is known. Then the volume V_c of the sample after compaction to the density D_c will become

$$V_c = D/D_c \qquad (1)$$

and the percent porosity P, which is the percent reduction in volume for a sample of unit volume, becomes

$$P = (V - V_c) \times 100 \qquad (2)$$

$$= (1 - D/D_c) \times 100 \qquad (3)$$

$$= \frac{D_c - D}{D_c} \times 100 \qquad (4)$$

To illustrate: Find the percent porosity of dry sample of St. Clair County coal whose apparent density is 1.20 and whose pore-free density is known to be 1.32.

Substituting these values in equation 4

$$P = \frac{1.32 - 1.20}{1.32} \times 100 = 9.09 \qquad (5)$$

Nebel[1] made a careful experimental study of both the apparent density and the pore-free density of various dry Illinois coals. He arrived at the conclusions that (a) fresh coal of the Illinois type is saturated with moisture, and (b) this coal, when dried, may be resaturated with the same percentage of moisture as that of the fresh coal. From this it follows that the percent porosity of Illinois coal is approximately the percent mine moisture or the percent moisture required to saturate dry Illinois coal.

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[1] Nebel, M. L., Specific gravity studies of Illinois coals: Univ. of Ill. Eng. Exp. Sta. Bull. No. 89, July 1916.

TABLE 5.—PORE-FREE DENSITY (CRITICAL DENSITY) AND CRITICAL PRESSURE OF VARIOUS COALS

Coal		Pore-free density	Critical pressure (lb. per sq. in.)
Location	Sample		
St. Clair Co.	Crushed lump	1.32	25,100
Will Co.	Crushed lump	1.32	25,100
Franklin Co.	Crushed lump	1.38	44,700
Pocahontas (W. Va.)	Crushed lump	1.38	56,200
Franklin Co.	Deduster dust	1.40	39,800
Franklin Co.	Vitrain[a]	1.27	35,500
Franklin Co.	Durain[a]	1.29	31,600

[a] Crushed hand-picked samples.

Using the pore-free density method, the porosity of briquets which have been subjected to various degrees of compaction may be calculated from their apparent density provided that the pore-free density has been determined experimentally for the coal from which the briquet is made. The characteristic critical density D_c (pore-free density) of various coals subjected to the critical pressure P_c necessary to produce the density are shown in table 5.

The pore-free density of a coal compacted by briquetting at its critical pressure, or higher, is the density of the resultant briquet when the pressure is removed. It has been found that when several briquets are made from the same samples of coal at various pressures from 60,000 to 450,000 pounds per sq. in. (which is higher than the "critical" pressure), upon removal of the briquets from the die, the density of each briquet returns to a constant value (1.32 for a particular sample of St. Clair County coal) believed to represent the pore-free value.

RESISTANCE TO WEATHERING

The study of weathering characteristics of Illinois cylindrical briquets made on laboratory scale without binder consisted in determinations of (a) the effect upon the briquets of standard accelerated weathering tests used in testing coal, (b) possible disintegration effect of continuous outside exposure, and (c) the effect upon the calorific value of the briquets.

ACCELERATED WEATHERING TESTS

The accelerated weathering tests applied to the briquets followed the procedure recommended by the U. S. Bureau of Mines for determining the weathering characteristics of coal,[2] which is briefly as follows:

1. Not less than three and preferably five samples of fresh coal should be taken from the mine representing different locations.
2. The samples should consist of 30-50 lumps of approximately 1¾-inch cubes. These cubes should be placed in a sample can and the voids around the cubes filled with fine coal to prevent abrasion and oxidation of the cubes in transit to the laboratory.
3. On the receipt at the laboratory, screen out the fine coal used for packing by placing the coal on a ¼-inch screen. The fine material simply drops through the screen without the necessity of shaking.
4. Discard any pieces that show evidence of being cracked or crushed. Weigh and determine the drying loss in a standard oven at 30° to 35°C. for 24 hours.
5. Remove the sample from the oven, weigh and immerse in water for one hour.
6. Drain and dry coal again in the oven at 30° to 35° C. for 24 hours.
7. Remove the sample from the oven and place the coal on a standard ¼-inch square-mesh sieve. The sieve is shaken

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[2] Fieldner, A. C., Selvig, W. A., and Frederic, W. H., Accelerated laboratory test for determination of slacking characteristic of coal: U. S. Bureau of Mines, Rept. Inv. 3055, 1930.

TABLE 6.—ACCELERATED SLACKING TESTS OF ILLINOIS COALS[a]

Cycle	Accumulated percentage weight loss	
	Will County coal	Franklin County coal
1	1.1	0.5
2	5.2	1.4
3	7.6	2.9
4	12.6	6.4
5	19.1	8.8
6	21.9	9.4
7	25.4	10.5
8	29.5	11.5

[a] Mitchell, D. R., Accelerated slacking tests of some Illinois coals: Trans. Ill. Acad. Sci. vol. 23, No. 3, 1931.

gently so that the fine particles of coal will drop through. The sieve should not be shaken vigorously enough to break any of the cubes.

8. Weigh the oversize and the undersize and calculate percentage of undersize.

9. This constitutes the first cycle. Repeat the alternate wetting and drying until 8 cycles have been completed in the case of coals that do not slack readily. The cumulative percentage of fines produced at each cycle is taken as an index of the slacking characteristic of the coal.

In general, Illinois coals show less than 5 percent degradation at the end of the first cycle, whereas coals of lower rank (sub-bituminous) show 5 percent degradation or more, usually more.

Cylindrical briquets given the accelerated weathering tests represented Will County, Sangamon County, and Franklin County coals; the moisture and ash contents of the coals, as received basis, were moisture, 16.9, 12.9, and 8.7 percent, respectively, and ash, 3.4, 9.2, and 10.0 percent, respectively. Tests were carried through 8 cycles.

None of the briquets tested showed disintegration. The same briquets were subjected to an additional 8 cycles, making a total of 16 cycles. Slacking losses were as follows: Will County, 0.16 percent; Sangamon County, 0.11 percent; and Franklin County, 0.12 percent.

The relative resistance of the briquets to these accelerated weathering tests may be compared to that of coal by reference to table 6, which shows the results obtained by Mitchell[3] on a variety of Illinois coals through a series of 8 cycles.

OUTSIDE EXPOSURE TESTS

The outside exposure tests were made in order to ascertain the effect of weathering on the disintegration and the change of calorific value of briquetted Illinois coals.

The cylindrical briquets tested were made under standard laboratory conditions from Will County, Washington County, and Franklin County tipple samples of lump coal.

Three cylindrical briquets from each county were placed in separate compartments of a wooden tray, each briquet being entirely exposed. The tray was placed on the exposed flat roof of the Survey laboratory for a period of 90 days from February 24 to May 25, 1934. The exposure included six snow falls totaling 19.4 inches, each followed by thaws, average ranges in daily temperature of 22°F. (including 22 instances across the freezing temperature), a maximum daily range of 36°F., and a total range of 101°F., with relative humidity ranging from 100 to 30.3 percent.

Except for a slight surface cracking, at the end of the period the briquets had the same appearance as freshly made briquets.

EFFECT ON CALORIFIC VALUE

Some chemical change took place during the exposure of these sets of briquets as shown by the analyses of the composite samples in table 7. There was a decrease in unit B.t.u. value of from 1.04 to 1.61 percent, variable increases in moisture, the amount apparently increasing with the rank of the coal. Difference in ash and sulfur content are probably due to the slight changes in the weight of the briquets due to the variation in moisture and volatile matter, although there is some possibility of the oxidation of pyrite.

It is evident that briquets having the pore-free density of those formed under

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[3] Mitchell, D. R., Accelerated slacking tests of some Illinois coals: Trans. Ill. Acad. Science, 23rd Annual Meeting, Vol. 23, No. 3, March, 1931.

Table 7.—Analyses of Cylindrical Briquets Used in Outdoor Exposure Tests[a]

County	Will		Washington		Franklin	
Bed	2		6		6	
Condition[a]	A	B	A	B	A	B
Moisture	1.2	3.8	1.6	4.2	1.6	6.2
Ash	5.2	5.0	11.1	10.9	7.0	6.8
Volatile	46.3	44.8	45.3	43.2	38.6	38.1
Sulfur	3.6	3.3	3.3	3.4	1.2	1.2
B.t.u. (unit coal)	14,200	14,010	14,290	14,140	14,380	14,150

[a] Analyses A and B are for briquets before and after exposure, respectively.

laboratory conditions at critical pressures possess a resistance to weathering considerably greater than that of representative Illinois coals.

CHEMICAL PROPERTIES

Ignition and Quenching Temperature

The experimental briquets were pore-free and hence essentially moisture-free, and the burning properties should theoretically reflect this moisture-free condition. The validity of this expectation was tested by a series of determinations of the ignition and quenching temperature of the raw coal and of briquets made from the same coal.

The ignition and quenching characteristics of fuel are two characteristics that can be determined on a laboratory scale using only a small quantity of fuel. Their significance lies in their usefulness as an index of ease of lighting and of holding fire. Ignition temperature is also an important factor determining the suitability of coal for storage and bunkering. Because the composition of Survey briquets differs from that of the original coal mainly in containing less moisture, the ignition and quenching temperatures should be slightly lower than those characteristic of the coal. The results of tests substantiate the probability that this is the case.

Definitions and Methods

There is no standard method for the determination of ignition temperature. Arms[4] has summarized the various suggested ignition temperatures as follows:

1. The temperature at which self heating begins.
2. The temperature to which coal must be raised in order that it may unite with oxygen and burn.
3. The temperature (zone) at which rapid self heating begins.
4. The temperature to which coal must be raised so that it maintains its own combustion.
5. Definitions on a time basis, such as the time required for a given external temperature to ignite the coal or cause it to glow.
6. The temperature at the glow point.
7. The temperature at which a flame appears.
8. The crossing point of the outside heat, coal-heat curves (Wheeler).

Arms found that none of these definitions were entirely satisfactory. In addition, all these methods require coal of very fine size.

In the present study it was desired to compare the ignition temperatures of Survey experimental cylindrical briquets with

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[4] Arms, R. W., The ignition temperature of coal: Univ. of Ill. Eng. Exp. Sta. Bull. 128, 1922.

those of corresponding natural coals, so all samples were in lump form to permit the effect of textural differences to be observed.

Preliminary tests indicated that reproducible results may be obtained for lumps of coal (or briquets) under constant conditions of rate of heating and air supply, using the appearance of a flame (Arms, 7) as the indicator of ignition temperature. Therefore, in this report ignition temperature is defined as the temperature at which the yellow flame appears, since this is readily reproducible for identical samples.

Quenching temperature, for the purpose of this investigation, is defined as the temperature at which the flame from burning coal disappears if the temperature is lowered. It is evident that the minimum temperature of sustained combustion approaches this quenching temperature, the interval diminishing with increased precision of operation. Thus, the quenching temperature is a limiting value of the maintenance temperature.

EQUIPMENT

Equipment and procedure of the present series of tests were devised to test the ignition and quenching temperatures of Survey cylindrical briquets and the coal similar to that from which these briquets were made. No comparison was made with results obtained on Illinois coals by earlier investigators of ignition temperature, since the purpose was simply to inquire into the relative behavior of the two kinds of fuel under similar conditions of operation.

An electric muffle furnace was constructed for use in the ignition and quenching temperature tests. It is described in Article 3 on smoke-index experiments.

PROCEDURE

For the determination of ignition and quenching temperatures, samples were prepared from the laboratory briquets and from blocks of the corresponding coal by cutting them into cubes weighing approximately 3 grams each.

Before performing duplicate tests, the approximate ignition temperature of the particular sample was obtained by exploratory trial. Then the temperature of the rear half of the furnace was set 15 degrees higher than this approximate temperature. This was to assure a slow rate of temperature rise of the sample as it was gradually moved from the cooler front half to the hotter rear half of the furnace. At the instant a yellow flame appeared, the temperature of the sample as measured by the thermocouple, whose junction was attached to the dish in which the sample was placed, was recorded as ignition temperature.

The quenching temperature was obtained by drawing the tray supporting the flaming sample into the cooler front half of the furnace, thereby causing the flame to be quenched. By means of exploratory tests this lower temperature was set slightly below quenching temperature, thereby assuring a slow rate of temperature drop of the sample through its quenching temperature. At the instant the yellow flame disappeared, the temperature of the sample as measured by the thermocouple was recorded as quenching temperature.

EFFECT OF AIR SUPPLY

Since the air supply undoubtedly has an important bearing on ignition and quenching temperatures, standardization of condition of air admission was necessary and a series of tests was run for this purpose.

Cylindrical briquets, four months old, made from Washington County coal, were used in this standardization. Table 8 shows both the ignition and quenching temperature values for an air supply ranging from 2.2 to 5.4 cubic feet per minute. Series (a) represents tests, made from pieces of the same briquet, showing the effect of various rates of air flow. Series (b), (c), (d), and (e) are duplicate tests of briquets formed from the same coal under identical conditions. The average values of both ignition temperature and quenching temperature are not affected by wide variations of air flow within the middle of the range investigated, and therefore the median value of 4 cubic feet per minute was selected for use in all tests.

Table 8.—Effect of Air Supply on Ignition and Quenching Temperature of Cylindrical Briquets Made from Washington County Coal

	Air (cubic feet per minute)						
Test	2.2	2.4	3.0	3.5	4.5	5.0	5.4
	Ignition temperature °C.						
a	544	509	549	549	549	554	544
b	578	549	549	554	544	554	549
c	558	554	551	563	529	558	549
d	529	558	549	563	558	549	549
e	563	558	551	558	554	549	549
mean	554	545	550	557	547	553	548
	Quenching temperature °C.						
a	480	509	494	470	509	539	519
b	578	519	534	485	534	529	539
c	558	499	485	563	509	549	534
d	529	558	509	534	534	509	534
e	558	504	549	509	544	544	524
mean	541	519	514	512	526	534	530

Briquets Compared with Natural Coals

The cylindrical briquets for these tests were prepared from coals from four counties, Will, Sangamon, Washington, and Franklin, with analyses as shown in table 9. From samples of lump coal similar to those used for the briquets, pieces were selected for corresponding tests. The coals at the time the briquets and tests were made had been in the laboratory about four months.

Table 9.—Analyses of Samples Used in Determination of Ignition and Quenching Temperatures

County	Will	Sangamon	Washington	Franklin
Bed..........	No. 2	No. 5	No. 6	No. 6
Moisture[a]....	9.1	12.7[c]	8.5	8.7
Ash[a].........	4.7	9.2	7.2	10.0
Volatile[b].....	50.4	46.6	49.2	40.0
Sulfur[b].......	3.4	5.0	5.0	1.1
B.t.u. (unit coal).......	14,520	14,520	14,450	14,670

[a] "As received" basis.

[b] Moisture-free and ash-free basis.

[c] The experimental moisture of 12.7 percent for Sangamon County coal simply means that this was the moisture of the sample when tested, and it should not be inferred that the moisture of Sangamon County coal is higher than that of Will County coal.

IGNITION TEMPERATURE

For each coal investigated (table 10) data show a consistently lower ignition temperature due to briquetting. Only for Sangamon County coal is the amount of decrease so slight as to be comparable with the magnitude of mean deviation.

QUENCHING TEMPERATURE

Although from its very nature the experimental determination of quenching temperature is less accurate than that for ignition temperature, nevertheless the mean values (table 10) show the same general lower values for briquets compared with the corresponding coals.

EFFECT OF MOISTURE

It is inferred that the lower ignition and quenching temperature of the briquets as compared with the corresponding coals are due to their lower moisture content. This seems valid in view of the fact that coal

Table 10.—Ignition Temperature and Quenching Temperature, Briquets versus Coals

Test	Will Co.		Sangamon Co.		Washington Co.		Franklin Co.	
	Briquet	Coal	Briquet	Coal	Briquet	Coal	Briquet	Coal
				Ignition temperature				
a	426	475	529	524	534	558	539	529
b	441	477	509	519	539	558	544	529
c	431	470	494	519	529	549	524	524
d	451	467	499	509	544	558	519	529
e	441	475	499	509	544	544	509	509
f	431	470	494	509	519	549	519	539
g	426	482	509	494	534	558	499	558
h	436	475	534	519	534	544	460	549
mean	435	474	508	513	535	552	514	533
				Quenching temperature				
a	...	417	529	519	499	485	485	524
b	...	412	470	514	524	509	534	524
c	387	387	412	509	509	509	485	524
d	...	377	412	499	534	524	485	524
e	412	436	412	509	534	534	460	514
f	407	441	417	494	499	534	475	534
g	377	431	509	485	524	534	436	534
h	431	475	529	504	519	529	436	534
mean	403	422	461	504	518	530	475	527

when dried to a "moisture-free" condition has a lower ignition and quenching temperature than coal from which moisture has not been expelled (table 11). These tests established the superiority of the laboratory briquets over the natural coals with respect to ignition and quenching characteristics and indicated that such briquets would ignite more easily and hold fire longer than the natural coal.

COMBUSTION CHARACTERISTICS

Combustion characteristics could not be determined with the small quantity of cylindrical briquets available from laboratory production. The following discussion is therefore based largely on the experience accumulated in the Survey laboratories on burning the biscuit shaped briquets that were made in the large pilot press, corresponding Illinois coals, and commercial briquets made with binder from various American coals. The distinctive burning properties of briquets made without binder as contrasted to those of natural coals and to those of briquets made with binder are, in general, those which would be expected to result from intrinsic differences in these three types of fuel. Miscellaneous combustion

Table 11.—Influence of Moisture on Ignition and Quenching Temperatures
(Tests on Washington County Coal)

Tests	Ignition temperature		Quenching temperature	
	As received	Moisture-free	As received	Moisture-free
a	558	529	485	524
b	558	529	509	519
c	549	539	509	534
d	558	544	524	534
e	544	509	534	460
f	549	534	534	519
g	558	558	534	549
h	544	539	529	460
mean	552	535	520	512

characteristics include radiant heat, short blue flame, absence of sparking, absence of clinkers, fluffy light-colored ash, porous firebed, absence of cracking or swelling, absence of disintegration due to melting of binder, easy temperature regulation by means of air draft, ease of ignition, long period of holding fire, smokeless combustion, and high thermal efficiency.

Radiant Heat

Observation reveals that briquets made without binder from Illinois coals tend to burn in a manner similar to anthracite coal, burning from the outside inwardly. The outer surface of a briquet becomes incandescent, thereby liberating its heat of combustion principally in the form of radiant heat. The dense low-porosity texture of the briquet provides excellent thermal insulation against the high surface-temperature in the direction toward the center of the briquet. This relatively low interior temperature of the briquet prevents excessively rapid vaporization of the volatile matter; and the low permeability of the briquet results in a slow evolution of the volatile gases through the surface of the briquet. The rate of evolution is such as to permit complete combustion of these gases as they pass through the incandescent surface of the briquet.

Short Blue Flame

Briquets made without binder burn with a characteristic short blue flame. The color of a flame is an index of its temperature; the spectral shift from red to blue denotes increasing temperature of combustion within the flame zone; thus the blue color of the flame indicates a high-temperature flame. The length of a flame is likewise another index of its temperature; the shortening of the length of a flame denoting increased temperature of combustion within the flame zone; thus a short flame also indicates a high-temperature flame. From this it is seen that the characteristic short blue flame is compatible with the existence of an incandescent surface, all of which is conducive to high radiant heat.

Absence of Sparking

There is substantially a complete absence of sparking (the shooting off of embers) in the burning of binderless briquets. The apparent reason is the absence of high gaseous pressure within the briquet; such pressures would result in the projection of ignited particles from the surface of the briquet. The writer has observed the burning of briquets made by the Survey's press in an open grate in the living room of his home for several years.

Absence of Clinkers

Briquets made without binder may be burned with a minimum of clinker formation. Doubtless this is partially due to the fact that such briquets are free burning (maintain an open firebed) and tend to hold a relatively low firebed temperature while dissipating large amounts of radiant heat. In making large-scale smoke tests in conventional equipment over a period of years, it was noted that a minimum of clinkering resulted even when the equipment was used beyond its rated thermal capacity. However, it seems probable that, since the chemical composition of the ash in a binderless briquet is the same as that of the coal from which it is made, a binderless briquet made from a highly clinkering coal would have some tendency to clinker, although less than that of the coal itself.

Fluffy Light-colored Ash

The typical ash from burning binderless briquet is fluffy in texture and in color resembles cigar ash. Normally the ash may be sifted completely through a 10-mesh sieve. This condition seems to be due to the very complete combustion of the coal at a firebed temperature that is lower than the fusion temperature of the ash.

Porous Firebed

As the briquets are uniform in size and shape, a pile of them has normally from 30 to 50 percent gross pore space. If the briquets do not swell and adhere to each other, the firebed tends to remain open throughout the burning of the briquets. Experience has shown that these conditions exist in the burning of Illinois briquets made without binder.

Absence of Cracking or Swelling

As each briquet burns, its volume is diminished, due to its ashing, and it becomes surrounded by its own ash residue. This condition is characteristic of binderless briquets made from Illinois coals and from all similar coals which possess a low swelling index. However for binderless briquets made from coals such as Pocahontas, which have a high swelling index, there is some tendency for the briquets to swell and to adhere to each other during combustion although these characteristics are less pronounced than those of the coals from which such briquets are made.

Absence of Disintegration due to Melting of Binder

The melting temperature of the conventional binders is much lower than that of the firebed temperature during the combustion of the briquets. When a hot furnace is refired with a charge of such briquets, normally a period follows during which the binder melts, the briquets lose their cohesive property, and if the furnace is shaken or the firebed stirred with a poker, the briquets disintegrate to coal dust. This instability continues throughout the liberation of the volatile matter; then the briquets may become firm again during their incandescent stage because of coking, if the briquets are made from coal with the necessary agglutinating property. As contrasted to this, briquets made without binder are not subject to melting of binder during combustion with resultant disintegration.

Easy Temperature Regulation by Means of Air Draft

As noted above, a firebed made up of binderless briquets remains open throughout its entire burning. For this reason, it is easy to maintain the desired temperature regulation by the means of air draft control.

Ease of Ignition

Data have been presented which reveal that the ignition temperature of binderless briquets is lower than that of the corresponding coals. In burning such briquets in an open grate, it has been found that they may be kindled by means of burning paper. This is characteristic of smokeless briquets made either from deduster dust or from partially volatilized coal. Perhaps this ease of kindling binderless briquets is further due to the fact that their combustion is primarily a surface reaction.

Long Period of Holding Fire

Observation has revealed that binderless briquets will hold fire without banking for 24 hours in an open grate and from 48 to 72 hours in a tight furnace with closed draft. It appears that the reason for this long period of fire maintenance is due to the low quenching temperature of the briquets (p. 40) and to the fact that each individual briquet becomes thermally insulated by its own blanket of fluffy ash.

Smokeless Combustion

The degree of smoke liberated by a briquet burned under standardized conditions depends both on the chemical composition of the briquet and the physical texture of the briquet. In numerous tests made at the Survey, smoke results have revealed that the texture of a binderless briquet results in a reduction of 25 to 50 percent of the smoke index of the corresponding lump coal from which the briquet is made. However, in order to be accepted as an equivalent of 23 percent volatile coal, it is necessary that a binderless Illinois briquet be made from deduster dust containing about 15 percent fusain or a partially volatilized coal (about 10 percent reduction in volatile matter, e.g., from 40 to 30 percent volatile matter content).

High Thermal Efficiency

The high thermal efficiency of binderless briquets is due to the fact that the volatile matter is consumed efficiently. Conventional heating devices are so designed that the equipment efficiency is somewhat greater for a fuel whose heat is liberated primarily in the form of radiant heat, and for this reason the practical efficiency of binderless briquets is further increased.

ARTICLE 3—SMOKE-INDEX METHOD OF MEASURING THE SMOKINESS OF FUEL

INTRODUCTION

One of the essential necessities in the development of a satisfactory briquet for use as a domestic fuel in cities with rigid laws against the use of smoke-producing fuel is the smokeless property of such briquets. As one of the properties claimed for the briquet produced by impact was that its combustion was smokeless, or at least much less smoky than the coal from which it was formed, the perfection of some method of measuring the quantity of smoke produced by briquets and coal was needed. The smoke-index method was therefore developed and was correlated with results obtained by the standard Ringelmann chart method commonly used in determining the smokiness of stacks.

History of Smoke-Index Method

The smoke-index method was developed in 1933 as a precision tool for use in research on the production of smokeless briquets made from high volatile Illinois coals. So far as is known, the term "index" had not been used previously in smoke literature; the term was selected to designate the idea of a "yardstick" by which the amount of smoke liberated in the burning of a fuel may be measured in comparison with that of a standard fuel burned under identical conditions.

The first phase of the development of the smoke-index method consisted of the measurement of the smoke liberated from a one cm-cube of coal (about one gram) burned under constant conditions. As the research on smokeless fuels approached the stage of commercial development, it became desirable to enlarge the smoke-index method for use in large-scale tests. This adaptation of the smoke-index method, made about 1936, consists of the measurement of the total amount of smoke liberated during the combustion of a 20-pound sample of fuel burned under a standard set of conditions.

Nature and Definition of Smoke

Smoke, which is a general term applied to the visible exhalations from burning materials, is discussed by the Encyclopedia Britannica as follows:

"Nearly all fuels consist essentially of carbon, hydrogen, oxygen and nitrogen, in various proportions and variously combined. In addition, they usually contain a little sulfur, while in solid fuels varying amounts of incombustible mineral ash are also incorporated. If complete combustion were always attainable, no fuel would emit smoke, the final products in such an ideal case being limited to carbon dioxide, water vapor, and free nitrogen, all quite innocuous gases, and invisible unless the water vapor condenses to a cloud of steam. There would, however, if sulfur were present, also be produced small quantities of sulfur dioxide gas, which, also invisible, has a pungent smell, and in contact with air and moisture tends rapidly to be converted into a corrosive acid; while the mineral constituents would remain unburned in the form of ash.

"To achieve such finality it is necessary only that a fuel should be brought into contact with enough air for full oxidation while maintained at a temperature sufficiently high for combustion to take place. These conditions, although apparently simple, are by no means easy to realize, and in practice some proportion of a fuel always eludes complete combustion. The unburned products vary widely in amount and in composition according to the nature of a fuel and the manner of its use, being in some circumstances inappreciable, in others very large. They are moreover not necessarily in the form of smoke, since with insufficient air carbonaceous materials may emit gaseous intermediate products such as carbon monoxide and unsaturated hydrocarbons; but whether or not smoke is produced, incomplete combustion is always indicative of thermal loss.

"Thorough admixture with air is relatively easy to secure in the case of gaseous fuels, which in properly constructed and properly adjusted burners produce neither smoke nor other unburned products in appreciable quantity. An inadequate air supply, however, or the chilling or smothering of the flames, may result in the evolution of unburned gaseous products, including carbon monoxide and oxides of nitrogen, both highly poisonous; or in extreme cases may even cause the deposition of soot.

"Owing to the relatively high density of solid fuels, the problem of bringing them into contact with sufficient air for complete oxidation is greatly intensified, and, even with an air supply far in excess of that theoretically required, perfect combustion cannot in practice be counted upon.

"With bituminous coals, smoke production to a greater or lesser degree, according to the circumstances, is practically unavoidable; for such coals are subject to decomposition at temperatures below the ignition point, with the evolution of combustible gases and condensable tarry vapors. These are of so complex a character, and under the action of heat are subject to such complicated chemical changes, that although the more readily ignitible constituents may burst into spasmodic flames, others almost inevitably escape unburned. Coal smoke consists of such unconsumed distillation products, in association with carbon and tarry matter condensed by premature chilling of flame, together with dust and ash entrained by the upward rush of hot air and gases from the grate. Some of this settles on the walls of the flue as soot; the remainder is carried out through the chimney into the atmosphere with the excess air and gaseous products of combustion, both burned and unburned."

The smoke-index method of expressing smoke density is based on the above description of the nature of smoke. The amount of smoke is measured in terms of its absorption of the intensity of a light beam which passes through the smoke column. In general, there is lack of equivalence between this optical smoke density and the weight of the smoke; the two are related only under the specific conditions when all the smoke particles are of identical size, shape, and specific gravity, and also possess identical optical characteristics.

Need for Smoke-Index Method

The almost universal method of smoke measurement for use in the enforcement of smoke ordinances has been the visual Ringelmann chart method. This is reasonably satisfactory for gross smoke conditions, but it is inadequate as a research tool. Sherman, Kaiser and Limbacher[1] have shown that the visual results of an experienced smoke observer will vary from 3 to 18 smoke units and from 5 to 25 smoke units in reading Nos. 2 and 3 Ringlemann numbers, respectively. In both instances, there is a smoke concentration ratio of 5 to 1, or more, which appear the same to the eye.

There is also need of standard large-scale smoke test in various fuel laboratories. Some of these laboratories recently have installed photo-electric equipment to obtain such reliable smoke results.

Scope of Article

This article discusses the use of the smoke-index method in determining the relative smokiness of briquets and other fuels. It includes the theory of light absorption by smoke, a review of the previously published description[2] of the small-scale smoke-index method, and a presentation of the large-scale smoke-index method. The inclusion of the theory is essential to the proper understanding of the method and the review of the small-scale method avoids the necessity of reference to the previous publications.

Acknowledgments

At the beginning of this work Jacob Kunz, Professor of Physics, University of Illinois, reviewed and endorsed the underlying photo-electric theory on which the smoke-index method is based. J. M. Nash, Physics Assistant of the Survey staff, carried out the large part of the experimental work with assistance furnished by the Civil Works Administration as follows: F. W. Cooke, Physicist, J. J. Gibbons, Physicist, R. W. Tyler, Physicist; and P. G. Jones, Physics Assistant. H. C. Roberts, Physics Assistant of the staff, designed and constructed the small-scale smoke-index equipment. R. J. Helfinstine, Mechanical Engineer of the Coal Division of the Survey, has added an ingenious attachment to the large-scale smoke-index equipment for checking the zero photo-electric reading during a smoke test.

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[1] Sherman, R. A., Kaiser, E. R., and Limbacher, H. L., The relation of size of bituminous coals to their performances on small underfeed stokers, Part II., Burning tests on four typical coals: Bituminous Coal Research, Inc., Tech. Rep. No. 1, Part II. See Fig 4-A, p. 46.

[2] Piersol, R. J., Smoke Index: a quantitative measurement of smoke: Fuel, Vol. 15, Nos. 9, 10, 11, 12, 1936; Illinois Geol. Survey Report Inv. No. 41, 1936; Proceedings 34th Annual Convention of Smoke Prevention Assn. of Am., Inc., 1940.

THEORY OF MEASUREMENT OF SMOKE DENSITY BY LIGHT ABSORPTION

LAMBERT'S LAW

When a beam of light passes through a column of smoke a percentage of the light intensity is absorbed by the smoke; the percentage of light absorption increases with the increase of smoke density. This relationship is given by Lambert's Law (the analogue is Beer's Law for light absorption by liquids) which may be stated mathematically as follows:

$$I_a = I_o (1 - e^{-kD}) \qquad (1)$$

where I_a and I_o are the intensities of the absorbed light and of the original light, respectively, e is the base of natural logarithms, k is a proportionality constant, and D is the density of the smoke.

By the Survey's smoke density equipment, it was found that a smoke density of Ringelmann No. 2 (40 percent) corresponds to a light absorption of 76 percent for the smoke produced by the types of coal used in this study. This permits the calculation of K for this particular equipment as follows:

$$76 = 100 (1 - e^{-40K}) \qquad (2)$$

Transferring to natural logarithms

$$k = \frac{\log_e 100 - \log_e (100 - 76)}{40} = 0.0357 \qquad (3)$$

and equation 1 becomes

$$I = I_o (1 - e^{-0.0357D}) \qquad (4)$$

Logarithms to the base 10 are used more generally than natural logarithms and are used in the accompanying table. The conversion to base 10 logarithms may be made by the use of a new constant K where

$$K = k \log_{10} e = k \log_{10} 2.718 = 0.434\ k \qquad (5)$$

and from equation 3, the value K is

$$K = 0.434 \times 0.0357 = 0.0155 \qquad (6)$$

where the proportionality constants k and K are associated with natural logarithms and logarithms to the base 10, respectively.

Table 12 and corresponding figure 15 show the percentage of light absorbed for various smoke densities as calculated from equation 4.

Expressed in simpler terms, Lambert's Law, when applied to smoking stacks, means that if 10 percent smoke density absorbs 30 percent of the light, then 20 percent smoke density will absorb an additional 30 percent of the remaining 70 percent which is 21 percent or a total of 51 percent; and likewise 30 percent smoke density will absorb an additional 30 percent of the remaining 49 percent or a total of 65.7 percent as shown in table 12. It follows that only an infinite concentration of smoke will absorb all the light intensity, and at any finite smoke density a percentage of light intensity is transmitted through the smoke. To illustrate by table 12: 97.2 percent of the light intensity is absorbed by 100 percent smoke density in the Survey's smoke equipment.

As noted above, 40 percent smoke density was arbitrarily taken to correspond to a Ringelmann chart at Ringelmann No. 2 smoke. The other significance of smoke density is that the values are numerically comparable; e.g., 40 percent smoke density is exactly double 20 percent smoke density. However, smoke-index equipment using a different length of light path through the smoke, a different smoke velocity, or a different smoke stack diameter would require a different constant K to make the results comparable. In other words, equation 1 represents a family of curves. Table 13 shows data for two other members for hypothetical values of K equal to 0.01 and to 0.02. Figure 16 is the graph of these members of the family.

COMPARISON OF RINGELMANN AND LIGHT ABSORPTION METHODS

The Ringelmann method of determining the density of smoke consists of visually matching the smoke to a set of six comparison charts which represent different degrees of gray, ranging from white to black: No. 0 is 100% white; No. 1 is 80 % white and 20% black; No. 2 is 60% white and 40% black; No. 3 is 40% white

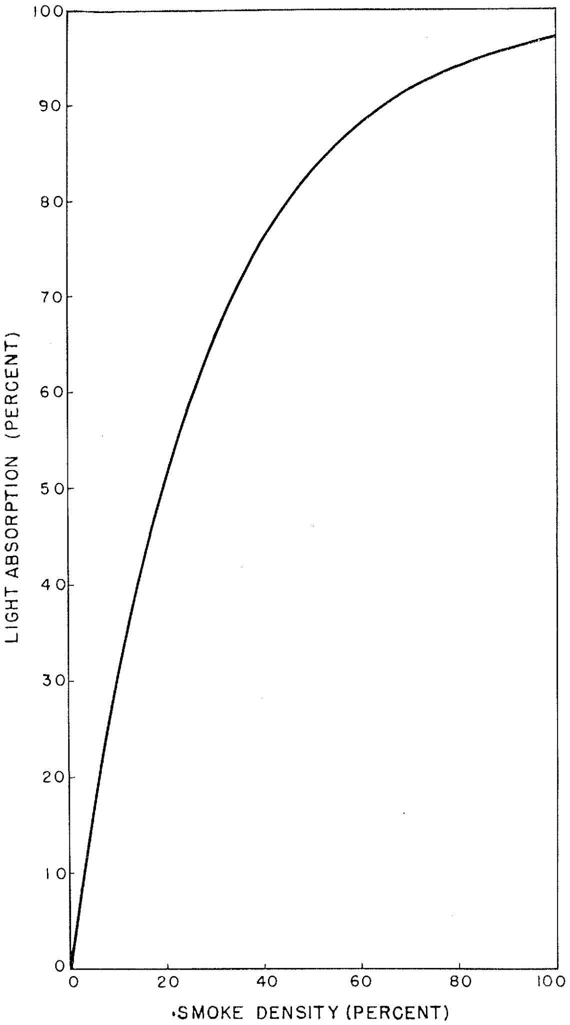

FIG. 15.—Influence of smoke density on absorption of light intensity where K = 0.0155, $I_a = I_o\ (1 - e^{-kx})$. (Data from table 12)

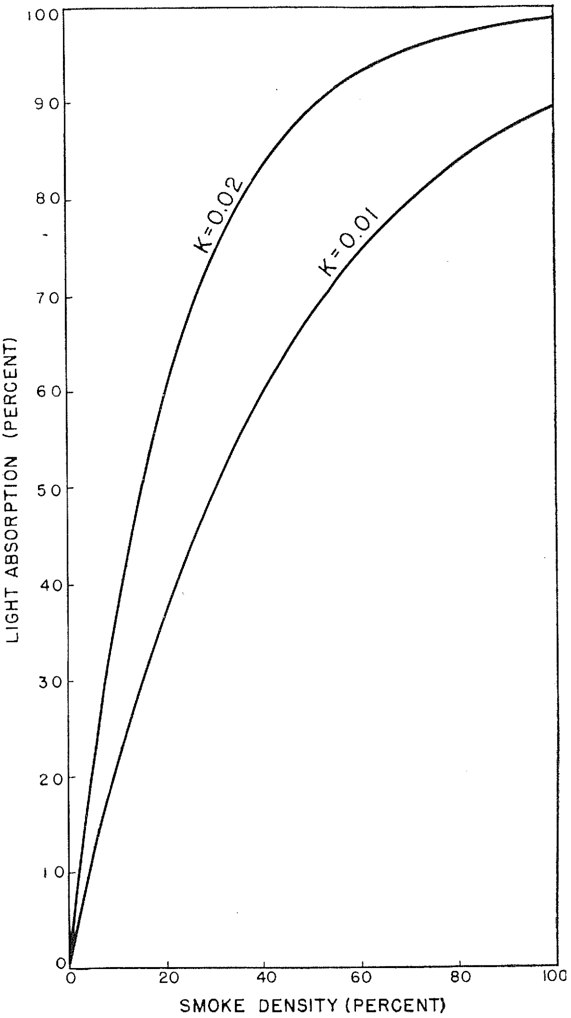

FIG. 16.—Influence of smoke density on absorption of light intensity. (Data from table 13.)

TABLE 12.—INFLUENCE OF SMOKE DENSITY ON ABSORPTION OF LIGHT INTENSITY

(Data for Fig. 15)

Smoke density (percent)	Light absorption (percent) K=0.0155
0	0.0
10	30.0
20	51.0
30	65.7
40	76.0
50	83.2
60	88.2
70	91.8
80	94.2
90	96.0
100	97.2

TABLE 13.—INFLUENCE OF CONSTANT K ON RELATION OF SMOKE DENSITY TO ABSORPTION OF LIGHT INTENSITY

(Data for Fig. 16)

Smoke density (percent)	Light absorption (percent)	
	K=0.01	K=0.02
0	0.0	0.0
10	20.6	36.9
20	36.9	60.2
30	49.8	74.9
40	60.2	84.2
50	68.4	90.0
60	74.9	93.7
70	80.0	96.0
80	84.2	97.5
90	87.4	98.4
100	90.0	99.0

TABLE 14.—RELATIONSHIP OF RINGELMANN NUMBERS AND ABSORPTION OF LIGHT INTENSITY

(Data for Fig. 17)

Ringelmann		Light absorption (Percent)
Number	(Percent)	
1	20	43
2	40	76
3	60	91
4	80	96
5	100	100

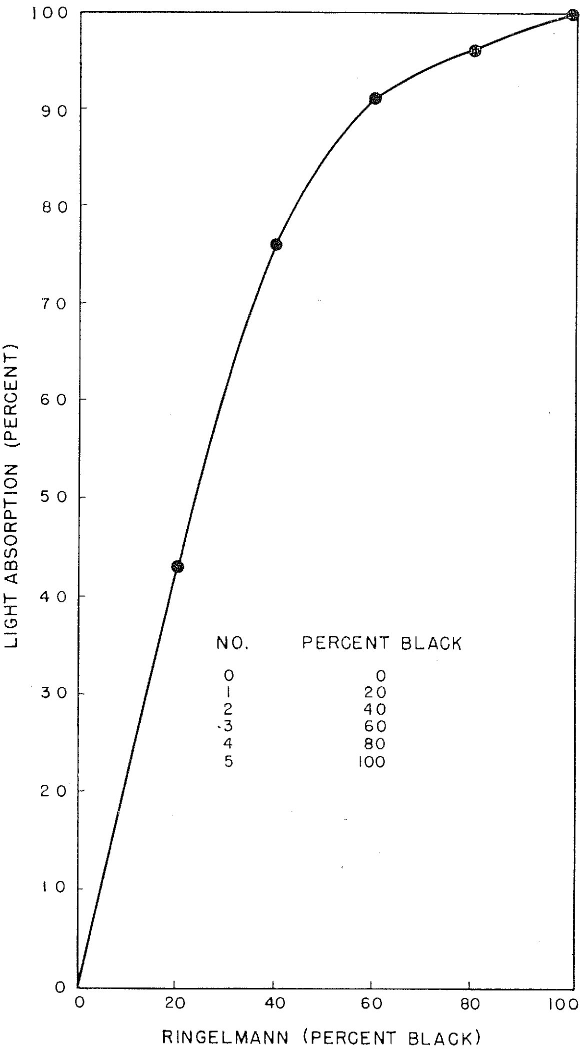

FIG. 17.—Relationship of Ringelmann numbers and absorption of light intensity. (Data from table 14)

and 60% black; No. 4 is 20% white and 80% black; and No. 5 is 100% black. The white on the chart is the clear background of white cardboard on which the chart is made, and the black is in the form of lines in cross-section, for charts Nos. 1, 2, 3, and 4, and the width of the lines is such that the proportional amount of black is shown. The whole surface of chart No. 5 is black.

By placing the Ringelmann charts far enough from the eye, the cross-section lines on the four charts (Nos. 1, 2, 3 and 4) become diffused to the eye and appear as different shades of gray, whereas the white chart (No. 0) and the black chart (No. 5) appear unchanged in color.

Comparative observations of smoke by the Ringelmann method are made by placing the six charts at the proper distance between the observer and the smoke to be observed, with a clear background for the smoke and with no direct rays of the sun entering the eye of the observer. The color of the smoke emitted is then compared with the colors of the six charts. The density of the smoke may be expressed in percent by multiplying the chart number by 20.

Using this method, an experienced smoke observer determined the Ringelmann readings for the density of smoke issuing from the smoke stack and at the same time readings of light absorption by the smoke were made by the Survey's photo-electric recorder. The average results (table 14 and fig. 17) reveal closely similar relationships between smoke density as measured by the Ringelmann charts and by the photo-electric light absorption method and the theoretical smoke density curve (fig. 15).

APPROXIMATE LINEAR RELATIONSHIP BETWEEN LIGHT ABSORPTION AND SMOKE DENSITY FOR ITS LOWER VALUES

In the development of a smoke-index, useful in determining the smokiness of briquets, we are interested only in values of less than 50 percent light absorption. The lower part of the logarithmic curve in figure 15 is characteristically essentially linear in its lower part. Hence an essentially linear relationship between light absorption and smoke density is characteristic in the range below 50 percent light absorption. Accordingly it is practical to use the percentage of light absorption as a measurement of the amount of smoke. Expressed algebraically,

$$S = C\, I_a \qquad (7)$$

where both the smoke S and the absorbed light's intensity I_a are expressed in units of percent and C is the proportionality constant.

Influence of Velocity of Smoke Stack Gases on Smoke Measurement

The light absorption or smoke-index method for smoke determination when applied to stack merely measures the concentration of smoke particles in the stack gases (number of smoke particles per unit volume). However, the amount of smoke which passes through the stack per unit time is the product of the concentration of the smoke particles and the velocity of the smoke stream.

For any other than the standardized velocity of the stack gases, equation 1 becomes

$$I_a = I_o\,(1 - e^{-kvD}) \qquad (8)$$

where the stack velocity v is measured in terms of its ratio to the standardized velocity v_o.

Influence of Diameter of Smoke Stack on Smoke Measurement

In the comparison of smoke measurement in two smoke stacks, their ratios of diameter affect (a) the length of light absorption (diameter of the smoke stack) and (b) the velocity of the smoke stack gases.

For any circular smoke stack other than that of standardized diameter L_o, equation 8 becomes

$$I_a = I_o\,(1 - e^{-kvLD}) \qquad (9)$$

where the smoke stack diameter L is measured in terms of its ratio to the standardized diameter L_o.

Equation 9 not only is valid for circular smoke stacks, but also holds for the comparison of any two smoke stacks of similar cross section, such as square, hexagonal, octagonal, and so forth.

In two circular smoke stacks of different diameters, the ratio of velocities of gases is inversely proportional to the ratio of the cross sectional areas of the two stacks for constant volume of flow of gases. Since the ratio of areas of these two stacks is equal to that of their diameters squared (L^2), equation 9 becomes

$$I_a = I_o\,(1 - e^{-kD/L}) \qquad (10)$$

which may be considered the general conversion equation for two smoke stacks of different diameter, but for the same constant volume of flow of gases.

Because it is doubtful, and perhaps accidental, that two different laboratories will use the same constant volume of flow of stack gases, it appears that the preferred method of comparison of the results of various laboratories is to determine experimentally the proportionality constant k by direct comparison with a Ringelmann No. 2 smoke density as shown in equations 3, 4, and 5.

LARGE-SCALE SMOKE-INDEX TESTS

The smoke-index tests on the large scale were undertaken after the development of the method for laboratory tests, partly to compare the values for smoke density obtained by the smoke density method with those obtained by use of the Ringelmann chart, partly to obtain comparative determination of the smoke densities of various coals and commercial briquets made with a binder and partly to have some basis of comparison with results obtained in the small-scale tests. These large-scale tests, although not directly applicable to the development of the binderless briquets, were useful in providing a quantitative method for measuring the total amount of smoke liberated in the combustion of a fuel in a conventional hand-fired or a stoker-fired stove or furnace.

Comparison of Large- and Small-scale Tests

The large-scale method consists of the continuous measurement of smoke throughout the period of a series of tests in which a specified weight of fuel is stoked at definite intervals into a hand-fired stove, its temperature being maintained as constant as possible by uniform draft regulation. The amount of smoke is measured by means of a specially designed photo-electric recorder, the light beam passing horizontally through the vertical smoke pipe. Although the quantity of fuel charge may be of any weight, it has proved convenient to standardize on a 20-pound charge. Also, although any rate of burning may be used, it has proved convenient to maintain a rate of 10 pounds per hour which results in a two-hour firing interval. Furthermore, although any ratio of overdraft to underdraft may be used, it has been found that equal overdraft and underdraft provide the best burning condition. Experience has developed a test procedure consisting of a series of five consecutive firings not including the first firing. The purpose of the first firing is to raise the temperature of the stove to equilibrium, therefore the smoke results for the first firing are not included in the average results of the five subsequent refirings.

The method of calculation of the smoke-index is the same for both the large-scale and small-scale tests, that is, the smoke-index is equal to the product of the average smoke density percentages and the period of smoke production divided by the weight of the fuel. However, in large-scale tests the weight of the fuel is customarily expressed in pounds, therefore the unit of weight used in the large-scale smoke-index value is pounds and the unit of time is minutes; whereas the corresponding units in the small-scale smoke-index value are grams and seconds, respectively.

Both methods may be used to measure the comparative smoke density of two fuels, but the large-scale method may be used for some purposes for which the small-scale method is not feasible. To illustrate: The large-scale smoke-index method serves as a most useful research tool (a) for improving firing methods to reduce smoke, (b) for comparing the smokiness of the same fuel burned in various types of equipment, and (c) for determining the smoke produced at the various stages in the operation of a mechanical stoker.

Although the small- and large-scale smoke-index methods are essentially the same, the success of large-scale smoke tests is determined by a clear understanding of certain characteristic differences between the two kinds of tests. In the small-scale tests, both the temperature and the air supply are extraneously supplied; the temperature is not affected by the burning coal, nor is the rate of flow of smoke through the absorption tube appreciably affected by the release of gases during combustion. The purpose of large-scale smoke-index tests is to determine the amount of smoke liberated by a given coal in a given stove; hence normal burning conditions must be maintained as closely as possible. In the small-scale test, the velocity of the smoke through the absorption tube is independent of the rate at which the coal is consumed, but in the large-scale test, from 10 to 30 percent of the quantity of smoke pipe gases originates from the combustion of the coal and is in addition to the quantity of air supplied, thereby varying the flow of the discharge gases. Because the smoke-index is dependent on both the temperature of combustion and the velocity of gases through the smoke pipe, it is essential to burn the coal at the same rate, the same temperature, and with the same air draft for two comparative large-scale smoke-index tests.

EQUIPMENT

The essential equipment consists of a stove for burning the fuel, a connection by which a beam of light may be passed through the smoke in the smoke pipe, a source of controlled illumination, a photo-electric cell, and a smoke recorder.

Stove.—Due to the nature of the large-scale smoke-index method, any specified type of stove may be used. However, if the smoke characteristics of various coals are to be compared to those of a standard coal (for example, a 23-percent volatile Pocahontas coal), it is advantageous to standardize on one or more selected types of

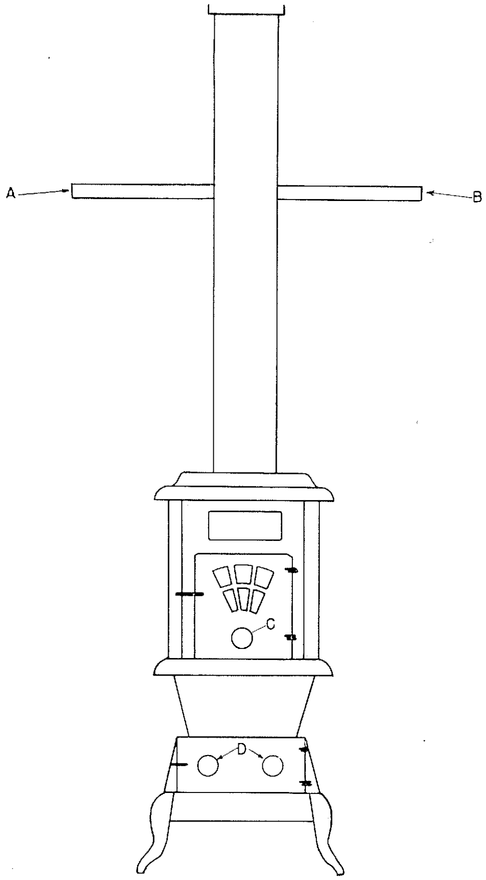

FIG. 18.—Large-scale combustion furnace. A—Light; B—Photo-electric cell; C—Overdraft damper; D—Underdraft damper.

stoves. In the Survey's studies on the development of smokeless briquets, the large-scale smoke-index method has been applied primarily as a means of ascertaining the smoke characteristics of smokeless briquets as compared with those of natural smokeless coals. Because there is a demand for such briquets in the tenement districts of large cities where lower priced hand-fired space heaters are used, stoves of this type were selected. The two identical stoves, used simultaneously for making smoke tests, are known as Supreme No. 25, manufactured by the Indianapolis Stove Company (fig. 18). The inside diameter of the hemispherical fire-pot is 18 inches with a 12-inch circular grate 10 inches below the top of the fire-pot. An 18-inch diameter cylindrical casing, 23 inches high, extends above the fire-pot. The top of each stove is connected to a separate chimney through a 7-inch smoke pipe. Each smoke pipe is equipped with a source of light A, and a photo-electric cell B. Also the stove is equipped with an overdraft damper C and double underdrafting dampers D, all adjustable.

In addition to these two space heaters, a hand-fired furnace was used for smoke testing. This furnace is known as Hot Water Heater No. 7, manufactured by the American Radiator Company. The inside width of the fire-pot is 18 inches; the breadth is 25 inches; the height from grate to bottom of hot water coils is 20 inches; and the height from grate to bottom of door is 10 inches. For a fuel bed even with the bottom of the door, the height of the effective combustion chamber is 10 inches with resultant high temperature gradient from that of the firebed to that of the overlying water coils, with resultant conditions favorable to the production of smoke. The top of the furnace is connected to a separate chimney by an 8-inch smoke pipe which is also equipped with a photo-electric unit. The furnace also has adjustable overdraft and underdraft dampers.

Photo-electric unit.—In large-scale smoke-index equipment, the beam of light is passed horizontally through the vertical smoke pipe; and thus the smoke pipe serves as an absorption tube, whose effective length is equal to the diameter of the smoke pipe. In addition the photo-electric unit consists of a source of light; an optical system for focusing the beam of light, which passes through the smoke pipe, upon the light-sensitive surface of the photo-electric cell; and a galvanometer.

The photo-electric unit is located approximately 3 feet above the top of the stove. On opposite sides of the smoke pipe, holes 1.5-inch in diameter are cut, over which are welded 1.5-inch pipe inner sleeves with long nipples to which outer sleeves are attached, with a distance of 18 inches from smoke pipe to end of sleeves. In the sleeve A (fig. 18), the head of an adjustable focus flash light (Lightmaster) is rigidly fixed. The head of the flash light consists of a reflector and a socket with a 6-volt, 0.5-ampere bulb with current furnished through leads attached to a 6-volt automobile storage battery. In the sleeve B, the photo-electric cell is fixed and has leads to the galvanometer. A ¼-inch hole is drilled through each nipple at the edge of the outside sleeve; this provides a slight air current toward the smoke pipe, thereby preventing the deposition of soot on either the glass of the flash light or the glass cover of the photo-electric cell.

The galvanometer consists of a strip recorder of the micromax type built according to our specifications by the Leeds and Northrup Company. The scale reads from zero to 100, the zero reading corresponding to full light intensity and the 100 reading to zero light intensity. A Weston photronic cell model 594 requires a light intensity of about 12 foot-candles for full light intensity (25 microamperes). The micromax recorder was built with a special circuit (fig. 19) which can be used in connection with a photo-electirc cell without regard to its resistance, and this special circuit results in a linear scale reading with respect to the intensity of illumination supplied.

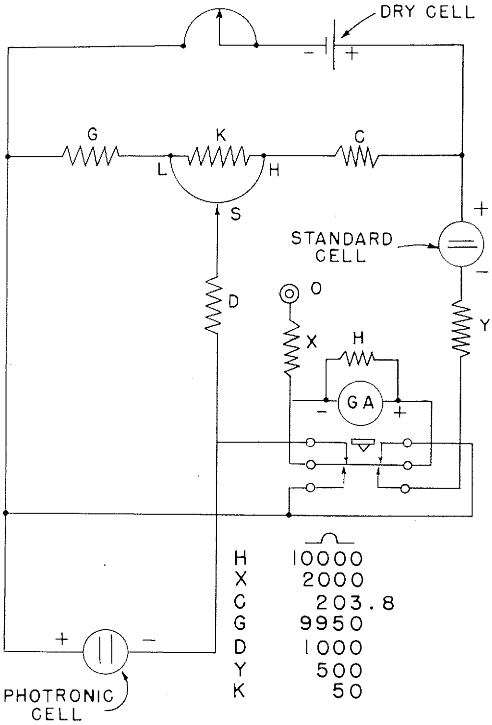

FIG. 19.—Electric circuit of smoke recorder.

The two photo-electric units used later by Helfinstine in his stoker research are substantially of the same type. He uses a multiple-pen micromax recorder with a 0 to 40 millivolt range, with a 100-ohm shunt across the photronic cell circuit which provides a reading of 30 millivolts from the full light intensity of about 70 foot-candles from an automobile sealed beam spot light. This light intensity necessitates cooling the photronic cells by water coils mounted in the cell housing; the photronic cells should be protected against being heated to a temperature beyond 60° C. (140° F.) because continued heating may result in permanent changes in sensitivity.

As stoker tests often are carried through several days' continuous operation, Helfinstine has made an ingenious contribution which deals with means for zero setting of the photo-electric system during testing. The sleeves A and B (fig. 18), which hold the lamp and the photo-electric cell, respectively, are fixed to a rotatable arm instead of the inner and outer nipples which are fixed to the smoke pipe. To obtain a zero setting, the arm is rotated to a 90-degree position, where the two outer sleeves fixed in a position outside the smoke pipe cover the ends of a single long nipple; the second position provides a condition identical to the first position with no smoke in the smoke pipe.

Although smoke-index equipment which includes a recording galvanometer is more convenient, a non-recording galvanometer (or micro-ammeter) is less expensive and equally accurate; however the latter requires an operator to make readings throughout the test.

PROCEDURE

In the assembly of the large-scale smoke-index apparatus, it is convenient to select a galvanometer with the proper shunt to provide a linear reading with increased light intensity.

Calibration of apparatus.—Unless the apparatus has been calibrated for the type

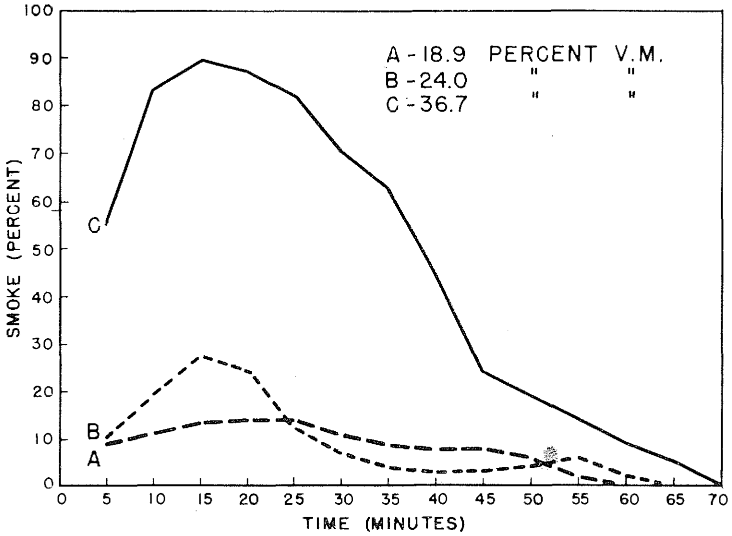

Fig. 20.—Large-scale smoke-index of various volatile coals. (Data from table 15)

of photo-electric cell to be used by a reliable manufacturer of the equipment, the investigator before using the apparatus should calibrate it according to the description for the calibration of the small-scale smoke-index apparatus.

Large-scale smoke-index tests on coal.—Before starting a series of tests to be carried out simultaneously with two identical stoves, the storage battery is connected to the lights and after an interval of about 10 minutes (which is essential to bring the battery and the photo-electric cells to equilibrium conditions) each light is focused so that the smoke-index recorder remains at zero reading (the dark reading of the recorder being 100).

Table 15.—Large-Scale Smoke-Index of Various Volatile Coals
(Data for Fig. 20)

Time (minutes)	Coals[a]		
	A	B	C
5	9	10	55
10	11	19	83
15	13	27	89
20	14	24	87
25	14	12	82
30	11	7	70
35	9	4	62
40	8	3	44
45	8	3	24
50	6	4	19
55	3	6	14
60	0	2	9
65	0	0	5
70	0	0	0
Total	114	121	643
Average	10.3	10.1	49.5
Time	55	60	65
Smoke-Index	28	30	161

[a] A 18.9 percent volatile West Virginia coal.
B 24.0 percent volatile Virginia coal.
C 36.7 percent volatile Illinois coal.

Stove A and stove B are used for smoke tests on the coal of unknown smoke characteristics and a standard coal, respectively. The standard coal used here normally is a 23 percent volatile Pocahontas coal, selected because such a coal is the highest volatile coal permissible for use in hand-fired furnaces according to the smoke ordinance of the City of St. Louis.

Having regulated the smoke-index apparatus, each stove is prepared with wood kindling and a 20-pound charge of coal and then ignited. The dampers are set at the same positions in each stove, with equal underdraft and overdraft, and so as to provide the desired rate of combustion. This preliminary cycle continues until the volatile matter has been completely removed; then each stove is refired with a 20-pound sample of the specified coal without shaking, poking, or otherwise disturbing the fuel bed; this second cycle continues for a specified period (two hours for a combustion

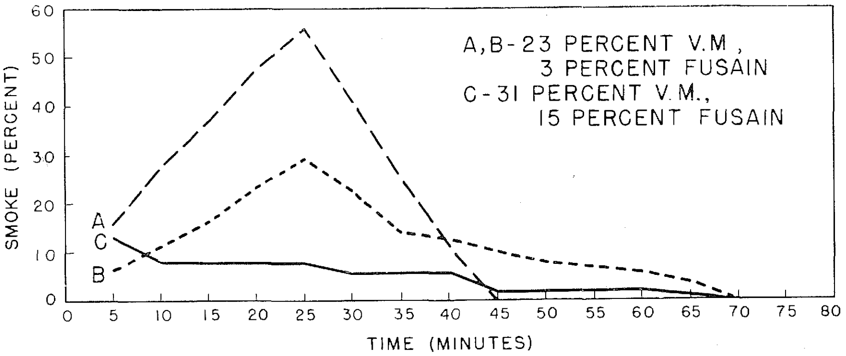

FIG. 21.—Large-scale smoke-index of various volatile briquets. (Data from table 16)

rate of 10 pounds per hour). This is followed by four more identical cycles.

Calculation of large-scale smoke-index.—The smoke-index is calculated from the micromax record for each of the five cycles (the preliminary cycle being omitted). The procedure used in calculation consists of tabulating the percent smoke at 5 minute intervals during the period of smoke liberation, which usually is from 45 to 90 minutes. The average percent of smoke is obtained by adding the individual smoke values and by dividing by the number of readings. And by definition, the smoke-index of the coal is the product of the average percent smoke and the period of cycle (in minutes) divided by the weight of the coal charge (in pounds).

Application of the Large-Scale Smoke-Index Method

Although this article is concerned primarily with the description of the smoke-index method as a research tool, it may be of assistance to the reader to refer briefly to a few of its applications. The illustrations selected include the large-scale smoke-index of coals of various volatile matter content; the smoke-index of briquets of various volatile matter content; and the smoke-index of a coal burned at various rates of combustion.

COALS OF VARIOUS VOLATILE MATTER CONTENT

Table 15 and the corresponding smoke graph (fig. 20) show the large-scale smoke-index results for burning in the standard hand-fired stoves at the rate of 10 pounds per hour, 20-pound samples of 18.9 percent volatile West Virginia coal A, of 24.0 percent volatile Virginia coal B, and of 36.7 percent volatile Illinois coal C, all reported on a moisture-free basis.

BRIQUETS OF VARIOUS VOLATILE MATTER AND FUSAIN CONTENT

Table 16 and corresponding smoke graph (fig. 21) show the large-scale smoke-index results for standard conditions of burning

TABLE 16.—LARGE-SCALE SMOKE-INDEX OF LOW VOLATILE BRIQUETS MADE WITH ASPHALT BINDER AND OF HIGH VOLATILE BRIQUETS MADE WITH SMOKELESS BINDER FROM COAL RICH IN FUSAIN
(Data for Fig. 21)

Time (minutes)	Briquets[a]		
	A	B	C
5	15	6	13
10	27	11	8
15	37	16	8
20	47	23	8
25	56	29	8
30	41	22	6
35	25	14	6
40	11	12	6
45	0	10	2
50	0	8	2
55	0	7	2
60	0	6	2
65	0	4	1
70	0	0	0
Total	259	168	72
Average	32.4	12.9	5.5
Time	40	65	65
Smoke-Index	65	42	20

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[a] A and B 23 percent volatile West Virginia briquets. C 31 percent volatile Illinois briquets containing 15 percent fusain.

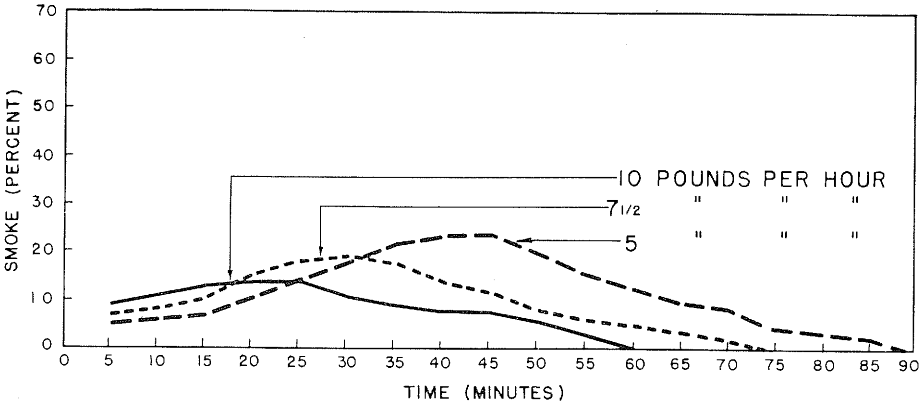

FIG. 22.—Influence of rate of burning on large-scale smoke-index of 18.9 percent volatile coal.

briquets A and B (two well known brands of commercial briquets that are made with asphalt binder from West Virginia Pocahontas coal, and contain about 23 percent volatile matter and less than 3 percent fusain) and briquets C (Fireballs that are made from Illinois deduster dust with a substantially smokeless binder, and contain about 31 percent volatile matter and about 15 percent fusain). The smoke-index of the high volatile Illinois briquets is less than one half of that of the two types of Pocahontas briquets for two reasons; first, the former are rich in fusain and second, the latter are made with a smoke-producing asphalt binder.

TABLE 17.—INFLUENCE OF RATE OF BURNING ON THE LARGE-SCALE SMOKE-INDEX OF AN 18.9 PERCENT VOLATILE WEST VIRGINIA COAL
(Data for Fig. 22)

Time (minutes)	Burning rate (pounds per hour)		
	5	7½	10
5	5	7	9
10	6	8	11
15	7	10	13
20	10	15	14
25	14	18	14
30	18	19	11
35	22	17	9
40	24	14	8
45	24	12	8
50	20	8	6
55	16	6	3
60	13	5	—
65	10	4	0
70	9	2	0
75	5	0	0
80	4	0	0
85	3	0	0
90	0	0	0
Total	210	145	114
Average	10.0	10.4	9.5
Time	105	70	55
Smoke-Index	53	36	28

VARIOUS RATES OF BURNING

Table 17 and corresponding smoke graph (fig. 22) show the influence of various rates of burning (5, 7½, and 10 pounds per hour) on the smoke-index of the 18.9 percent volatile West Virginia coal. All three of these tests were made under identical standard conditions, except for the rate of burning; the rates of 5 and 7½ pounds per hour required air drafts of approximately ½ and ¾, respectively, of the standard draft used for 10 pounds per hour.

In the previous theoretical description it was shown that in the comparison of smoke-index results obtained at two different velocities through the smoke pipe, the relative velocities must be considered. In these tests, the velocities correspond to the draft ratios and therefore are ½, ¾, and 1 for the three respective rates of burning. Therefore on a comparative basis, the three smoke indices are 26.5 (½ of 53), 27 (¾ of 36), and 28. This indicates that the amount of smoke produced (smoke-index corrected for velocity of smoke through the smoke pipe) is approximately the same for the three rates of burning.

SMALL-SCALE SMOKE-INDEX METHOD

The principles on which large-scale smoke-index tests are based are identical to

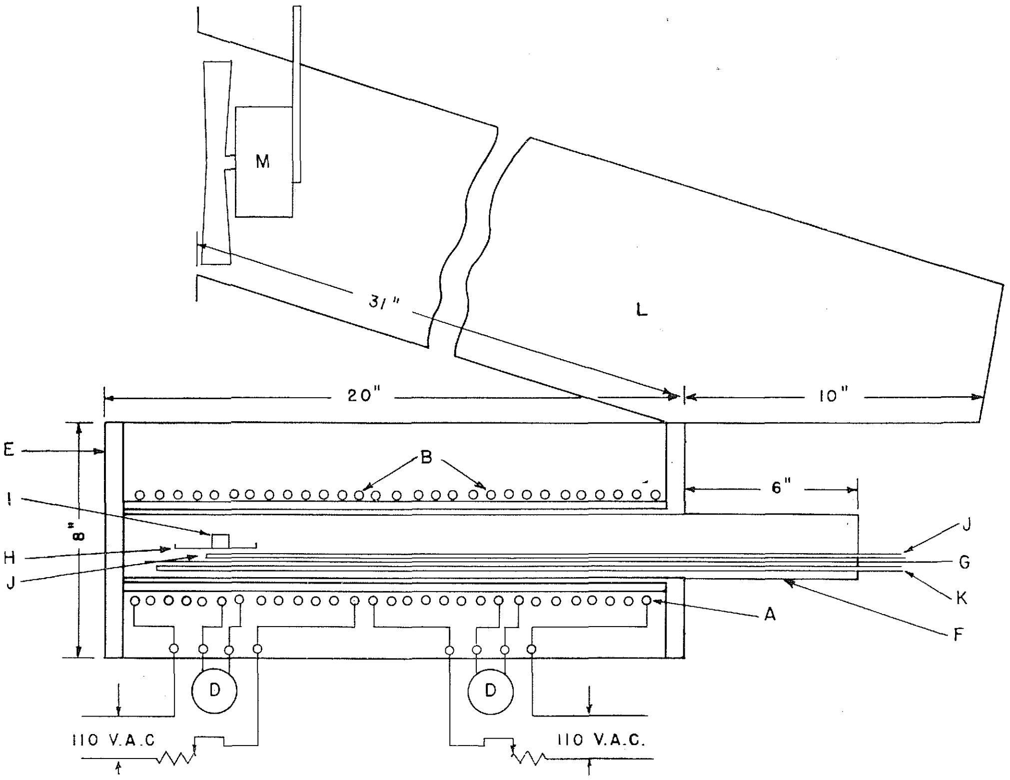

FIG. 23.—Combustion furnace.

those in small-scale tests. This review includes the description of the method, equipment, and procedure and shows the influence of temperature and air supply on the resulting smoke index as used in the small-scale tests.

The smoke-index method can be used as a quantitative laboratory scale test which may be performed on any sample of fuel of any convenient weight. The small-scale equipment used in these investigations was developed for a sample of approximately one gram. The use of a small sample has its advantages. For instance, tests may be made on one coal ingredient only, such as clarain. In this study, the samples used were all cut to the same size and shape on two parallel carborundum saws spaced 1 cm. apart, their weights being only slightly if any different.

EQUIPMENT

The essential equipment consists of an electric muffle furnace, a tube for light absorption by the smoke, a source of air supply, means for drawing the smoke through the absorption tube, a source of constant illumination, a photo-electric cell, and a galvanometer.

FURNACE

The electric muffle furnace (fig. 23) constructed for use in this investigation, consists of a three-inch inside diameter alundum tube A, 18 inches long, wound with two heating elements B, of No. 19 "Chromel" wire and each having a resistance of 15 ohms. Each of the two elements has a separate controlling rheostat C, and an ammeter D, in series with it, so that the temperature of the front and rear parts of the furnace may be controlled separately, if desired.

The alundum tube, with the heating coils, was given a coating of alundum cement about ¼ inch thick, and then placed in a steel and transite case E, 8 inches square and 20 inches long, packed with "Sil-O-Cel." A steel tube F, 2½ inches inside diameter and 26 inches long, was fitted into the alundum muffle to protect it and to increase the heat capacity of the furnace and thereby minimize small fluctuations in temperature.

A steel tray G, 1⅞ inches wide, ⅛ inch deep, and 30 inches long, was used to carry the container H, in which the sample I, was placed. The thermocouple J was mounted in the tray with its junction directly under the sample container. The thermocouple leads extended to a potentiometer near the open end of the furnace. Air was introduced into the furnace through a small iron pipe K, leading to the back of the furnace, passing along the bottom of the muffle beneath the tray. The amount of air admitted to the furnace was measured by a calibrated differential manometer of orifice type.

ABSORPTION TUBE

The smoke given off by the burning sample is drawn from the mouth of the furnace A, through the absorption tube B, by a compressed air aspirator C (fig. 24). This tube is 34 inches long and 1⅜ inches inside diameter, and its inner surfaces are blackened. At the end of the absorption tube nearest the furnace there is mounted a 15-watt, 110-volt A.C. inside frosted incandescent bulb D, in the sleeve, in such a manner that the surface of the bulb is 1 inch from the glass window F, closing the end of the absorption tube. On the other end of the absorption tube is a similar sleeve in which the photo-electric cell E is mounted. As the smoke passes through the absorption tube the beam of light from the incandescent bulb D, is partially obscured, the intensity of the transmitted light being measured by the photo-electric cell E. In the direction parallel to the axis of the cell and with no smoke present, the intensity of the illumination on the photo-electric cell is 0.75 foot-candles. The ends of the tube are closed by the thin glass plates F, which are placed 4 inches from the inlet and outlet of the absorption tube. These windows may be cleaned as required, but due to their position, remain fairly clean throughout one test.

The photo-electric cell used in this investigation was a Weston photronic cell, model 594. It was connected in series with a 3000 ohm resistance and a D'Arsonal type galvanometer (sensitivity equals 0.82 microamperes per millimeter at a distance of 1 meter).

PROCEDURE

Before using the smoke-index apparatus, it was necessary to calibrate the photo-electric cell, the incandescent lamp, and the differential manometer.

CALIBRATION OF APPARATUS

The incandescent lamp, used as a light source, was an ordinary commercial 15-watt

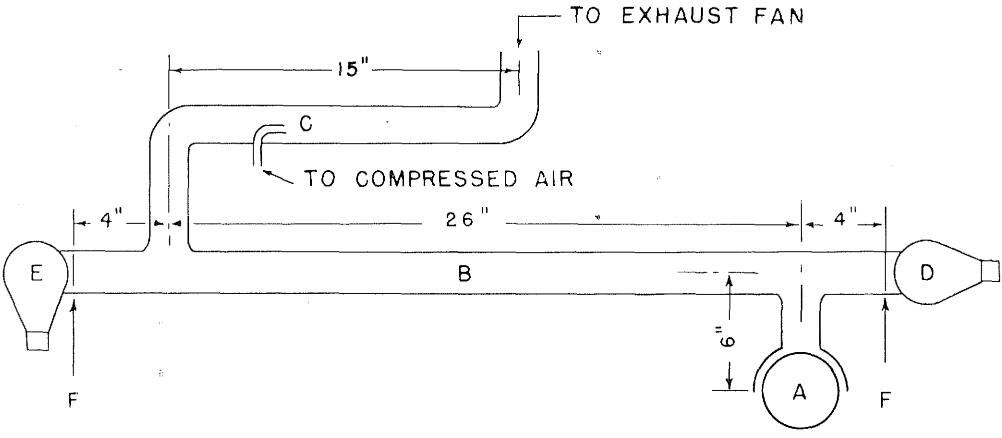

FIG. 24.—Photo-electric unit for determination of smoke-index.

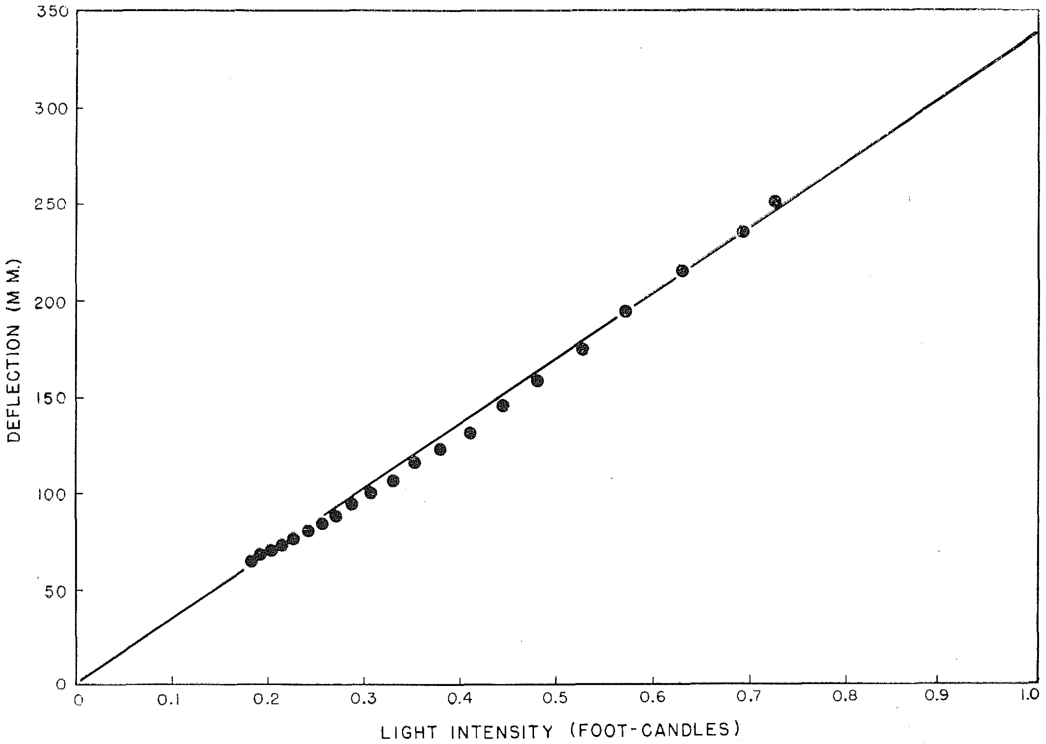

FIG. 25.—Calibration curve for Weston photo-electric cell. (Data from table 18)

General Electric bulb. Its candlepower was determined, using a Bunsen photometric bench and a standard lamp. The candle power of the incandescent lamp, in the direction along its axis from its rounded end, was found to be 20.4.

Also the photo-electric cell was calibrated in units of galvanometer deflection and intensity of illumination by means of the photometric bench using the standard lamp. The data for the calibration of the photo-electric cell are recorded in table 18 and the corresponding calibration curve is plotted (fig. 25).

An independent determination showed that the galvanometer deflection due to the light intensity on the photo-electric cell is 257 mm. for the smoke-index equipment. The calibration curve (fig. 25) shows that the intensity of illumination on the photo-electric cell is 0.75 foot-candles for no smoke, and that the calibration curve is approximately a straight line with zero deflection with complete absorption of light by smoke.

The differential manometer was calibrated against a Sargent wet-test gas meter; its calibration curve is shown in fig. 26.

TESTS ON COAL

In making smoke-index tests to determine the total amount of smoke liberated in the burning of a given quantity of coal, either

TABLE 18.—CALIBRATION DATA FOR WESTON PHOTO-ELECTRIC CELL
(Data for Fig. 25)

Deflection (millimeters)	Intensity (foot-candles)	Deflection (millimeters)	Intensity (foot-candles)
64	0.183	114	0.354
67	0.192	121	0.381
69	0.204	130	0.410
72	0.214	144	0.445
75	0.227	157	0.481
79	0.241	174	0.528
83	0.256	193	0.573
87	0.272	214	0.632
93	0.289	234	0.695
99	0.307	250	0.729
105	0.331	256	0.750

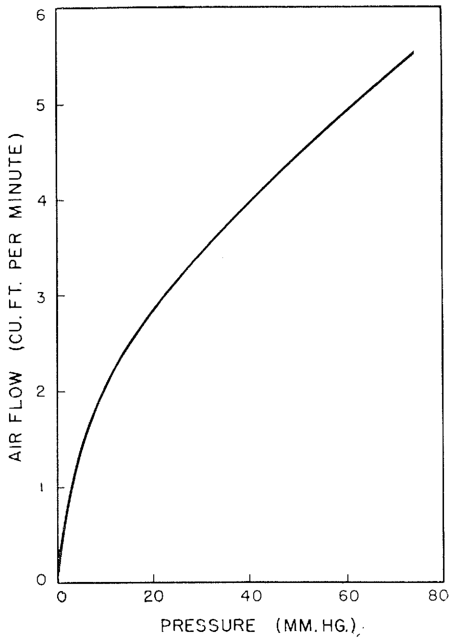

FIG. 26.—Calibration of manometer.

powdered or lump samples may be used. Powdered samples of coal will give more representative results if it is desired that the smoke-index should be that of the composite coal, but lump samples are essential if the effect of the texture of coal on its smokiness is to be considered. Furthermore, the burning of lump samples more nearly approaches the household use of coal. Lump samples of coal were therefore used for smoke-index tests made in this investigation.

In order to duplicate results, all samples were cut from one block of coal, selected on the basis of its apparent uniformity throughout. The most uniform coal available was a column sample of No. 5 seam from Mine No. 30 of the Black Mountain Corporation, Kenvir, Kentucky, with analysis as shown in table 19. The banded constituent of this coal block was clarain throughout.

The procedure in making a smoke-index test was to have the furnace at the desired temperature, the rate of flow of air being set at some given value, and then introduce into the furnace one of the small lump samples. The sample was placed on the small shallow nickel dish (fig. 23), which permitted a free circulation of air around the coal. The dish was placed on the furnace tray G, which was pushed into the furnace so that the sample, when burning occupied a position about half way back.

Since the lowest temperature (600° C.) used in making smoke-index tests was well above the ignition temperature of Illinois coals, the sample started to smoke soon after being put in place. Galvanometer readings were taken at five-second intervals, starting the instant the sample was placed in the furnace. They were continued until the sample stopped smoking as evidenced by the change from a yellow flame to a blue flame and also by the return of the galvanometer deflection to an approximately constant value.

ALGEBRAIC METHOD OF CALCULATING SMOKE-INDEX

The algebraic method of calculating smoke-index requires less time than the graphic method which consists of making a smoke graph plotting the percent smoke (percent light absorption obtained from galvanometer deflection readings) as ordinates and time (in seconds) as abscissae, the smoke-index being the area enclosed by the curve divided by the weight of the sam-

TABLE 19.—ANALYSIS OF COAL SAMPLE USED IN SMOKE-INDEX TESTS

	"As received"	Air dried	Moisture free	Moisture and ash free	Unit coal
Moisture	2.3	1.5	—	—	—
Volatile matter	35.6	35.9	36.4	37.4	—
Fixed carbon	59.6	60.1	61.1	62.6	—
Ash	2.5	2.5	2.5	—	—
Total sulfur	0.8	0.8	0.8	0.8	—
B.t.u.	14,251	14,362	14,581	14,960	15,013

ple (in grams). The algebraic method is as follows: The sum of all the galvanometer readings over the period of smoke production is obtained, and the average galvanometer deflection A is then calculated by dividing this sum by the total number of readings taken. The next step is to obtain the mean value B of the initial and final deflections. Then the average smoke density X, during the total time of combustion of the sample may be stated algebraically as follows:

$$X = \left(\frac{B - A}{A}\right) \times 100 \qquad (11)$$

This value of average smoke density X, when multiplied by the total time of combustion T gives the value of the area C, enclosed by the smoke density-time curve, and the area A represents the total amount of smoke given off by the sample tested. And algebraically

$$C = XT = \left(\frac{B - A}{A}\right) \times T \times 100 \qquad (12)$$

Then in order to convert to a common basis for comparison, this area C is divided by the weight W of the sample, which gives the smoke-index SI of the sample in units of percent smoke density times seconds per gram, or

$$S\,I = \frac{C}{W} = \frac{XT}{W} = \left(\frac{B - A}{A}\right) \times \frac{T}{W} \times 100 \qquad (13)$$

This gives a simple and reliable method of calculating the smoke-index of a fuel and is based on equation 7 which shows an approximately linear relationship between the amount of smoke and the light absorption by smoke for values of light absorption less than 50 percent.

Standardization of Small-Scale Smoke-Index Tests

It is well known that both the rate of air supply and the temperature of combustion affect the amount of smoke liberated by the burning of a fuel. Thus in the development of a method for determining the relative smokiness of various fuels it becomes necessary to establish and to standardize on preferred conditions for these two variables in smoke tests.

EFFECT OF AIR SUPPLY

To determine the effect of the air supply on the amount of smoke produced, a series of 25 tests were made on 1-cm. cubes of the coal cut from the same block of coal, using air supplies of 2, 3, 4, 5 and 6 cubic feet per minute, five tests being made for each rate of air supply. The furnace temperature was held at 600° C., and the tests were carried out in the usual manner except that the rate of air supply was changed every five tests. The results are given in table 20 (fig. 27) which gives the individual values of smoke-index for each of the five tests, for each air supply, and also the average value of smoke-index for each air supply. They indicate that increased air supply decreases the amount of smoke given off. For air supplies of less than 4 cubic feet per minute, there was quite an appreciable amount of soot deposited on the inner walls of the apparatus. For air supplies of 4 cubic feet per minute, or greater, this deposit was small. The results indicate only a small variation of smoke-index with variation of air supply from 3 to 5 cubic feet per minute. Therefore for all subsequent tests the value of air supply was standardized at 4 cubic feet per minute, which is sufficiently high to avoid excessive soot.

EFFECT OF TEMPERATURE

The amount and the character of smoke given off during combustion depends also, in part, on the temperature of the furnace. After determining a suitable rate of air supply, a number of tests were made to determine the temperature at which most accurate and reproducible results were obtained. The highest temperature of the upper portion of the bed of coal in a domestic furnace is from 600° C. to 1000° C.; accordingly, this range was investigated, in five steps of 100° C. each. Ten tests were made at each temperature, using duplicate samples from the same block of coal, but not that block used for samples for tests on effect of air supply.

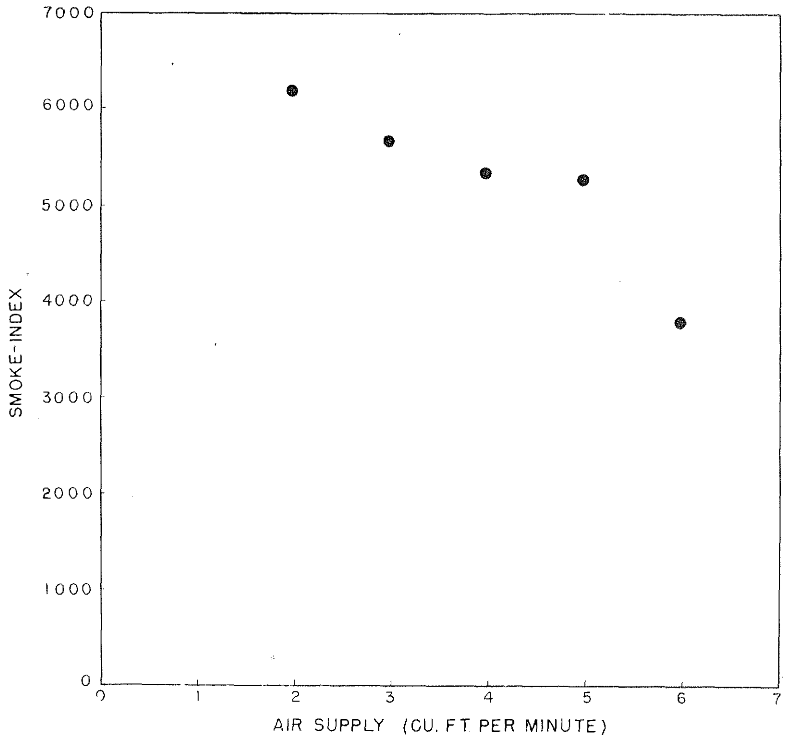

FIG. 27.—Effect of air supply on smoke-index. (Data from table 20)

The tests were carried out in the manner described previously, the air supply being held at a value of 4 cubic feet per minute. The temperature was raised 100° C. after every ten tests, starting at 600° C. and continuing to 1000° C. Table 21 summarizes the results, giving the ten individual values of smoke-index for each temperature used and, also, the average value of the smoke-index for each temperature (fig. 28).

TABLE 20.—EFFECT OF AIR SUPPLY ON SMOKE-INDEX
(Data for Fig. 27)

Test No.	Air Supply (cu. ft. per minute)				
	2.0	3.0	4.0	5.0	6.0
1.	5940	5040	5370	5410	3980
2.	6290	5810	5340	5490	3600
3.	6130	5680	5320	4980	3810
4.	6270	5570	4990	5470	3470
5.	6230	6270	5680	5060	4040
Average.	6170	5670	5340	5280	3780

The results of this series of tests show clearly a distinct decrease in smoke-index with increasing furnace temperature, the average smoke-index for 600° C. being 6390 and for 1000° C. being 2150, which is only one-third as great. This decrease takes place in a fairly uniform manner, although it is less pronounced in the middle than at the ends of the temperature range.

As regards the individual values of smoke-indices, table 21 shows that by far the most reproducible results were obtained at a temperature of 600° C.; the deviation from the average value varies from 0.9 to 6.3 percent with a mean deviation of 3.7 percent which represents the degree of reproducibility of the smoke-index method using the present equipment in which the temperature is maintained at 600 ± 3° C. and the air supply at 4.0 ± 0.1 cubic feet per minute.

LOGARITHMIC CALCULATION

As pointed out in the theoretical discussion, each time the density of smoke is

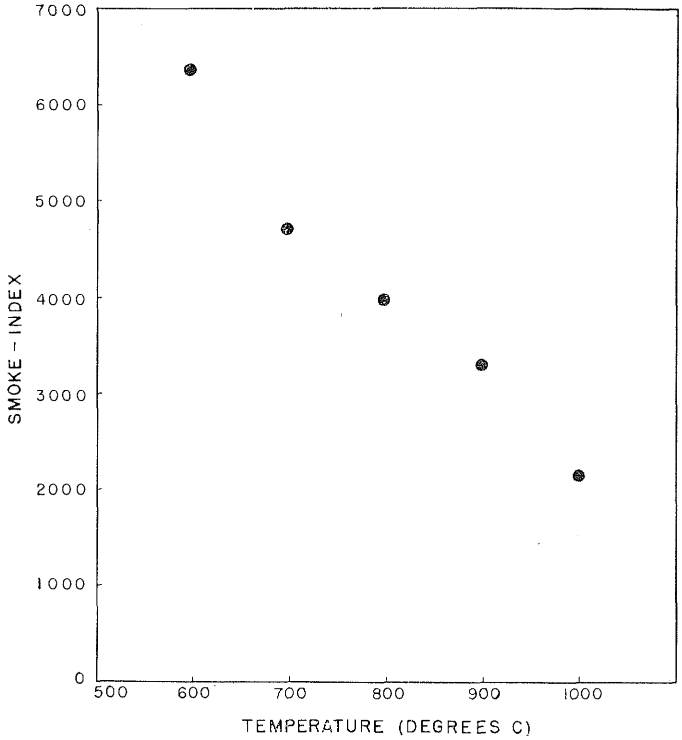

FIG. 28.—Effect of temperature on smoke-index.
(Data from table 21)

doubled, one half of the remaining light intensity is absorbed, but this results in an approximately linear relationship for conditions of less than 50 percent light absorption.

If desired, the smoke-index may be calculated on the logarithmic basis, but this has not been considered worthwhile on either the small- or large-scale smoke-index tests. However, as a matter of interest, both types of calculation were used for smoke-indices of coals and briquets having smoke values not higher than that of a 23 percent volatile natural coal. It was found that the comparative smoke-indices as calculated by the two methods agreed within two percent. This error is less than that of the reproducibility of tests.

GENERAL COMMENTS

In contrast to previous methods of measuring smokiness, the smoke-index method measures the total amount of smoke produced. Every particle of smoke passes through the smoke absorption tube, requiring an appreciable time for its passage. The use of the smoke-index method eliminates two defects of the previous methods: i.e., the necessity for the by-passing of a small fraction of the total smoke through the apparatus; and the irregularities in smoke

TABLE 21.—EFFECT OF TEMPERATURE ON SMOKE-INDEX
(Data for Fig. 28)

Test No.	Temperature °C.				
	600	700	800	900	1000
1..........	6740	4170	3470	3050	1630
2..........	6190	4870	4510	3730	3000
3..........	6080	3980	3760	2780	2030
4..........	6190	5220	3630	3670	1950
5..........	6320	4960	4120	3200	1430
6..........	6660	4960	3890	3800	2230
7..........	6560	4680	4080	3910	2110
8..........	6730	4190	3400	3380	2080
9..........	5980	4360	5450	3050	2750
10..........	6490	5700	3560	2490	2300
Average.....	6390	4710	3990	3310	2150

emission due to the periodic addition of fresh coal under ordinary firing conditions.

As all the smoke passes through the absorption tube in the smoke-index equipment, it is subject to measurement at every stage of burning, from before the time of ignition to complete ashing, if desired. The excessively large amounts of smoke liberated in the initial stages of burning are manifested, not being masked as they would be if other fuel in advanced stages of combustion were present at the same time. In fact, observed data are plotted so that they show clearly the relation of smoke produced to the stages of combustion.

The sample to be tested is placed in a muffle furnace, where conditions of temperature and air supply may be accurately controlled. The heat capacity of the furnace is sufficiently large that the heat which the small sample gives off while burning does not raise the temperature of the furnace appreciably. The furnace weighs about 30 pounds, being constructed of materials which have an average of about 0.2 specific heat. Thus the heat capacity of the furnace is equivalent to that of 6 pounds of water. The calorific value of bituminous coal is usually less than 15,000 B.t.u. Therefore the combustion of a one-gram sample of coal liberates not more than 33 B.t.u. which would raise the temperature of the furnace about 5.5° F. or 3.0° C. The sample is thus exposed to almost constant furnace temperature (within 3.0° C.) throughout all stages of combustion.

The smoke, as it issues from the burning sample, is drawn through the pipe in which the light is absorbed. A beam of light is constantly passing axially along the absorption tube, striking the light-sensitive photo-electric cell which is connected to a galvanometer. When no smoke is present to obscure the light beam, the galvanometer shows a maximum deflection. As smoke passes through the absorption tube it partially intercepts the light falling on the photo-electric cell, and the amount of obscurity, or the smoke density, may be calculated from the change in the galvanometer reading. That is, the amount by which the galvanometer reading is decreased, in percent, represents the proportion of light intercepted by the smoke in the absorption tube, in percent. This in turn is in direct ratio to the amount of smoke present. If these individual smoke density percentages, taken at regular intervals are averaged, the result is arbitrarily designated as the average smoke produced during the entire period of combustion. If this average is multiplied by the time required for combustion, in seconds, the total amount of smoke given off by that sample, in units of percentage smoke density and seconds time, is obtained. And if this total amount of smoke is divided by the weight of the sample used, the amount of smoke given off per gram of fuel, in terms of percentage smoke density and seconds time, is obtained. This value is called the smoke-index.

ARTICLE 4—INFLUENCE OF FUSAIN ON SMOKE-INDEX OF BRIQUETS

INTRODUCTION

PURPOSE OF INVESTIGATION

The discovery that the presence of considerable quantities of fusain enhanced the smokeless characteristics of briquets made from high volatile Illinois coal made it desirable to investigate the effect of varying quantities of fusain, to investigate the amount of fusain in Illinois coal, particularly in the various screen sizes of coal fines, and to promote the commercial application of this discovery.

Following the development of the smoke-index method for measuring the smokiness of coal in 1934 (Article 3), a study was made in 1935 of the smokiness of each of the four banded ingredients of coal—vitrain, clarain, durain, and fusain. The smoke-index of representative samples decreased 3260, 2500, 2090, and 13, respectively. By 1939 an extensive study had been made of the smokiness of briquets made from small sizes of representative Illinois fine coal containing various amounts of fusain.

Having discovered the low smoke-index value of fusain, and having investigated the smoke-index of briquets made from deduster dust containing varying quantities of fusain, the announcement of the discovery of the high volatile smokeless fusain-rich briquet was made at the thirty-fourth annual convention of the Smoke Prevention Association of America at St. Louis, May 21, 1940.[1]

NATURE AND DISTRIBUTION OF FUSAIN

Fusain, commonly known as mineral charcoal, occurs in two distinct types, the soft pulverant low-ash fusain and the hard highly mineralized fusain. The soft fusain, because it is very friable, tends to concentrate in the extremely fine screen sizes of coal.

PATENT PROTECTION

The process and the product of a smokeless briquet made from high volatile coal fines rich in fusain, either without or with binder, are covered by U. S. Patent No. 2,321,238, "Smokeless Briquets," granted June 8, 1943, for the protection of the people of the State of Illinois.

COMMERCIAL DEVELOPMENT

The Old Ben Coal Corporation has installed a plant at Buckner, Franklin County, Illinois, for making smokeless briquets from Illinois deduster dust rich in fusain, the product being known by the trade name, "Fireballs." This plant was in continuous operation from 1940 to 1945 with a capacity of 120,000 tons per year. The capacity has recently been increased to 300,000 tons per year. Fireballs contain slightly more than 30 percent volatile matter (as compared with 35 percent in the raw coal) and about 17 percent fusain, and they are made with a substantially smokeless starch binder. They possess a smoke-index somewhat less than that of 20 percent volatile Pocahontas coal.

ACKNOWLEDGMENTS

The smoke-index tests were made under the direction of the author by J. M. Nash, H. C. Roberts, P. J. Elarde, and D. O. Holland, all Physics Assistants, with assistance furnished by the Civil Works Administration as follows: F. W. Cooke, J. J. Gibbons, R. W. Tyler, all Physicists, and P. G. Jones, Physics Assistant, all of the Physics Division of the Survey.

The miscroscopic determination of the fusain content was made chiefly by B. C. Parks, Assistant Geologist of the Coal Division of the Survey. A few earlier determinations were made by L. C. McCabe, Geologist, and C. C. Boley, Associate Mining Engineer, both of the Coal Division of the Survey. The samples were collected by McCabe, Boley, and Parks.

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[1] Piersol, R. J., Smoke Index: Proc. 34th Annual Convention of Smoke Prevention Association of Am. Inc., pp. 20-23, 1940.

The chemical analyses of the samples, including the fusain determinations by the Fuchs method, all reported herein on a moisture-free basis, were made under the supervision of O. W. Rees, Chemist and Head of the Analytical Division of the Geochemical Section of the Survey.

Acknowledgment is made to the various Illinois coal operators who furnished the samples of coal used in this investigation.

EXPERIMENTAL METHODS

SMOKE-INDEX

The procedure and equipment for conducting smoke-index tests are presented in Article 3 of this report.

PETROGRAPHIC DETERMINATION OF FUSAIN

The sample of coal fines to be tested was sized into a series of screen fractions from 8-mesh to 300-mesh. Each screen size was weighed and then usually riffled down to about 4000 particles for larger sizes or about 1000 particles for smaller sizes; small numbers of particles were counted in very early analyses. Then with the use of a microscope, the fusain and non-fusain particles were separated and counted.

The appearance of the fusain is distinctive. The particles are needle-shaped, resembling finely macerated fragments of charcoal.

The percentage of fusain in each screen size is considered to be the number of fusain particles divided by the total number of fusain and non-fusain particles. The cumulative percent in fusain for two screen sizes may be expressed:

$$F = \frac{W_1 \times F_1 + W_2 F_2}{W_1 + W_2} \qquad (1)$$

where F, F_1, and F_2 are the percentages of fusain in the cumulative fractions in fraction 1 and fraction 2, respectively; and where W_1 and W_2 are the percentage weights of fraction 1 and fraction 2, respectively.

This cumulative process is extended through all the increasing sizes of screen fractions; in each step the F_1 and W_1 of above equations are the cumulative values of all previous steps.

CHEMICAL DETERMINATION OF FUSAIN

There are two chemical oxidation methods for the determination of the percentage of fusain in coal. Heathcoat[2] developed the method in which the coal is oxidized under such conditions that the non-fusain material becomes soluble in alkali whereas the fusain remains substantially unaltered; after washing away the oxidized non-fusain material

TABLE 22.—PROXIMATE ANALYSES OF VARIOUS SCREEN SIZES OF DEDUSTER DUST

Screen Size	Ash (percent)	Volatile matter (percent)	Fixed carbon (percent)	Sulfur (percent)				Calorific value B.t.u.
				Sulfate	Pyrite	Organic	Total	
Original....	10.8	30.0	59.2	0.03	0.80	0.49	1.32	12993
−200......	11.3	23.5	55.2	0.04	0.85	0.43	1.32	12848
100x200....	13.5	33.1	53.4	0.02	1.28	0.29	1.59	12615
80x100....	11.8	34.0	54.2	0.01	0.94	0.40	1.35	12613
60x 80....	11.9	34.2	53.9	0.01	0.85	0.48	1.34	12708
40x 60....	11.7	34.7	53.6	0.01	0.74	0.56	1.31	12634
20x 40....	9.0	35.7	55.3	0.01	0.62	0.56	1.19	13055
+20.......	6.7	36.2	57.1	0.02	0.48	0.55	1.05	13438

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[2] Heathcoat, F., The estimation of fusain: Fuel, p. 452, vol. 9, No. 10, 1930.

in alkali, the residual fusain is determined by weight.

Fuchs[3] developed an improved modification of the Heathcoat method of fusain determination. In the Fuchs method, which was used in this investigation, advantage is taken from the fact that, after the oxidation of the non-fusain material by concentrated nitric acid, the oxidation of the fusain continues with time according to a straight-line relationship. This straight line is extrapolated backward; the zero time intercept is the percent fusain on a moisture-free and ash-free basis. Because the samples were collected prior to 1940 and do not represent the products of present preparation practice, it is deemed permissible to identify the mine source rather than the district of origin which is the usual practice in survey publications.

EXPERIMENTAL RESULTS

PROXIMATE ANALYSES OF DEDUSTER DUST

Table 22 shows the proximate analyses of various screen sizes of a sample of Chicago, Wilmington and Franklin Coal Company Orient Mine No. 2 deduster dust collected in 1937. This sample was collected at the direction of H. A. Treadwell, vice president of the company, and represents a composite sample of a day's operation collected at 30-minute intervals.

FUSAIN ANALYSES OF DEDUSTER DUST

Table 23 shows the fusain content of various screen sizes of the same sample of Orient No. 2 deduster dust; columns from 1 to 8 show the screen size, the percent weight, the count of the fusain particles, the count of the non-fusain particles, the total counts of the fusain and non-fusain particles, the percentage of fusain (the count of fusain particles divided by the total count), the cumulative percentage fusain from small to large screen sizes, and the cumulative percentage fusain from large to small screen sizes, respectively.

INFLUENCE OF FUSAIN ON SMOKE-INDEX OF BRIQUETS MADE FROM DEDUSTER DUST

A series of 16 briquets containing uniformly decreasing percentages of fusain were made for smoke-index tests from vari-

TABLE 23.—FUSAIN CONTENT OF VARIOUS SCREEN SIZES OF DEDUSTER DUST

Size	Weight (percent)	Particle count			Fusain (percent)		
		Fusain	Non-Fusain	Total	Individual	Cumulative	
						Down	Up
−300	26.9	187	314	501	37.5	37.5	16.4
200x300	4.6	81	228	309	26.2	35.9	8.6
150x200	9.7	36	202	238	15.1	31.0	7.4
100x150	8.6	63	440	503	12.5	27.8	6.1
65x100	11.1	36	534	570	6.3	23.9	5.0
48x 65	9.7	17	182	199	8.5	21.8	4.7
35x 48	9.4	49	922	971	5.0	19.8	3.4
28x 35	7.8	8	225	233	2.4	18.2	2.7
20x 28	5.8	31	723	754	4.1	17.4	2.9
14x 20	3.6	7	231	238	2.9	16.8	1.8
10x 14	1.8	0	153	153	0.0	16.5	0.3
+10	1.0	1	114	115	0.9	16.4	0.9

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[3] Fuchs, W., Gauger, A. W., Hsiao, C. C., and Wright, C. C., The chemistry of the petrographic constituents of bituminous coal. Part I—Studies on Fusain: Pennsylvania State College, Min. Ind. Exp. Sta. Bull. 23, 1938.

Table 24.—Influence of Fusain on Smoke-Index of Briquets Made from Various Screen Sizes of Deduster Dust
(Figure 29)

Weight (percent)	Screen size	Fusain percent		Smoke index
		Individual	Resultant	
100	+ 14	0.3	0.3	3390
100	20x28	4.1	4.1	3653
100	+150	6.1	6.1	3100
100	+200	7.4	7.4	2808
75	+200	7.4	9.7	2692
25	Original	16.4		
50	+200	7.4		
50	Original	16.4	11.9	2385
25	+200	7.4		
75	Original	16.4	14.2	2839
100	Original	16.4	16.4	1725
100	− 28	18.2	18.2	1579
50	− 28	18.2		
50	− 48	21.8	20.0	1693
100	− 48	21.8	21.8	1821
100	− 65	23.9	23.9	889
50	− 65	23.9		
50	−100	27.8	25.8	1031
100	−100	27.8	27.8	1062
50	−100	27.8		
50	−150	31.0	29.4	1062
100	−150	31.0	31.0	833

Table 25.—Influence of Fusain on Smoke-Index of Briquets Made from Blends of One High Fusain and One Low Fusain Component of Deduster Dust
(Figure 30)

Mixture		Fusain (percent)	Smoke-index
−300	20x100		
1.4	98.6	6	3164
7.6	92.4	8	2916
14.0	86.0	10	2453
20.4	79.6	12	2726
26.6	73.4	14	2269
32.8	67.2	16	2280
39.2	60.8	18	2075
45.6	54.4	20	1823
51.8	48.2	22	1554
58.2	41.8	24	1366
64.4	35.6	26	1079
70.6	29.4	28	949
77.0	23.0	30	970
83.4	16.6	32	706
89.6	10.4	34	527
95.8	4.2	36	255

ous blends of different screen sizes of the Orient No. 2 deduster dust; the results are shown in table 24 and figure 29. Following this a series of 20 briquets was made from various blends of two screen sizes of the same Orient No. 2 deduster dust, the minus 300-mesh and the 20 x 100 mesh; the former contained a large amount of fusain (37.5 percent) and the latter a small amount (5.5 percent), the actual amounts being unimportant. The results, also demonstrating a definite decrease of smoke content with increase of fusain, are shown in table 25 and figure 30.

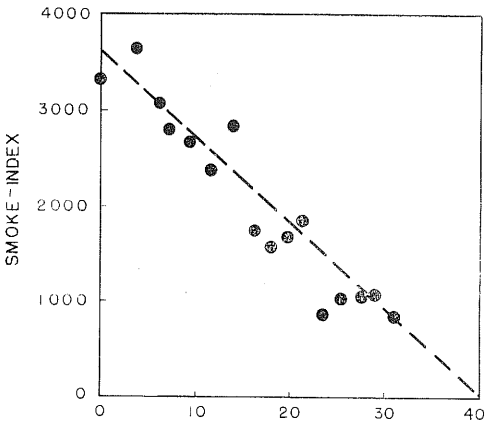

Fig. 29.—Influence of fusain on smoke-index of briquets made from various screen sizes of deduster dust. (Data from table 24)

Influence of Hand-Picked Fusain on Smoke-Index of Briquetted Coal

A series of 14 briquets was made from various blends of purified hand-picked fusain collected from the Perry Coal Company St. Ellen Mine and the 20 x 100 mesh fraction of Orient No. 2 deduster dust noted above; the results paralleled those of the

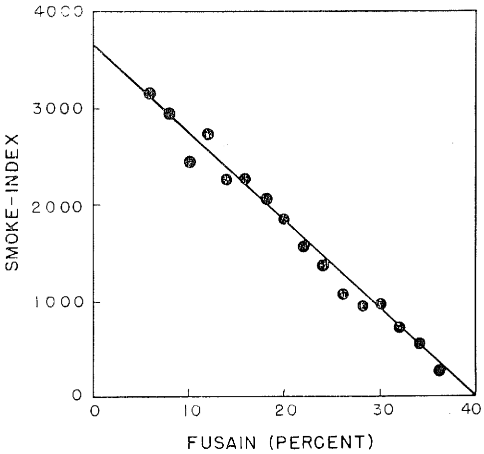

Fig. 30.—Influence of fusain on smoke-index of briquets made from blends of one high-fusain and one low-fusain component of deduster dust. (Data from table 25)

TABLE 26.—INFLUENCE OF FUSAIN ON SMOKE-INDEX OF BRIQUETS MADE FROM BLENDS OF HAND-PICKED FUSAIN AND 20x100-MESH FRACTION OF DEDUSTER DUST
(Figure 31)

Mixture		Fusain (percent)	Smoke-index
Fusain	Coal		
4.8	95.2	10	2540
6.8	93.2	12	2041
8.9	91.1	14	1667
11.1	88.9	16	1654
13.2	86.8	18	1225
15.3	84.7	20	1079
17.4	82.6	22	957
19.5	80.5	24	970
21.6	78.4	26	997
23.8	76.2	28	783
25.9	74.1	30	937
28.0	72.0	32	397
30.2	69.8	34	429
32.3	67.7	36	608

TABLE 27.—INFLUENCE OF FUSAIN ON SMOKE-INDEX OF BRIQUETS MADE FROM BLENDS OF HAND-PICKED FUSAIN AND COAL BOTH FROM ST. ELLEN MINE
(Figure 32)

Mixture		Fusain (percent)	Smoke-index
Fusain	Coal		
1.03	98.97	4	3667
3.1	96.9	6	4018
5.2	94.8	8	3391
7.2	92.8	10	3653
9.3	90.7	12	3880
11.4	88.6	14	3673
13.4	86.6	16	3836
15.5	84.5	18	2884
17.5	82.5	20	2313
19.6	80.4	22	3079
21.7	78.3	24	3138
23.7	76.3	26	2919
25.8	74.2	28	2356
27.8	72.2	30	1882
29.9	70.1	32	1376
32.0	68.0	34	1524
34.0	66.0	36	1642
36.1	63.9	38	1280
38.2	61.8	40	759
40.2	59.8	42	785
42.3	57.7	44	715

previous tests and are shown in table 26 and figure 31. The proximate analyses of the hand-picked fusain is as follows: volatile matter, 11.3 percent; fixed carbon, 84.7 percent; ash, 4.0 percent; total sulfur, 0.80 percent; and calorific value, 14,079 B.t.u.

Tests were also made which showed that hand-picked fusain mixed with crushed lump coal produced the same influence on the smoke-index of the resultant briquet. The hand-picked fusain was a portion of the sample referred to above. The lump coal was collected from the St. Ellen mine, and was assigned a value of 3 percent fusain based on a study by L. C. McCabe of the fusain content of lump coal from the O'Fallon coal district. The proximate analyses of the sample of St. Ellen lump coal is as follows: volatile matter, 43.1 percent; fixed carbon 47.7 percent; ash, 9.2 percent; total sulfur 3.94 percent; and calorific value, 12,973 B.t.u. The results of smoke-index tests for a series of 22 briquets are shown in table 27 and figure 32.

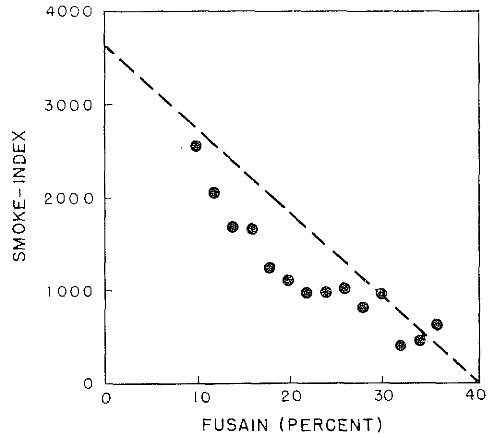

FIG. 31.—Influence of fusain on smoke-index of briquets made from hand picked fusain from St. Ellen mine and 20x100-mesh fraction of deduster dust. (Data from table 26)

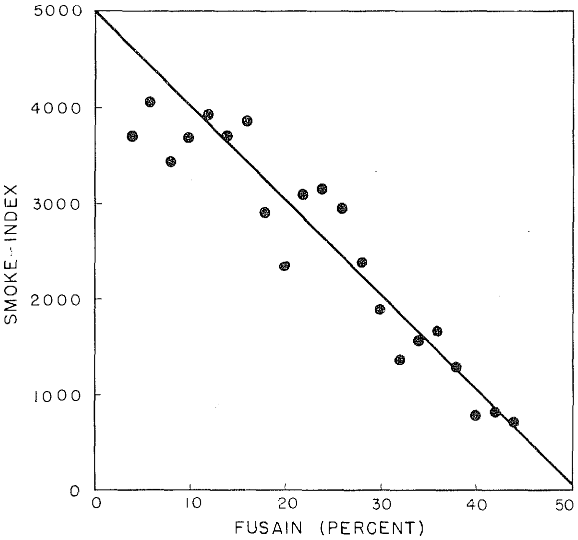

FIG. 32.—Influence of fusain on smoke-index of briquets made from hand picked fusain and coal, both from St. Ellen mine. (Data from table 27)

Table 28.—Ash Determination of 35 Samples of Illinois Coal Fines

Company	County	Size of coal	Ash (percent)
Penwell Coal Mining Co.	Christian	Raw carbon	20.5
Beckmeyer Coal Co.	Clinton	"	14.4
Citizens Coal Co.	"	"	25.3
Bell & Zoller Coal & Mining Co., Mine 2	Franklin	"	14.5
Old Ben Coal Corporation, Mine 8	"	"	10.4
Mt. Olive Coal Co.	Macoupin	"	18.2
Burnwell Coal Co.	Madison	"	20.6
East Side Coal Co., Mine 1	"	"	19.3
Madison County Coal & Mining Co.	"	"	24.6
Mt. Olive & Staunton Coal Co., Mine 2	"	"	17.7
Livingston & Mt. Olive Coal Co.	"	"	27.5
Lumaghi Coal Co.	"	"	15.7
Marion County Coal Co.	Marion	"	17.3
Pinckneyville Mining Co.	Perry	"	16.6
Illinois—Missouri Coal Mining Co.	Randolph	"	25.7
Lensburg Coal Co.	St. Clair	"	33.9
Mulberry Hill Coal Co.	"	"	43.9
Pep Coal Co.	"	"	25.3
Perry Coal Co., St. Ellen Mine	"	"	34.3
White Rose Coal Co.	"	"	28.6
Centralia Coal Co.	Washington	"	25.5
Consolidated Coal Co.	Williamson	"	9.3
Franklin County Coal Co., Mine 5	"	"	11.5
Peabody Coal Co., Mine 24	Vermilion	Washed carbon.	11.5
Old Ben Coal Corp., Mine 8	Franklin	Face Sample...	8.0
Bell & Zoller Coal & Mining Co., Mine 2	"	Deduster dust	12.2
Peabody Coal Co., Mine 18	"	"	19.3
Peabody Coal Co., Mine 14	Perry	"	23.1
Peabody Coal Co., Mine 43	Saline	"	17.8
Peabody Coal Co., Mine 47	"	"	17.6
Peabody Coal Co., Mine 18	Franklin	Sludge	14.5
Peabody Coal Co., Mine 14	Perry	"	11.0
Moffat Coal Co.	Randolph	"	26.2
Perry Coal Co., St. Ellen Mine	St. Clair	"	24.1
Peabody Coal Co., Mines 43 and 47	Saline	"	14.6

Fusain Content of Various Screen Sizes of Various Illinois Coals, Including Ash Determinations of Original Samples

Petrographic determination of the percentage of fusain in various screen sizes was made for 35 samples of coal fines representing various Illinois coal districts; the samples consisted of 23 raw ⅜-inch screening, one washed ⅜-inch screening, one face sample, five deduster dusts, and five sludges. Table 28 shows company, mine location by county, type of sample, and percent ash. For compactness, the results for the various screen sizes are arranged in three tables as follows: table 29 shows the percentage weight distribution; table 30 shows the percent fusain; and table 31 shows the cumulative percent fusain.

TABLE 29.—SCREEN ANALYSES OF 35 SAMPLES OF ILLINOIS COAL FINES

Company	Screen Sizes												
	−300	200× 300	150× 200	100× 150	65× 100	48× 65	35× 48	28× 35	20× 28	14× 20	10× 14	8× 10	+8
Penwell Coal Mining Co.	9.32	1.29	2.41	2.41	3.81	3.86	4.95	6.21	7.25	8.62	10.52	12.98	26.39
Beckmeyer Coal Co.	3.35	0.61	1.51	1.67	3.10	2.78	3.92	5.10	6.66	9.47	13.35	18.58	29.89
Citizens Coal Co.	4.20	1.16	3.48	4.51	7.83	7.96	9.62	11.09	11.62	11.69	10.93	9.43	6.49
Bell & Zoller Coal & Mining Co., 2	9.11	1.57	3.31	3.31	4.83	5.69	6.75	8.60	10.39	12.20	14.21	13.04	7.00
Old Ben Coal Corporation, Mine 8	5.75	1.35	4.99	3.43	3.52	3.83	4.41	4.93	6.92	8.20	9.80	13.59	29.29
Mt. Olive Coal Co.	7.45	1.29	2.94	3.00	5.73	3.45	5.23	6.38	6.73	7.38	9.38	11.89	29.15
Burnwell Coal Co.	5.79	1.50	2.91	2.85	3.81	3.45	4.41	5.70	7.56	9.93	12.99	16.20	22.92
East Side Coal Co., Mine 1	5.65	0.82	2.01	1.78	4.09	3.05	5.35	7.95	9.73	12.11	14.49	15.53	17.46
Madison County Coal & Mining Co.	7.67	1.48	2.65	2.70	4.48	4.04	5.47	6.98	8.40	10.17	12.03	14.51	19.42
Mt. Olive & Staunton Coal Co., 2	10.67	1.73	3.40	3.19	5.28	5.49	7.43	9.57	11.19	12.76	13.86	11.56	3.87
Livingston & Mt. Olive Coal Co.	7.04	1.32	1.84	1.68	3.04	2.24	3.60	4.84	5.92	7.92	11.12	14.36	35.08
Lumaghi Coal Co.	7.25	1.67	2.76	2.79	4.32	3.70	5.26	6.78	7.94	10.08	12.55	15.95	18.96
Marion County Coal Co.	7.80	0.97	2.82	2.78	4.62	4.19	5.67	7.33	8.78	10.98	13.37	15.17	15.57
Pinckneyville Mining Co.	2.91	0.56	1.27	1.41	3.29	1.93	3.85	5.54	7.42	9.72	13.06	16.25	32.79
Illinois—Missouri Coal Mining Co.	6.51	1.44	2.75	3.25	5.70	5.63	6.82	8.95	10.20	10.89	11.45	11.39	15.02
Lensburg Coal Co.	4.63	1.08	1.97	2.63	4.60	4.50	6.82	8.59	10.27	11.70	13.60	14.42	15.19
Mulberry Hill Coal Co.	5.40	1.09	2.14	2.28	4.56	4.03	6.03	8.10	8.24	12.10	14.27	15.99	15.78
Pep Coal Co.	3.41	0.49	0.81	0.67	1.39	0.94	2.38	5.29	10.72	16.46	20.63	19.78	17.04
Perry Coal Co., St. Ellen Mine	2.69	0.39	0.72	0.96	2.48	1.75	4.45	7.01	9.87	9.69	8.44	10.17	41.38
White Rose Coal Co.	5.86	1.53	2.27	2.37	3.70	3.70	4.98	6.46	7.49	9.22	11.43	14.79	26.22
Centralia Coal Co.	6.38	1.47	3.12	3.40	5.66	4.81	6.38	7.99	9.53	10.86	13.22	13.98	13.20
Consolidated Coal Co.	5.05	1.04	2.07	2.20	3.80	3.15	4.45	5.96	7.69	10.28	14.51	20.60	19.21
Franklin County Coal Co., Mine 5	8.83	1.37	2.74	2.51	4.33	3.99	5.82	7.35	8.78	11.06	14.03	16.48	12.71
Peabody Coal Co., Mine 24	3.92	0.52	1.08	1.08	2.31	1.73	2.72	3.30	3.43	6.91	9.60	14.91	48.49
Old Ben Coal Corporation, Mine 8	2.68	0.44	1.09	1.12	1.95	1.73	2.71	3.40	4.67	6.36	9.18	15.14	49.54
Bell & Zoller Coal & Mining Co., 2	9.11	1.57	3.31	3.31	4.83	5.69	6.75	8.60	10.39	12.20	14.21	13.04	7.00
Peabody Coal Co., Mine 18	21.15	3.36	10.18	11.06	17.08	16.37	16.11	3.72	0.97				
Peabody Coal Co., Mine 14	8.77	1.69	4.43	5.14	8.58	9.68	14.56	20.01	18.06	7.27	1.80		
Peabody Coal Co., Mine 43	12.78	2.66	6.27	5.78	8.81	10.42	9.90	12.61	14.00	8.20	4.82	2.57	1.17
Peabody Coal Co., Mine 47	11.96	2.63	6.73	6.46	9.81	8.89	12.84	13.26	10.75	7.45	4.12	2.86	2.24
Peabody Coal Co., Mine 18	6.86	1.40	4.01	4.70	4.91	10.49	10.74	15.17	14.30	10.42	5.15	3.27	5.58
Peabody Coal Co., Mine 14	5.24	1.31	3.71	4.08	6.38	6.25	8.55	11.65	14.80	15.24	10.07	7.62	5.10
Moffat Coal Co.	18.35	4.15	8.86	8.04	10.38	9.43	9.86	8.92	8.36	6.11	4.31	3.23	
Perry Coal Co., St. Ellen Mine	20.47	3.22	6.77	6.89	10.22	9.95	10.63	9.65	8.98	6.06	3.73	2.17	1.25
Peabody Coal Co., Mines 43 and 47	15.88	10.14	6.70	6.03	6.89	7.45	8.11	10.50	10.80	10.10	4.69	1.19	1.62

TABLE 30.—PETROGRAPHIC DETERMINATION OF PERCENT FUSAIN IN VARIOUS SCREEN SIZES OF 35 SAMPLES OF ILLINOIS COAL FINES

Company	Screen Sizes												
	−300	200× 300	150× 200	100× 150	65× 100	48× 65	35× 48	28× 35	20× 28	14× 20	10× 14	8× 10	+8
Penwell Coal Mining Co.	80.00	49.10	32.19	15.10	10.08	8.96	7.77	8.27	5.70	6.34	5.72	5.30	5.05
Beckmeyer Coal Co.	70.00	39.36	27.00	19.35	10.00	9.55	9.13	8.88	8.61	8.31	8.07	7.60	7.29
Citizens Coal Co.	55.00	18.33	11.11	7.83	5.21	4.83	5.00	4.79	4.60	4.45	4.29	4.11	4.02
Bell & Zoller Coal & Mining Co., 2	60.00	30.67	25.23	8.53	6.40	5.91	5.28	5.10	4.78	4.65	4.06	3.90	2.43
Old Ben Coal Corporation, Mine 8	80.00	35.89	20.07	13.23	9.86	9.10	8.45	7.93	7.41	6.95	6.41	5.93	5.29
Mt. Olive Coal Co.	70.00	30.80	23.08	10.10	9.12	8.05	7.58	6.92	4.48	5.50	5.54	4.55	5.04
Burnwell Coal Co.	45.00	21.03	13.52	7.96	7.02	6.68	5.86	5.33	4.96	4.54	4.26	3.90	3.50
East Side Coal Co., Mine 1	80.00	49.72	30.02	20.58	16.02	11.35	10.42	9.78	9.14	8.22	7.30	6.47	5.63
Madison County Coal & Mining Co.	58.00	32.83	19.40	11.50	9.03	7.51	7.02	6.50	5.96	5.43	4.95	4.59	4.01
Mt. Olive & Staunton Coal Co., 2	75.00	44.93	24.81	17.55	12.90	11.42	9.92	9.07	8.21	7.67	7.14	6.55	5.76
Livingston & Mt. Olive Coal Co.	85.00	65.45	46.61	27.27	15.27	12.10	11.90	10.33	9.61	8.32	7.25	7.10	6.60
Lumaghi Coal Co.	70.00	39.25	27.00	14.68	9.64	8.05	6.47	6.18	5.90	5.50	5.11	4.55	4.00
Marion County Coal Co.	60.00	35.48	20.00	10.14	7.73	7.15	6.56	6.25	5.95	5.60	5.06	4.65	4.04
Pinckneyville Mining Co.	55.00	30.01	16.94	9.10	7.09	6.51	6.09	5.51	5.05	4.50	4.00	3.50	3.02
Illinois—Missouri Coal Mining Co.	70.00	30.55	16.67	9.09	6.54	5.86	5.18	4.75	4.33	3.77	3.21	2.80	2.39
Lensburg Coal Co.	48.00	17.70	11.07	7.14	5.61	5.05	5.61	4.23	4.16	4.00	3.76	3.43	3.09
Mulberry Hill Coal Co.	75.00	31.09	23.48	11.70	7.24	6.76	6.25	5.68	4.54	4.37	4.27	4.33	4.09
Pep Coal Co.	80.00	49.00	31.03	18.70	11.50	9.81	8.13	7.19	6.26	5.92	5.58	4.96	4.38
Perry Coal Co., St. Ellen Mine	36.81	25.92	20.87	10.58	7.00	6.79	5.99	4.92	3.78	2.60	3.06	2.95	1.99
White Rose Coal Co.	80.00	45.71	28.57	16.67	9.16	8.94	8.72	7.45	6.17	5.44	4.70	5.04	5.39
Centralia Coal Co.	50.00	17.19	9.97	6.47	5.14	4.95	4.73	4.50	4.37	3.15	3.95	3.74	3.49
Consolidated Coal Co.	45.00	23.49	13.25	7.33	6.90	6.04	5.75	3.57	4.70	4.14	3.51	2.93	2.49
Franklin County Coal Co., Mine 5	75.00	36.38	23.08	13.45	9.09	7.95	7.03	6.12	5.68	5.19	4.85	4.42	4.02
Peabody Coal Co., Mine 24	40.00	16.08	9.05	4.64	4.39	3.60	2.84	2.32	1.92	2.00	1.62	1.97	2.49
Old Ben Coal Corporation, Mine 8	70.00	27.00	23.20	19.30	14.30	10.20	7.70	5.30	4.30	3.30	3.00	2.80	1.14
Bell & Zoller Coal & Mining Co., 2	39.04	30.67	25.23	8.53	6.40	5.91	5.28	5.10	4.78	4.65	4.06	3.90	2.43
Peabody Coal Co., Mine 18	60.00	25.53	16.00	11.10	7.54	5.56	4.74	4.07	3.58				
Peabody Coal Co., Mine 14	37.58	29.44	23.32	7.54	4.77	3.99	3.29	3.12	2.92	2.62	1.78		
Peabody Coal Co., Mine 43	38.64	30.56	20.49	7.26	6.23	4.89	3.81	3.35	2.45	2.48	2.65	1.74	1.85
Peabody Coal Co., Mine 47	37.21	30.04	20.50	4.47	3.65	3.62	4.42	2.38	2.34	2.32	1.81	2.07	3.02
Peabody Coal Co., Mine 18	36.89	27.50	22.80	6.58	4.18	4.02	4.06	3.44	3.12	1.67	2.01	2.00	1.36
Peabody Coal Co., Mine 14	38.40	27.45	22.14	9.92	5.46	4.86	4.26	3.86	3.92	3.63	2.50	2.61	2.06
Moffat Coal Co.	27.17	18.33	12.63	6.85	4.98	4.17	3.80	3.61	3.32	2.66	2.65	5.12	
Perry Coal Co., St. Ellen Mine	35.56	25.99	20.08	10.01	8.04	6.18	6.69	5.64	4.68	2.88	3.66	2.86	4.00
Peabody Coal Co., Mines 43 and 47	37.09	28.64	21.13	7.13	6.51	4.90	4.10	3.81	3.22	2.91	2.58	1.69	1.61

Table 31.—Cumulative Percent Fusain for Various Screen Sizes of 35 Samples of Illinois Coal Fines

Company	Screen Sizes												
	−300	200× 300	150× 200	100× 150	65× 100	48× 65	35× 48	28× 35	20× 28	14× 20	10× 14	8× 10	+8
Penwell Coal Mining Co.	80.00	76.24	68.09	59.81	49.99	43.11	36.88	31.69	27.16	23.57	20.48	17.80	14.44
Beckmeyer Coal Co.	70.00	65.28	54.71	45.97	35.08	29.63	24.89	20.71	17.90	15.52	13.59	12.00	10.59
Citizens Coal Co.	55.00	47.06	32.91	24.44	17.33	13.92	11.70	10.16	9.11	8.37	7.84	7.46	7.24
Bell & Zoller Coal & Mining Co., 2	60.00	55.69	48.48	40.84	33.32	27.71	23.33	19.70	16.81	14.55	12.69	11.46	10.82
Old Ben Coal Corporation, Mine 8	80.00	71.61	50.34	42.44	36.17	31.67	27.89	24.84	21.75	19.19	17.00	14.87	12.07
Mt. Olive Coal Co.	70.00	64.21	53.86	44.92	34.87	30.99	26.78	23.21	20.22	18.09	16.09	14.27	11.58
Burnwell Coal Co.	45.00	40.07	32.49	27.14	22.59	19.89	17.39	15.13	13.10	11.33	9.82	8.58	7.41
East Side Coal Co., Mine 1	80.00	76.16	65.23	57.48	45.66	39.65	32.78	26.82	22.57	19.26	16.67	14.75	13.16
Madison County Coal & Mining Co.	58.00	53.93	46.18	39.72	32.47	28.09	24.08	20.59	17.79	15.47	13.55	11.94	10.39
Mt. Olive & Staunton Coal Co., 2	75.00	70.81	60.92	53.63	44.77	38.61	32.89	28.01	24.19	21.19	18.90	17.42	16.97
Livingston & Mt. Olive Coal Co.	85.00	81.91	75.54	68.72	57.83	51.86	44.93	38.39	32.98	28.03	23.46	19.84	15.20
Lumaghi Coal Co.	70.00	64.24	55.44	47.58	38.86	33.79	28.61	24.21	20.79	17.85	15.32	13.20	11.46
Marion County Coal Co.	60.00	57.29	48.22	40.85	32.79	28.16	23.91	20.33	17.53	15.16	13.21	11.66	10.48
Pinckneyville Mining Co.	55.00	50.97	41.85	34.34	24.84	21.73	17.75	14.50	12.01	10.09	8.53	7.31	5.90
Illinois—Missouri Coal Mining Co.	70.00	62.85	50.98	41.22	31.16	25.53	21.20	17.62	14.97	13.01	11.48	10.32	9.13
Lensburg Coal Co.	48.00	42.27	34.27	27.35	20.64	17.03	14.06	11.64	9.93	8.71	7.75	7.02	6.42
Mulberry Hill Coal Co.	75.00	67.63	56.68	47.68	35.45	29.52	24.03	19.61	16.64	13.89	11.88	10.49	9.44
Pep Coal Co.	80.00	76.11	68.35	62.17	52.36	46.65	37.56	27.12	18.55	13.66	11.02	9.58	8.69
Perry Coal Co., St. Ellen Mine	36.81	35.43	32.67	28.22	20.95	18.19	14.15	10.99	8.64	7.18	6.46	5.86	4.04
White Rose Coal Co.	80.00	72.90	62.48	53.46	43.36	36.80	31.07	26.13	22.23	18.98	16.21	13.97	11.73
Centralia Coal Co.	50.00	43.86	34.22	27.65	21.29	18.13	15.39	13.17	11.45	9.94	8.85	8.03	7.43
Consolidated Coal Co.	45.00	41.33	34.21	28.50	22.70	19.67	16.82	13.97	11.96	10.20	8.59	7.15	6.25
Franklin County Coal Co., Mine 5	75.00	69.81	59.92	52.37	42.89	37.03	31.13	26.15	22.22	18.90	16.12	13.91	12.65
Peabody Coal Co., Mine 24	40.00	37.19	31.69	27.26	21.33	18.45	15.28	12.71	10.87	8.60	6.77	5.38	3.98
Old Ben Coal Corporation, Mine 8	70.00	63.94	53.39	46.22	37.67	33.20	26.69	21.88	17.73	14.22	11.30	8.75	4.98
Bell & Zoller Coal & Mining Co., 2	39.04	37.81	34.84	29.80	24.69	20.85	17.81	14.36	11.67	9.59	7.96	6.90	6.43
Peabody Coal Co., Mine 18	60.00	55.27	43.75	35.94	28.16	25.52	20.32	19.71	19.55				
Peabody Coal Co., Mine 14	37.58	36.33	32.44	26.06	19.68	15.72	12.30	9.77	8.41	7.98	7.87		
Peabody Coal Co., Mine 43	38.64	37.24	32.38	27.10	22.04	18.22	15.70	13.45	11.59	10.77	10.37	10.14	10.04
Peabody Coal Co., Mine 47	37.21	35.92	31.00	24.84	19.31	16.31	13.74	11.67	10.46	9.79	9.45	9.24	9.09
Peabody Coal Co., Mine 18	36.89	35.35	31.21	24.44	17.97	13.83	11.56	9.55	8.34	7.52	7.21	7.03	6.72
Peabody Coal Co., Mine 14	38.40	36.18	31.09	25.03	18.96	15.72	12.95	10.71	9.09	8.00	7.37	6.98	6.75
Moffat Coal Co.	27.17	25.54	21.89	18.82	15.69	13.85	12.41	11.41	10.63	10.10	9.77	9.61	
Perry Coal Co., St. Ellen Mine	35.56	34.26	31.10	27.22	23.10	20.17	18.07	16.53	15.30	14.49	14.07	13.82	13.65
Peabody Coal Co., Mines 43 and 47	37.09	33.80	31.20	27.82	24.29	21.57	19.26	17.00	15.29	13.94	13.39	13.25	13.04

TABLE 32.—COMPARISON OF PERCENT FUSAIN IN 13 ILLINOIS COAL FINES AS DETERMINED BY PETROGRAPHIC AND FUCHS METHOD

Company	Ash (percent)	Fusain (percent)		
		Fuchs	Petrographic	Difference
Penwell Coal Mining Company	20.5	15.9	14.4	−1.5
Citizens Coal Co.	25.3	5.4	7.2	+1.8
Bell & Zoller Coal & Mining Co., Mine 2	14.5	10.9	10.8	−0.1
Old Ben Coal Corporation, Mine 8	10.4	13.8	12.1	−1.7
Burnwell Coal Co.	20.6	10.1	7.4	−2.7
Madison Coal & Mining Co.	24.6	12.8	10.4	−2.4
Livingston & Mt. Olive Coal Co.	27.5	18.0	15.2	−2.8
Lensburg Coal Co.	33.9	6.4	6.4	0.0
Mulberry Hill Coal Co.	43.9	14.2	9.4	−4.8
Centralia Coal Co.	25.5	8.5	7.5	−1.0
Franklin County Coal Co., Mine 5	11.5	11.5	12.6	+1.1
Peabody Coal Co., Mine 24	11.5	4.2	4.0	−0.2
Peabody Coal Co., Mine 18	19.3	19.0	19.5	+0.5

PERCENT FUSAIN DETERMINED BY FUCHS METHOD

Thirteen of the above samples of coal were tested for percentage of fusain by the Fuchs chemical method. Table 32 shows the results, including percent ash, percent fusain by the chemical method and by the petrographic method, and the percent difference in fusain determined by the two methods.

EFFECT OF FUSAIN ON SMOKE-INDEX OF BRIQUETS MADE FROM CARBON SIZE COAL

Smoke-index tests were made on briquetted samples of 22 of the carbon size coal.

TABLE 33.—EFFECT OF PERCENT FUSAIN ON SMOKE-INDEX OF BRIQUETS MADE FROM 22 ILLINOIS CARBON COALS
(Figure 33)

Company	Ash (percent)	Fusain (percent)	Smoke-index
Penwell Coal Mining Co.	20.5	14.44	4190
Beckmeyer Coal Co.	14.4	10.59	4130
Citizens Coal Co.	25.3	7.24	4020
Bell & Zoller Coal Mining Co., Mine 2	14.5	10.82	3050
Old Ben Coal Corporation, Mine 8	10.4	12.07	3050
Mt. Olive Coal Co.	18.2	11.58	3780
Burnwell Coal Co.	20.6	7.41	4440
East Side Coal Co., Mine 1	19.3	13.16	4070
Madison County Coal & Mining Co.	24.6	10.39	4140
Mt. Olive & Staunton Coal Co., Mine 2	17.7	16.97	3900
Livingston & Mt. Olive Coal Co.	27.5	15.20	3820
Lumaghi Coal Co.	15.7	11.46	4360
Marion County Coal Co.	17.3	10.48	4270
Pinckneyville Mining Co.	16.6	5.90	3560
Illinois—Missouri Coal Mining Co.	25.7	9.13	2950
Lensburg Coal Co.	33.9	6.42	3500
Mulberry Hill Coal Co.	43.7	9.44	2770
Pep Coal Co.	25.3	8.69	3260
White Rose Coal Co.	28.6	11.73	2970
Centralia Coal Co.	25.5	7.43	4390
Consolidated Coal Co.	9.3	6.25	3090
Peabody Coal Co., Mine 24	11.5	3.98	4980

Table 33 shows the results, including percent fusain, percent ash, and smoke-index; figure 33 shows the same results graphically.

Effect of Fusain on Smoke-Index of Briquets Made from Certain Screen Sizes of Carbon Coals

Smoke-index tests were also made on briquetted samples of minus 10-mesh, minus 20-mesh, and minus 48-mesh screen fractions of 8 of these carbon samples. The results demonstrating the improvement effected by increasing fusain, are shown in table 34 and figure 34.

DISCUSSION AND SUMMARY

Effect of Fusain on Smoke-Index of Briquets Made from Deduster Dust

As shown by the broken line in figure 29, a roughly approximate straight-line relationship exists between the smoke-index and percent fusain in briquets made from various screen size blends of deduster dust; the extrapolated line shows that the smoke-index for zero percent fusain is 3650, and that for 40 percent fusain the smoke-index is zero.

The normal effect of blending a smoky and a smokeless coal is a decrease in smoke-index, the amount reasonably to be expected to be equivalent to the percent of the smokeless coal. That is, it might be expected that it would require 100 percent instead of 40 percent fusain to entirely eliminate smoke. Herein lies the invention upon which the patent is based. One reasonable explanation of the unexpected phenomenon is that the fusain reacts as a catalyst, thereby effecting more complete combustion of the volatile matter than would otherwise take place.

Certain of the individual smoke-index values (fig. 29) deviate considerably, some lying above and others below the straight line. That this is due to experimental error in the petrographic determination of the percent fusain in the various screen size fractions of the deduster dust is indicated by results obtained by use of blends in various proportions of one low-fusain and one high-fusain screen-size fraction of the dust. The results, shown in figure 30, indicate that an increase in fusain always is accompanied by a lower smoke-index.

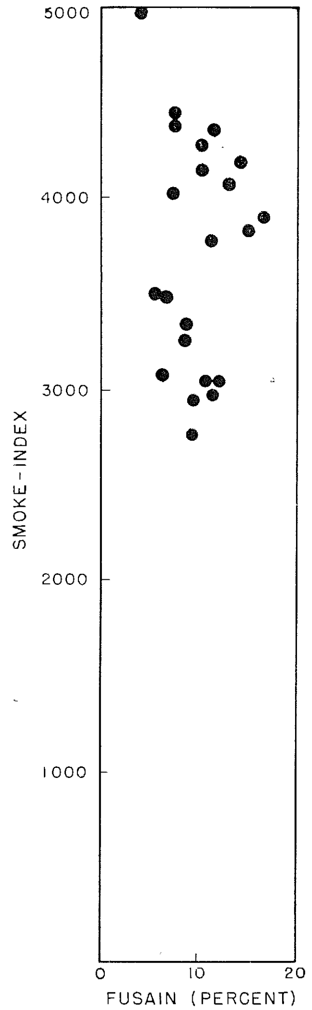

FIG. 33.—Effect of fusain on smoke-index of briquets made from ⅜-inch carbon coal. (Data from table 33)

Parenthetically, it may be pointed out that the extremely low experimental deviation, evidenced by figure 30, indicates the high degree of quantitative accuracy characteristic of the smoke-index method.

Also a comparison of figures 29 and 30 indicates that the same type of fusain is present throughout with respect to its catalytic ability to eliminate smoke. This is significant because there was a possibility

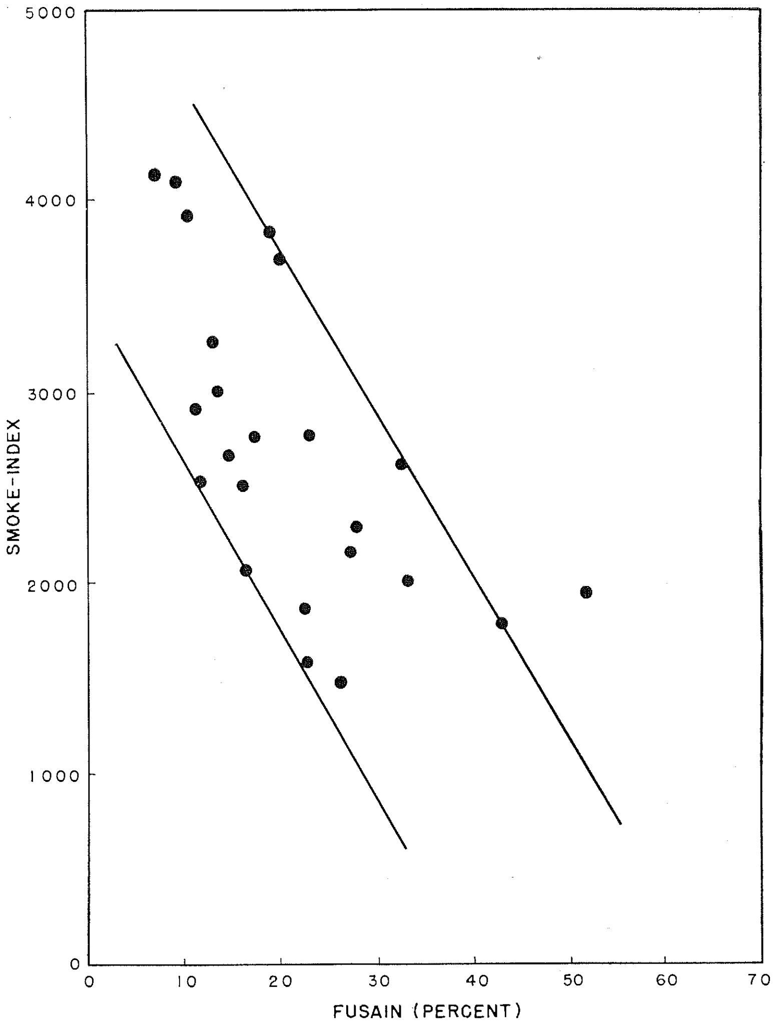

FIG. 34.—Effect of fusain on smoke-index of briquets made from fine coal, 10 to 48-mesh. (Data from table 34)

that the catalytic effect attributed to fusain might be due to some ingredient other than fusain, the amount of which might vary with screen size.

EFFECT OF HAND-PICKED FUSAIN ON SMOKE-INDEX OF BRIQUETS MADE FROM DEDUSTER DUST

In order to restrict the smoke-reducing effect to fusain only, smoke-index tests were determined for briquets made from various blends made up from a quantity of a certain screen-size fraction of deduster dust having low-fusain content and various parts of purified hand-picked fusain which happened to come from a mine in a different Illinois coal mining district.

The hand-picked fusain was purified, after drying at 100°C., by passing through a 20-mesh screen as much as could be separated by gentle rubbing, the residue being discarded. Because of its low ash content it may be assumed that the purified sample consisted of non-mineralized fusain.

The smoke-index results, as shown in figure 31 are definite proof that fusain is the catalytic ingredient which affects the smoke-index of the briquets.

TABLE 34.—EFFECT OF PERCENT FUSAIN ON SMOKE-INDEX OF BRIQUETS MADE FROM 4 SCREEN SIZE FRACTIONS OF 8 ILLINOIS COALS
(Figure 34)

Company	Fusain (percent)				Smoke-index			
	—⅜ inch	—10 mesh	—20 mesh	—48 mesh	—⅜ inch	—10 mesh	—20 mesh	—48 mesh
Penwell Coal Mining Co.	14.44	20.48	27.16	43.11	4190	3690	2140	1760
Burnwell Coal Co.	7.41	9.82	13.16	19.89	4440	4100	3250	3350
Madison County Coal & Mining Co.	10.39	13.55	17.79	28.09	4140	3000	2760	2280
Livingston & Mt. Olive Coal Co.	15.20	23.46	32.98	51.86	3820	2770	2600	1910
Illinois-Missouri Coal Mining Co.	9.13	11.48	14.96	22.87	2950	2920	2660	1580
Mulberry Hill Coal Co.	9.44	11.88	16.64	26.14	2770	2530	2045	1460
White Rose Coal Co.	11.73	16.21	22.23	33.27	2970	2500	1830	1990
Peabody Coal Co., Mine 24	3.98	6.77	10.87	18.45	4980	4140	3910	3840

A comparison of the results obtained from specially added purified fusain (fig. 31) with those obtained from fusain naturally occurring in deduster dust (fig. 29 and 30) reveals a somewhat greater efficiency in smoke reduction by the use of purified fusain, especially in the range of 12 to 28 percent fusain. A possible explanation for this experimental finding is that the fusain occurring in the deduster dust probably is a mixture of non-mineralized fusain (which is identical to the purified fusain) and of mineralized fusain. However the effect of mineralized fusain on smoke reduction was not specifically investigated.

EFFECT OF HAND-PICKED FUSAIN ON SMOKE-INDEX OF BRIQUETS MADE FROM CRUSHED LUMP COAL

It was anticipated that fusain would react as a smoke-reducing catalyst in briquets made from any high volatile coal. This prediction was proved correct by the results, shown in figure 32, on the effect of purified fusain on the smoke-index of briquets made from crushed lump coal from the Belleville district, where a coal is produced which is quite different from that produced in Franklin County.

Although comparison of the effect of fusain on the smoke-index of briquets made from coal from the two districts shows a similar straight-line relationship, there is a distinct difference in the position of the straight lines. In the St. Clair County Coal, the smoke-index is about 5000 for zero percent fusain, is zero for about 50 percent fusain, and is 3650 for 40 percent fusain, as previously noted for Franklin County coal. The reason for this difference is believed to be in the greater (43.1) percentage of volatile matter in the St. Ellen coal as contrasted to the smaller (35) percentage of volatile matter in the Orient No. 2 deduster dust. As shown in Article 3 of this report, an increase in the volatile matter of a coal causes an approximately linear increase in the smoke-index.

Figure 32 also indicates that 25 percent fusain is required to produce from Belleville coal a briquet with the same smoke-index as is possessed by a briquet made from Franklin County coal containing 15 percent fusain.

Ash Content of Illinois Coal Fines

Table 28 shows that the ash content of Illinois carbon size coals, deduster dusts, and sludges ranges from about 10 percent to more than 40 percent.

In the preparation of washed Illinois coal, these fine sizes and sludges constitute the discard; the percent ash in the discard is much higher than that in the raw coal. In dry preparation, the clay constituent of the mineral matter, being soft and friable, tends to concentrate in the fine sizes; in wet cleaning, the clay disintegrates and concentrates in the sludge.

Screen Analyses of Illinois Coal Fines

An inspection of table 29 shows that there is a wide variation of distribution of percentage weight of different screen size fractions for various Illinois carbon size coals, deduster dusts, and sludges. This variation is due partly to intrinsic differences in the mineral impurities and mineral composition of different Illinois coals; partly to differences in coal preparation practices at different mines; partly to differences in blasting or shooting practices; and finally to variations in the type of crushing equipment employed in the artificial breakage of coal.

Distribution of Fusain in Various Screen Sizes of Coal Fines

An inspection of table 30 shows that there is a general increase in fusain with a decrease of the screen size. The graph of percent fusain versus screen size should theoretically show a smooth curve; any deviations may be assigned to experimental error in fusain determination. Because the validity of this assumption was trusted, the fusain in later determinations was counted only in alternate screen sizes and the fusain values for sizes not counted were interpolated from the smooth curve drawn through the experimentally determined alternate values.

Such fusain values for the minus 300-mesh fraction as are shown in even percent were calculated from the Fuchs fusain value of the original sample. Such fusain values (for the same screen size) as are shown in fractional percent were based on microscopic count. The values calculated from Fuchs values is 79 percent higher than those obtained directly by microscopic count. However, it is difficult, if not impossible, to determine accurately the percent fusain in minus 300-mesh coal by microscopic count because such a size range is from 300-mesh to submicroscopic.

Table 32 gives fusain values obtained by the Fuchs method and those obtained by petrographic determination. The cause of the close agreement must be assigned mostly to the above mentioned practice of calculating the fusain value of the minus 300-mesh fraction in determining the petrographic composition of the 13 samples of carbon size coal.

Effect of Percent Fusain on Smoke-Index of Briquets Made from 22 Illinois Carbon Sized Coals

The smoke-index results recorded in table 33 show little effect upon the smoke-index of variation in fusain content in the briquets made from 22 Illinois carbon size coals. On the other hand, the data in table 34 show that for briquets made from the smaller screen fractions of eight of these carbon size coals there was a marked reduction in the smoke-index. That this decrease in smoke-index is due to the increase in the percent fusain is shown graphically in figure 34. The results lie within a zone bounded by two parallel straight lines. The breadth of the zone is due primarily to the difference in the volatile matter content of various coals; but it doubtless also is due to the fact that a portion of the fusain of certain of the coals may be mineralized and perhaps is catalytically inert.

Smoke-Index Tests as a Criterion of Amount of Effective Fusain

As yet little or no work has been done on the analytical determination of the percent

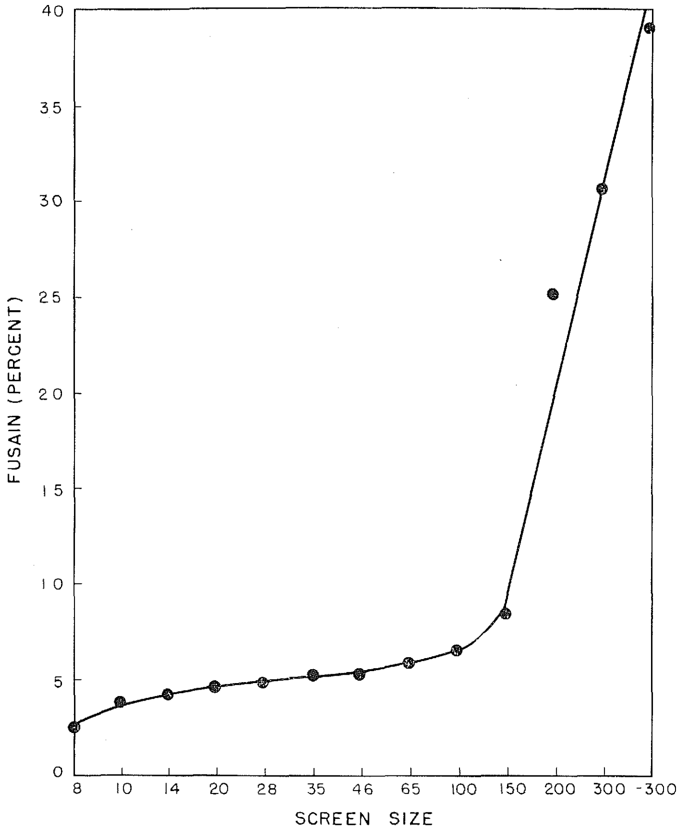

FIG. 35.—Percent fusain in various screen sizes of deduster dust from Bell and Zoller Mine No. 2. (Data from table 35)

of mineralized and non-mineralized fusain in coal. Accumulated experience suggests that the mineralized fusain probably does not react as a catalyst; therefore actual smoke-index tests appear to be the preferred criterion in the determination of the effective percent fusain in a briquet.

SCREEN ANALYSIS AS MEANS OF PLANT CONTROL OF FUSAIN

For a period of five years, frequent smoke-index tests and screen analyses have been made on Old Ben deduster dust used in the production of Fireball briquets. The results have shown that the percent fusain characteristic of a particular screen size of deduster dust remains constant. Thus the principal factor which produces changes in

TABLE 35.—PERCENT FUSAIN IN VARIOUS SCREEN SIZES OF DEDUSTER DUST
(Bell & Zoller Mine No. 2)
(Figures 35 and 36)

Screen size data		Fusain (percent)	
Mesh	Weight (percent)	Individual	Cumulative
8	7.00	2.43	6.43
10	13.04	3.90	6.90
14	14.21	4.06	7.96
20	12.20	4.65	9.59
28	10.39	4.78	11.67
35	8.60	5.10	14.36
48	6.75	5.28	17.81
65	5.69	5.91	20.85
100	4.83	6.40	24.69
150	3.31	8.53	29.80
200	3.31	25.23	34.84
300	1.59	30.67	37.81
−300	9.11	39.04	39.04

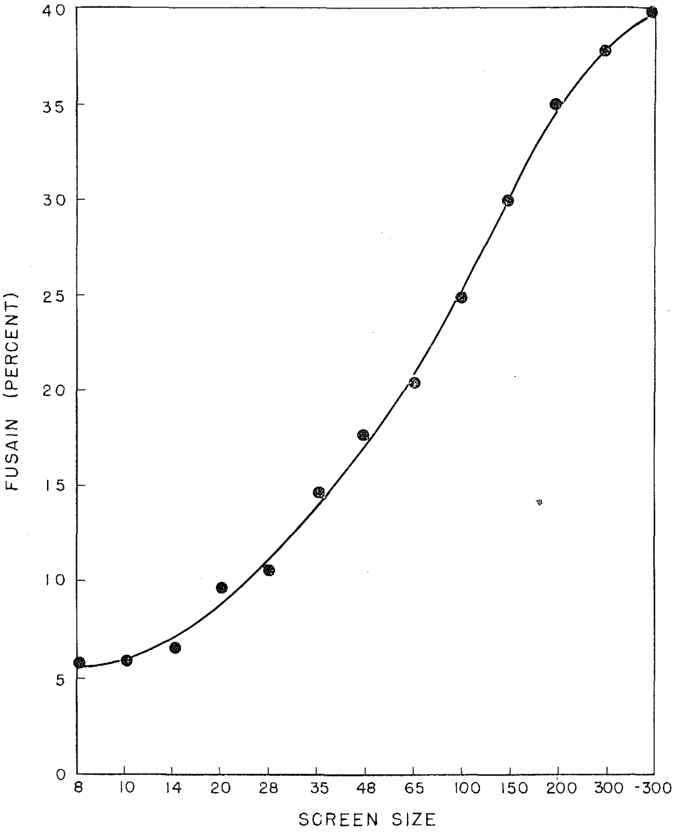

FIG. 36.—Cumulative percent fusain in various screen sizes of deduster dust from Bell and Zoller Mine No. 2. (Data from table 35)

the percent of fusain in this particular deduster dust is changes in the distribution of screen sizes.

Screen analysis may be used for plant control of percent fusain, based on prior petrographic determination of percent fusain in each screen size, provided that the percent fusain remains constant in each screen size. The procedure may be illustrated by a specific example as follows:

Consider deduster dust from Bell & Zoller Mine No. 2. Figure 35 shows the percent fusain in the various screen sizes (data from table 30). Table 35 gives the screen analysis for a specific sample of the same deduster dust (data from table 29). The cumulative fusain is then calculated for each screen size; these values are tabulated in the last column of table 35 (previously shown in table 31) and are presented graphically in figure 36. Assume a desired plant control of operation at 15 percent fusain; figure 36 reveals that in order to do this, the dedusting equipment should be so regulated as to produce an approximate minus 35-mesh deduster dust.

REACTION OF FUSAIN AS A CATALYST

The exact method by which fusain eliminates smoke in a high volatile briquet is not positively known. In the absence of definite experimental proof, it is possible only to speculate as to the manner in which fusain accelerates the combustion of the volatile matter in the briquet.

A catalyst is a substance which by its mere presence increases the speed of a reaction. Thus it seems plausible that fusain may react in a manner similar to activated charcoal; fusain may possess the property of occluding large volumes of various gases, including hydrogen gas. The presence of such occluded gases would accelerate the rate of combustion of the volatile matter which would be burned immediately upon leaving the surface of the briquets.

Also fusain appears to be extremely porous; and such porosity might serve as a gauze producing complete combustion of the emerging volatile gases in a manner analogous to a Welsbach mantle in a gas lamp.

SUMMARY

The results of this investigation may be summarized as follows:

1. Pulverant fusain concentrates in the very fine sizes of coal.
2. The percent of fusain in coal fines may be determined either by microscopic count or by the Fuchs chemical method.
3. There are two distinct types of fusain:
    (a) the soft pulverant low-ash fusain.
    (b) the fusain which is hard because of mineralization.
4. All 35 Illinois coals investigated contain increasing percentages of fusain in decreasing screen sizes.
5. Typical Illinois minus 48-mesh deduster dusts and sludges contain in excess of 15 percent fusain.
6. It was discovered that fusain produces an unexpectedly large reduction in the smoke-index of a briquet.
7. Briquets made from 35 percent volatile Franklin County deduster dust containing 15 percent fusain have a smoke-index less than 20 percent that of low volatile Pocahontas coals.
8. Increased fusain is required to produce a smokeless briquet from a higher volatile coal; a briquet made from 43 percent volatile Belleville coal must contain about 25 percent fusain to have the same smoke-index as a 15 percent fusain Franklin County briquet.
9. Although analyses of percent fusain assist in the prediction of the smoke-index of briquets, the practical criterion of the percent of effective fusain in a briquet is an actual smoke-index determination because the mineralized fusain does not reduce smoke.
10. Once having determined the percent fusain in the various screen sizes of coal fines from a particular mine, then a cumulative percent fusain curve based on daily screen analyses may be used as a plant control to maintain briquets at a specified smoke-index.
11. The findings that Illinois briquets rich in fusain are smokeless have been commercialized with a present annual production of 300,000 tons per year.

ARTICLE 5—SMOKELESS BRIQUETS FROM HOT PARTIALLY VOLATILIZED ILLINOIS COALS

INTRODUCTION

CONCEPTS AND DEFINITIONS

When pure coal is completely carbonized, the end products are fixed carbon and volatile matter, which do not exist as such within the coal itself. Partial volatilization or incomplete carbonization results when coal is heated away from air to any amount less than that necessary to remove all volatile substances. The residue of completely volatilized Illinois coal is usually coke. Partially volatilized coal is, as the phrase suggests, the product of partial volatilization or partial carbonization. In this investigation such partial volatilization has been produced in a piece of carbonizing equipment which will be referred to as a prevolatilizer.

PURPOSE OF INVESTIGATION

This article discusses the results of an exploration of the possibility of forming smokeless briquets from partially prevolatilized coal, the significance of such partial volatilization as a means of producing smokeless fuel, and the physical qualities of the resulting briquets.[1]

NEED FOR AND POSSIBLE SOURCE OF SMOKELESS FUEL

An analysis of the 1944 U. S. Bureau of Mines report on the distribution of bituminous coal indicates that in the natural market area for Illinois coal there is an annual potential minimum demand for at least 10 million tons of smokeless fuel processed from Illinois coals for use in hand-fired stoves and furnaces.

At present smokeless briquets (Fireballs) are being produced at the rate of 300,000 tons per year from fusain-rich deduster dust. Production even at the rate of 2,000,000 tons per year, which would exhaust the annual deduster dust and sludge in the State, could supply only 20 percent of the potential demand for smokeless fuel. In view of the evident inadequacy of the deduster dust and sludge to meet the potential demand for a smokeless briquet using a substantially smokeless binder, inquiry may appropriately be directed toward possible means for producing smokeless briquets from Illinois coals which have low, or normal, rather than high-fusain content.

Because partial prevolatilization as here described produces a fuel which is essentially smokeless, and because this laboratory has demonstrated the possibility of producing briquets from such prevolatilized coal, an unlimited source of smokeless fuel has been opened up.

Successful use of prevolatilized coal in the manufacture of smokeless briquets hinges on the possibility of volatilizing the coal rapidly.

DEVELOPMENT OF A PROCESS FOR THE VOLATILIZATION OF COAL

Many reports have been printed about the rapid liberation of the volatile matter from coal; the interest in this method dates back to the beginning of the carbonization of coal and the manufacture of blue gas from the carbonized coal.

The basic principle underlying the process for rapid volatilization of coal and its various modifications consists of maintaining conditions favorable to rapid heating of the coal and to rapid disposal of the liberated volatile matter. Such conditions necessitate the fine pulverization of the coal (which facilitates surface heating) and agitation (which promotes free removal of the liberated gases). Various terms used to describe the rapid removal of volatile matter from coal include "instantaneous carbonization," "flash distillation," "fluidization" and "contact vaporization."

One of the earliest processes for rapid distillation of coal was developed by Bassett[2]

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[1] Piersol, R. J., Smokeless briquets: impacted without binder from partially volatilized Illinois coals. Illinois State Geol. Survey Rpt. Inv. No. 41, 1936.

[2] Bassett, J. A., U. S. Patent No. 118-579 Improvement in the manufacture of coal gases. Granted August 29, 1871.

in 1871. Finely pulverized coal was dropped by gravity down a retort about 40 feet high and about 18 inches in diameter; ascending hot gases resulted in the distillation of the volatile matter from the coal.

In 1918, Whitaker and Suydom[3] obtained rapid carbonization of 20 x 60 mesh coal dropped by gravity down a tube 6 feet high and 4 inches in diameter at temperatures between 650° and 900° C. at a rate of about 0.4 to 0.8 pound per hour.

In 1924, Newall and Sinnatt[4] studied the effect of dropping fine particles of coal through a vertical silica tube, 28.5 inches high and 1.5 inches in diameter, heated to various temperatures. The original 23.7 percent volatile matter in the 60 x 90 mesh coal was reduced to 23.4, 22.0, and 17.5 percent by heating 12 seconds at temperatures of 420°, 500°, and 530° C. respectively; and to 13.6 and 12.2 percent by heating 6 seconds at temperatures of 580° and 620° C. respectively. The resulting carbonized particles, which are referred to as cenospheres, are bubble-like in form.

In 1926, White[5] made a similar study in which he dropped powdered coal through a a vertical furnace, 84 inches high and 3 inches in diameter, heated to various temperatures. He tested Elkhorn No. 2 Kentucky coal, Will County No. 2 Illinois coal, and South Dakota lignite. The furnace was heated to temperatures from 650° to 900° C., and the coal was heated for the length of time required to drop by gravity through the furnace. The particles of coal were reduced to various amounts of volatile matter down to 3.4 percent. The resultant bulk density of the carbonized coal was about one-third of that of the original powdered coal. The average calorific value of the liberated gases was 480 B.t.u. per cu. ft.

In 1932, Hobart and Demorest[6] investigated the feasibility of White's process. They concluded that the resultant capacity is low as compared to that of other low-temperature processes and that the very low bulk density of the char made it unfavorable for briquetting without prior grinding.

In 1931, Dieterle[7] developed a process for water gas generation which includes a method for the distillation of powdered coal, dropping through a stream of ascending hot gases obtained by passing steam upward through an incandescent coal bed.

In 1931, St. Jacques[8] developed a furnace for contact distillation of injected pulverized coal which is maintained in a turbulent state (fluidization).

History of Development of the Method of Smoke-Index Determination

Because exploratory laboratory investigations indicated that briquets made from partially volatilized Illinois coal would burn with substantially less smoke than raw coal, it was desirable to develop a more exact method of measuring smoke than any of the methods in general use. Therefore, during 1933 and 1934 the author developed the smoke-index method as a precision laboratory tool for accurately determining the amount of smoke produced by coal or briquets, or any other combustible substance, during combustion (see Article 3 of this report).

History of Development of Smokeless Briquets

In 1935 and 1936, a detailed laboratory investigation was made on smokeless briquets prepared from partially volatilized coal, the results of which were described in 1936 in a progress report.[9]

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[3] Whitaker, M. C., and Suydon, J. R., Jr., A comparative study of the thermal decomposition of coal and some of the products of its carbonization. Jour. Ind. Eng. Chem., vol. 10, p. 431, 1918.

[4] Newall, H. E., and Sinnatt, F. S., The carbonization of coal in the form of fine particles.—I. The production of cenospheres: Fuel in Science and Practice, p. 424, vol. 3, No. 12, 1924.

[5] White, A. H., The instantaneous carbonization of crushed coal: Proc. First Int. Conf. on bituminous coal, p. 419, 1926.

[6] Hobart, F. B., and Demorest, D. J., Tests on the continuous carbonization of finely crushed coal by radiant heat. Ohio State Univ., Exp. Sta. Bull. No. 65, 1922.

[7] Dieterle, E. A., U. S. Patent No. 1-792-632, Gasification process. Granted Feb. 17, 1931.

[8] St. Jacques, C., St. Jacques turbulent furnace: Ind. and Eng. Chem. News Ed., p. 29, Vol. 15, No. 2, 1937.

[9] Piersol, R. J., Smokeless briquets: impacted without binder from partially volatilized Illinois coals: Illinois State Geol. Survey Rpt.. Inv. No. 41, 1936.

Since 1936 attention has been given to the design of equipment for making briquets from partially volatilized Illinois coal and to tests with such equipment.

PATENT PROTECTION

The present process consists of producing briquets from minus 4-mesh high volatile coal, made smokeless by elimination of the smoke-producing fraction (about one third of the volatile matter) by partial volatilization before briquetting. The equipment to make such smokeless briquets without added binder has been covered by U. S. Patent No. 2-119-243, "Briquetting Presses," granted May 31, 1937, for the protection of the people of the State of Illinois.

SCOPE OF ARTICLE

The small-scale laboratory investigation made by the author covered (a) the influence of the temperature of the coal upon the amount of the volatile matter in the resulting briquet, (b) the influence of the length of time of volatilization upon the amount of volatile matter in the resultant briquet, (c) the composition and the calorific value of the liberated volatile gases, (d) the influence of the degree of prevolatilization upon the smoke-index of the resultant briquet, (e) the influence of the degree of prevolatilization upon the mechanical strength of the resultant briquets, and (f) the influence of the temperature and pressure of briquetting upon the mechanical strength of the resultant briquet.

ACKNOWLEDGMENTS

The small-scale smokeless briquets were made by an impact machine of the Department of Theoretical and Applied Mechanics of the University of Illinois which was available through the courtesy of M. L. Enger, Dean of the College of Engineering. Larger scale smokeless briquets were made, in certain instances, by equipment in experimental laboratories of various Illinois coal operators.

J. M. Nash and H. C. Roberts, assistants in the Survey's Physics Division, and for a brief time F. W. Cooke, Physicist, carried on laboratory tests and assisted in the construction of equipment. Chemical analyses were made under the supervision of O. W. Rees, Chemist and Head of the Analytical Division of the Chemistry Section of the Survey.

COALS USED

A large number of coals have been tested, and from all the results, those for eight coals, distributed fairly well through the range of rank variation in Illinois, have been selected as examples and their proximate analyses are shown in table 36.

Samples 1 and 2, from Will County and Franklin County respectively, were selected for volatilization tests because they represent the upper and lower extremes of variation of volatile matter in commercial Illinois coals. The proximate analyses for these two were made from samples after preheating to 250° C., which accounts for their low unit coal B.t.u. Samples 3 to 8, inclusive, consist of low volatile eastern coals and high volatile Illinois coals, and were selected as representative of various ranks of bituminous coals in order to determine the influence of the amount of volatile matter on the smoke-index of raw coals.

LABORATORY EQUIPMENT

PREVOLATILIZER

The laboratory equipment used for partially volatilizing Illinois coal consisted of a rotary furnace with an exhaust system for the removal of the volatilized gases.

Various kinds of rotary prevolatilizers were used as the investigation progressed. The earliest form, which is still regarded as satisfactory and is described in a previous publication,[10] consists of a heating cell, constructed from a 5¾-inch length of 3⅛-inch pipe, so mounted as to rotate within a stationary 6-inch length of 3½-inch pipe, around which is wound the heating element. For the insertion of a thermocouple, a ¼-inch copper tube, with its inner end closed, extends to the center of the cell through the rear end which is removable by means of a spanner wrench. The front end of the cell

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[10] Piersol, R. J., Op. cit.

TABLE 36.—PROXIMATE ANALYSES OF COAL USED FOR TESTS

Sample No.	Location			Condition[a]	Proximate analyses					
	County	State	Seam		Moisture	Ash	Volatile matter	Fixed Carbon	Total Sulphur	B.t.u.
1[b]	Will	Ill.	2	1	9.5	4.8	39.7	46.0	3.1	12040
				2	—	5.3	43.9	50.8	3.4	13300
				3	—	—	45.6	54.4	—	14210
2	Franklin	Ill.	6	1	8.4	6.5	32.9	52.2	1.0	12130
				2	—	7.1	35.9	57.0	1.1	13250
				3	—	—	38.0	62.0	—	14380
3	Will	Ill.	2	1	9.1	4.7	43.5	42.7	2.9	12370
				2	—	5.2	47.8	47.0	3.2	13600
				3	—	—	49.8	50.2	—	14520
4	Washington	Ill.	6	1	8.5	7.2	41.5	42.8	4.2	11910
				2	—	7.8	45.4	46.8	4.6	13030
				3	—	—	48.2	51.8	—	14370
5	Franklin	Ill.	6	1	8.7	10.0	33.8	47.5	2.0	11640
				2	—	10.9	37.0	52.1	2.1	12750
				3	—	—	40.5	59.5	—	14520
6	Raleigh	W. Va.	Beckley	1	0.7	5.2	16.2	77.9	0.7	15120
				2	—	5.2	16.3	78.5	0.7	15230
				3	—	—	16.9	83.1	—	16100
7	Beckley	W. Va.	Beckley	1	1.0	5.0	17.5	76.5	0.6	14700
				2	—	5.0	17.7	77.3	0.6	14850
				3	—	—	10.1	81.9	—	15720
8	Wyoming	W. Va.	Jewell	1	1.4	4.0	22.5	72.1	0.6	14750
				2	—	4.1	22.8	73.1	0.6	14960
				3	—	—	23.4	76.6	—	15670

[a] Condition: 1—as received basis; 2—moisture-free basis; and 3—Unit Coal basis (dry mineral matter-free).
[b] Sample Nos. 1 and 2 were heated to 250° C. prior to analyses, which resulted in decrease of calorific value.

is closed by a permanent steel inset, through which extends outwardly a 3-inch length of ¼-inch steel tubing that serves both as an outlet for the escaping gas and as a means for rotating the heating cell. The rear end of the stationary pipe is closed by a transit inset with an opening through which the thermocouple passes; the front end is open. The capacity of this oven is about 50 grams of coal which is sufficient to make a 1½-inch cylindrical briquet.

Although this small prevolatilizer was used exclusively and satisfactorily for making the laboratory briquets for detailed study, two larger scale prevolatilizers were used in processing coal for larger size experimental briquets. Their construction points the way toward the design necessary for commercial-scale operation.

When in the course of this investigation it became desirable to increase the capacity of the rotary oven to 1000 grams of coal in order to make a 4-inch cylindrical briquet, the size of the inner rotary cell was increased to 6-inch diameter and 8-inch length, which was enclosed in a larger electrically heated stationary furnace. The inner cell was rotated at 17 r.p.m. by a ¼-horsepower electric motor through a speed reducer.

The capacity of the rotary oven was eventually increased in various steps until the final cell, used for preparing coal for the commercial-scale press, had a capacity for 100 pounds of coal and consisted of an 18-inch diameter steel drum with a 29-inch length. The permanently closed end has an inserted filter, packed with steel wool, through which the volatile gases escape. The opposite end is 45-degree taped to a 4-inch diameter opening into which is fitted a removable 4-inch plate, in the center of which a thermocouple well extends inwardly. This cell is within a larger steel drum which is motor driven at 3 r.p.m. and is heated by a large circular gas burner. The unit is inclosed in a rectangular steel housing, 60 inches high, 44 inches long, and 39 inches wide, with a vent to a chimney for removal of liberated gases.

Equipment Used for Briquetting

The briquetting equipment consisted of a press and a briquetting die.

Two types of presses,[11] described in detail in an earlier publication, were used; a Turner impact press and a hydraulic press.

The Turner impact press consists of two vertical standards, serving as guides for drop hammers of various weights, from 50 to 500 pounds, which are raised to the desired height by an electro-magnet and dropped by breaking the electric circuit, thereby forming briquets from 2 to 250 grams in weight, 1/2 inch to 2 1/2 inches in diameter. Later on a larger impact machine was built at Marion, Ohio, by Marion Steam Shovel Company, which dropped a 2200-pound hammer from heights up to 13 feet, thereby forming 4-inch diameter briquets up to 1000 grams in weight.

The first hydraulic press was a Riehle 25-ton hand operated press that made cylindrical briquets of the same range of sizes as the small Turner impact press. Later an electrically driven 50-ton hydraulic press was used that made cylindrical briquets of the same size as the larger impact press.

All the laboratory briquetting dies, used both for impact briquets and compression briquets, are of the same general design as those described in an earlier report.[12] A set of dies consists of a hollow cylinder, with tightly fitting lower and top plungers. The lower plunger is set within and flush to the bottom of the die. The top plunger is set on top of the loose coal within the die and extends upward beyond the top of the die. The die and plunger are made from various high-tensile strength heat-resisting alloys, heat treated and ground to size.

In the first series of dies, the cylinder was machined in the form of a spool, upon which was wound a heating coil, protected by an asbestos jacket. In the later dies, the set of dies was fitted into a secondary removable spool, which formed the heating unit, in order to protect the heating unit which was removed during the instant of briquetting.

Equipment Used in Determining Mechanical Strength

A tumbling barrel[13] was used to determine the mechanical strength of the briquets in terms of their resistance to crushing during handling. It consists of an 8-inch length of pipe, with an 8-inch inside diameter and ¼-inch wall, the ends of which are closed by round steel plates, ¼-inch thick, one being removable for the insertion and removal of briquets. Three equally spaced 1-inch angle irons that run the length of the barrel act as baffles. The barrel is half filled with flint pebbles, that have a total weight of 5000 grams and an approximate weight of 25 grams each.

Smoke-index Apparatus

The smoke-index equipment[14] used in this investigation consisted of (a) an electric muffle furnace, so equipped that a specified temperature and air supply can be maintained; (b) a light-absorption tube through which all smoke is drawn; and (c) a smoke density system composed of a source beam of constant intensity which passes through the absorption tube, a photo-electric cell at the other end of the tube, and a galvanometer. This apparatus is more fully described in Article 3 of this report.

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[11] Piersol, R. J., Briquetting Illinois coals without a binder by compression and by impact. Illinois State Geol. Survey Rpt. Inv. No. 31, 1933.

[12] Piersol, R. J., Op. cit.

[13] Piersol, R. J., Op. cit.

[14] Piersol, R. J., Smokeless briquets: impacted without binder from partially volatilized Illinois coals. Illinois State Geol. Survey Rpt. Inv. No. 41, 1936.

PREPARATION OF COAL SAMPLE

Size Preparation

The size of material which gave most uniform results and which was best adapted to briquetting was minus 4-mesh. All coal samples were therefore reduced to this size upon their receipt at the laboratory and were then stored in air-tight receptacles to avoid excessive moisture loss and oxidation. Immediately before use, in either volatilization or briquetting tests, the samples needed were obtained by quartering from the storage sample.

Removal of Low-Temperature Volatile Matter

The steps in the prevolatilization procedure were as follows: (1) the temperature of the prevolatilizer (measured by the thermocouple inserted in the copper tube) was raised to a predetermined value by use of an appropriate equilibrium heating current, which maintained a constant temperature throughout the test; (2) the heating cell was removed from the stationary pipe, its removable end opened, the weighted quantity of coal inserted, the end closed, and the loaded cell replaced, the entire operation requiring about 30 seconds; (3) the exhaust motor was started or natural draft from chimney was used; (4) during the heating, the prevolatilizer was hand-rotated rapidly at 1-minute intervals or it was motor driven, to prevent the coal from sticking and to insure uniform distribution of temperature and degree of volatilization; (5) at the end of the predetermined period of volatilization, the temperature of the coal was recorded; (7) the coal was cooled to a predetermined temperature and was transferred to the briquetting die which had been previously heated to various selected temperatures. The top surface of the coal in the die was leveled, and the movable plunger was lightly pressed down so that it entered the cylinder for a short distance. The loaded die was placed either under an impact hammer or between the plates of an hydraulic press and the coal was briquetted. The bottom plunger was removed and the briquet was pressed out of the die. Each briquet was weighed immediately in order to determine its combined moisture and volatile loss.

TESTING OF BRIQUETS

Tumbling Tests

The tumbling barrel was rotated at 40 r.p.m. for two minutes in the determination of the tumbling loss for cylindrical briquets made from partially volatilized coal. As the tumbling losses of briquets of the same size and shape are directly comparable, the results obtained for a 50-gram sample of partially volatilized coal can be compared directly with those made from a 45-gram sample of nonvolatilized coal.

SMOKE-INDEX DETERMINATION

Procedure

In preparing samples for smoke-index determination, seven or eight 1-cm. cubes were cut by a carborundum saw from each briquet and three or four cubes from the center of a lump of each coal tested. The latter were cut immediately before testing in order to avoid air-drying loss as much as possible. They were all approximately the same weight, as determined by actual weighing.

A complete statement of the smoke-index method is given in Article 3. Briefly, the procedure for the determination was as follows: The cube of coal, on a nickel dish set on a movable tray, was placed at the center of the furnace. The furnace was maintained at a temperature of 600° C. and with an air supply of 4 cubic feet per minute. Galvanometer readings were taken at 5-second intervals, starting at the instant the sample was placed in the furnace and continuing throughout the period of smoke liberation.

The total smoke was calculated as the product of the average amount of smoke produced and the time required for its liberation. The smoke-index (smoke per gram) was obtained by dividing this total smoke content by the initial weight of the sample.

CALCULATION OF VOLATILE MATTER IN PARTIALLY VOLATILIZED COAL

The percentage of volatile matter in partially volatilized coal may be calculated from the percent volatile matter in the original coal and the percent weight loss (all on a dry basis), according to the following formula:

$$VM_2 = \left(\frac{VM_1 - L}{100 - L}\right) \times 100 \qquad (1)$$

where VM_1 and VM_2 are the percentage volatile matter in the original coal and the partially volatilized coal respectively, and L is the percent weight loss above 275° C. (or on the dry basis).

Removal of volatile matter will of course produce a corresponding increase in fixed carbon and ash according to following formulae:

$$FC_2 = \left(\frac{FC_1}{100 - L}\right) \times 100 \qquad (2)$$

$$A_2 = \left(\frac{A_1}{100 - L}\right) \times 100 \qquad (3)$$

where the subscripts have the same connotation as in the first equation.

TABLE 37.—VOLATILE MATTER CONTENT OF WILL COUNTY COAL AS AFFECTED BY VARIOUS VOLATILIZATION TEMPERATURES MAINTAINED FOR 10-MINUTE PERIODS
(Figure 37)

Test No.	Temperature °C.		Weight loss (percent)	Volatile matter (percent) [a]
	Oven	Coal		
1	400	350	0.0	43.9
2	425	375	0.4	43.7
3	450	395	1.2	43.2
4	480	430	1.9	42.8
5	475	430	2.8	42.3
6	490	450	5.8	40.5
7	500	460	6.9	39.8
8	510	470	8.8	38.5
9	520	475	11.8	36.4
10	525	475	11.3	36.8
11	530	485	12.7	35.7
12	540	495	16.2	33.0
13	550	505	17.6	31.9

[a] Percentage volatile matter is calculated from weight loss (dry basis).

EXPERIMENTAL RESULTS

INFLUENCE OF VARIOUS TEMPERATURES FOR A CONSTANT PERIOD OF VOLATILIZATION ON THE FINAL VOLATILE CONTENT

Table 37 and corresponding figure 37, which give the percentage of volatile matter remaining in Will County coal after 10-minute volatilization periods at various temperatures, reveal an approximately linear

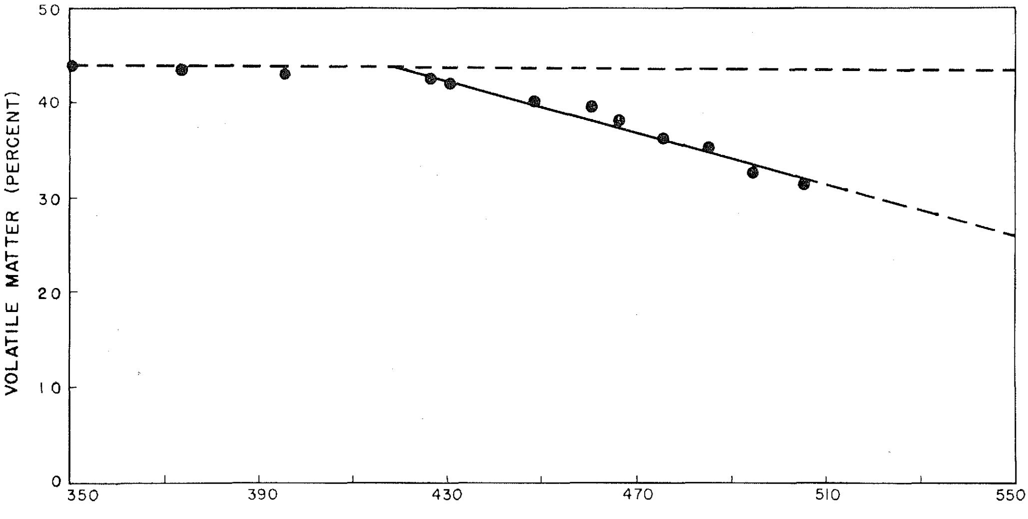

FIG. 37.—Volatile matter content of Will County coal as affected by various volatilization temperatures maintained for 10-minute periods. (Data from table 37)

Table 38.—Volatile Matter Content of Franklin County Coal as Affected by Various Volatilization Temperatures Maintained for 10-minute Periods
(Figure 38)

Test No.	Temperature °C.		Weight loss (percent)	Volatile matter (percent)
	Oven	Coal		
1	330	290	0.0	35.9
2	460	425	4.3	33.0
3	480	440	7.3	30.9
4	500	455	10.3	28.6
5	520	470	16.1	23.6
6	540	480	17.2	22.6

relationship between the temperature and the volatile matter in the partially volatilized coal; the first appreciable reduction in the volatile matter starts at about 420° C.

Table 38 and corresponding figure 38, which present similar data for Franklin County coal, reveal the same characteristic relationship; in this coal the first appreciable reduction in the volatile matter starts at about 410° C.

Influence of Length of Time of Volatilization upon the Amount of Volatile Matter in the Resultant Briquet

Table 39 presents data for determining the influence of both the time and the temperature on the volatile matter content of partially volatilized Will County coal.

It is shown that a reduction of 15 percent or more in the weight of dry Illinois coal (which necessarily represents a reduction of volatile matter) results in a commercially smokeless briquet. When time-temperature data are plotted for values from table 39 for about 15.6 percent weight reduction (fig. 39), there is apparent an approximately linear relationship between time and the temperature necessary to secure the desired reduction in volatile matter required to produce a smokeless briquet. The temperature decreases with the increase of time of volatilization.

Composition and Calorific Value of the Liberated Volatile Gases

The percent composition and the calorific values of the gases liberated in the 15 percent weight reduction of dry coal was determined (table 40) for a 10-minute volatilization period for Will County and Franklin County coals. Columns 1 and 2 show the density (lbs. per cu. ft.) for each gaseous component; columns 3 and 4 show the percentage of gases for Will County coal by volume and weight, respectively; and columns 5 and 6 show similar data for Franklin County coal. Also the overall density, calorific value (both B.t.u. per cu. ft. and B.t.u. per pound of volatile matter) is shown for Will County and Franklin County coals.

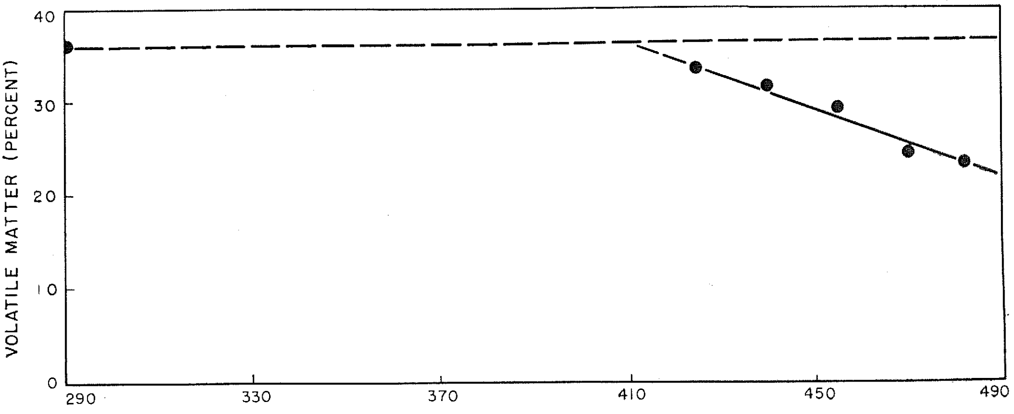

Fig. 38.—Volatile matter content of Franklin County coal as affected by various volatilization temperatures maintained for 10-minute periods. (Data from table 38)

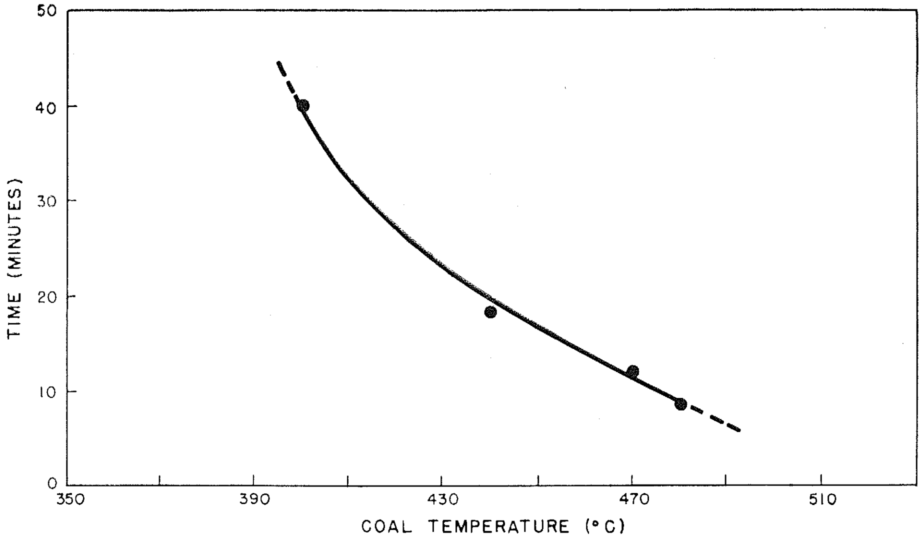

FIG. 39.—Time-temperature data for optimum volatile matter loss for Will County coal. (Data from table 39)

TABLE 39.—TIME-TEMPERATURE DATA FOR OPTIMUM VOLATILE MATTER LOSS FOR WILL COUNTY COAL (Figure 39)

Test No.	Time (minutes)	Temperature °C.		Weight loss (percent)	Volatile matter[a] (percent)
		Oven	Coal		
1	10	400	350	0.0	43.9
2	90	400	390	10.6	37.3
3	75	400	390	10.6	37.3
4	75	390	390	5.9	40.4
5	40	420	400	[b]15.3	33.8
6	40	405	400	9.4	38.1
7	35	415	400	11.8	36.4
8	30	410	400	11.8	36.4
9	20	500	445	17.7	31.8
10	18.5	450	440	[b]15.3	33.8
11	13	500	475	18.8	30.9
12	12	500	470	15.9	33.3
13	11	500	460	12.9	35.6
14	9	550	495	18.8	30.9
15	8.5	550	480	[b]15.9	33.3

[a] Percentage volatile matter is calculated from weight loss (dry basis).
[b] Optimum volatile matter loss is selected at a value of about 15.6 percent (weight loss).

TABLE 40.—CALORIFIC VALUE OF VOLATILE MATTER LIBERATED IN PARTIAL VOLATILIZATION OF COAL PRIOR TO BRIQUETTING

Gas[a]	Density (lb. per cu. ft.)	Will County coal		Franklin County coal	
		Volume (percent)	Weight (lb. per cu. ft.)	Volume (percent)	Weight (lb. per cu. ft.)
CO$_2$	0.121	25.8	0.031	23.9	0.029
Illuminates	0.073	6.4	0.005	5.7	0.004
CO	0.081	11.7	0.009	11.4	0.009
H$_2$	0.057	13.1	0.007	11.9	0.007
CH$_4$	0.049	31.9	0.016	41.2	0.020
C$_2$H$_6$	0.081	11.1	0.009	5.9	0.005
Density (lb. per cu. ft.)	—	—	0.077	—	0.074
Gas B.t.u. (per cu. ft.)	—	—	641	—	656
Gas B.t.u. (per lb.)	—	—	8340	—	8860

[a] Gas analysis is made in the Geochemical Laboratories of the Survey.

TABLE 41.—EFFECT OF AMOUNT OF VOLATILE MATTER ON SMOKE-INDEX OF NATURAL COALS (Figure 40)

Location	Bed	Moisture (percent)	Volatile matter (percent)	Smoke-index (percent)
Will County (series 1)	2	9.1	43.5	5350
Will County (series 2)	"	[a]	[a]	4220
Washington County	6	8.5	41.5	4380
Franklin County	"	8.7	33.8	3650
West Virginia (A)	Beckley	0.7	16.2	1770
" " (B)	"	0.0	17.7	1820
" " (C)	Jewell	1.4	22.5	2720

[a] Same coal as Will County Series 1 after three months storage.

INFLUENCE OF THE DEGREE OF VOLATILIZATION UPON THE SMOKE-INDEX OF RESULTANT BRIQUET

There is a general linear increase in smoke-index for increased volatile content in raw coals (table 41, fig. 40). The smoke-indices of natural coals provide a basis of comparison with the smoke-indices of briquets made from partially volatilized coal.

Data on the effect of various degrees of volatilization on the smoke-index of briquets made from partially volatilized Will County coal (table 42, fig. 41), reveal a rapid decrease in smoke-index with decrease in volatile content.

Similar data for briquets made from partially volatilized Franklin County coal (table 43, fig. 42), reveal a relationship similar to that for briquets made from Will County coal.

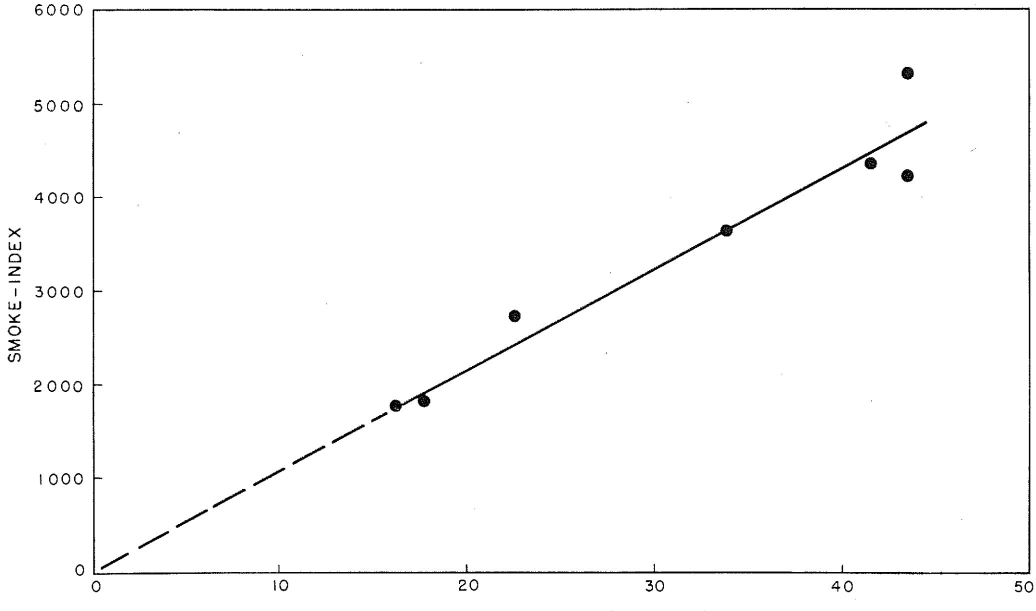

FIG. 40.—Effect of the amount of volatile matter on smoke-index of natural coals. (Data from table 41)

TABLE 42.—EFFECT OF AMOUNT OF VOLATILIZATION ON SMOKE-INDEX OF WILL COUNTY CYLINDRICAL BRIQUETS

Test No.	Coal T°C.	Weight loss (percent)	Volatile matter (percent)	Smoke-index
1	250	0.0	43.9	3640
2	477	7.6	39.3	2610
3	485	12.7	35.8	1770
4	505	17.6	31.9	510
5	515	25.9	24.3	140
6	535	32.9	16.4	140

TABLE 43.—EFFECT OF AMOUNT OF VOLATILIZATION ON SMOKE-INDEX OF FRANKLIN COUNTY CYLINDRICAL BRIQUETS

Test No.	Coal T°C.	Weight loss (percent)	Volatile matter (percent)	Smoke-index
1	250	0.0	35.9	2500
2	430	4.3	33.1	2160
3	465	7.3	30.9	1600
4	480	10.3	28.5	1220
5	495	16.1	23.6	250

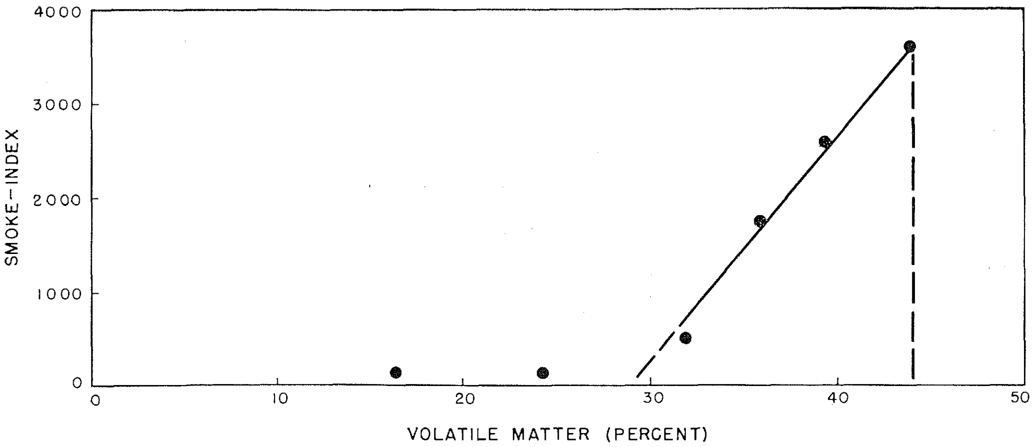

FIG. 41.—Effect of the amount of volatilization on the smoke-index of Will County cylindrical briquets. (Data from table 42)

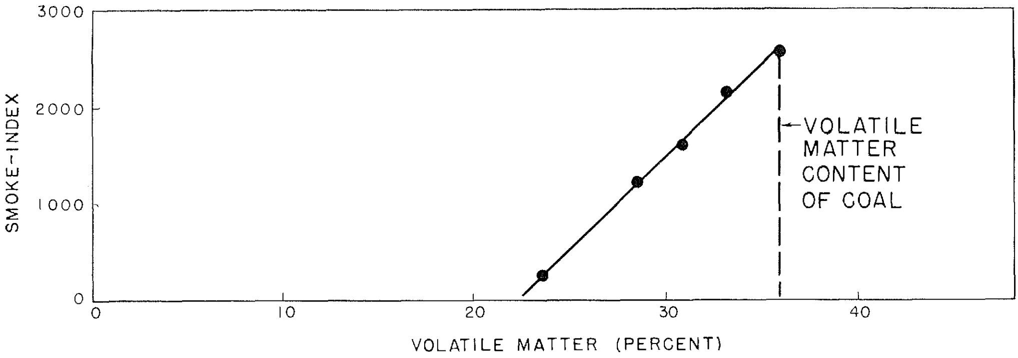

FIG. 42.—Effect of the amount of volatilization on smoke-index of Franklin County cylindrical briquets. (Data from table 43)

TABLE 44.—MECHANICAL STRENGTH OF WILL COUNTY CYLINDRICAL BRIQUETS AS AFFECTED BY VOLATILE MATTER CONTENT
(Figure 43)

Test No.	Temperature °C.		Weight loss (percent)	Volatile matter (percent)	Tumbling loss (percent)
	Oven	Coal			
1	425	375	0.4	43.7	4.8
2	490	450	5.8	40.5	1.8
3	500	460	6.9	39.8	2.7
4	510	465	8.8	38.5	1.3
5	520	475	11.3	36.8	2.9
6	525	475	11.8	36.4	1.8
7	530	485	12.7	35.7	3.4
8	540	495	16.2	33.0	2.2
9	550	505	17.6	31.9	2.8
10	570	525	21.0	29.0	[a]
Av.					2.5

[a] Briquet broke when tumbled.

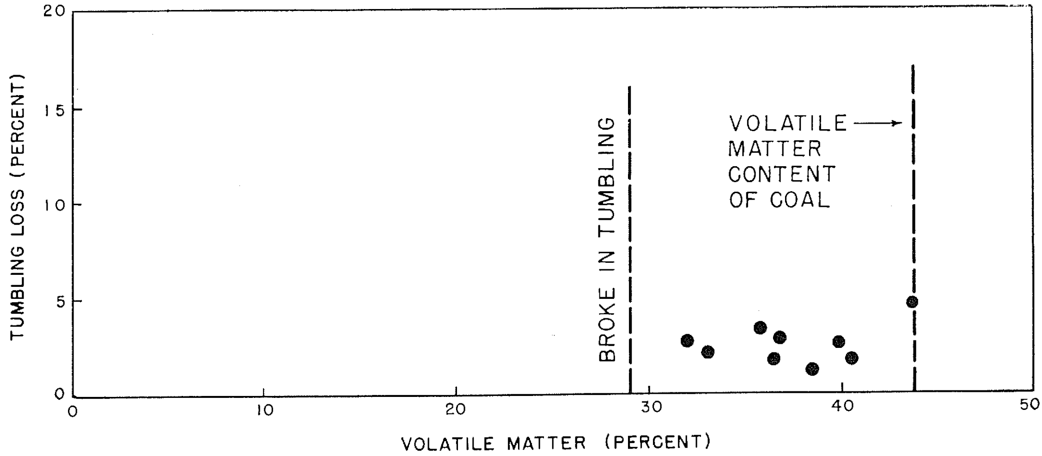

FIG. 43.—Mechanical strength of Will County cylindrical briquets as affected by volatile matter content. (Data from table 44)

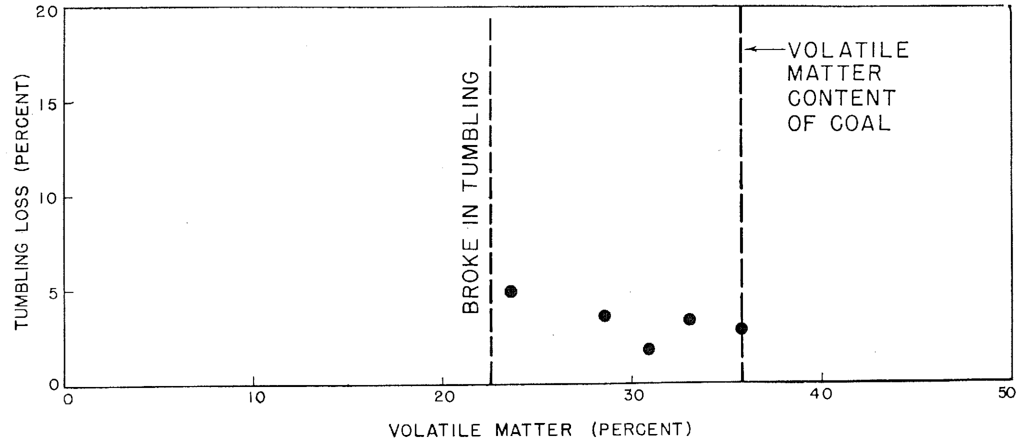

FIG. 44.—Mechanical strength of Franklin County cylindrical briquets as affected by volatile matter content. (Data from table 45)

TABLE 45.—MECHANICAL STRENGTH OF FRANKLIN COUNTY CYLINDRICAL BRIQUETS AS AFFECTED BY VOLATILE MATTER CONTENT
(Figure 44)

Test No.	Temperature °C.		Weight loss (percent)	Volatile matter (percent)	Tumbling loss (percent)
	Oven	Coal			
1	275	250	0.0	35.9	2.8
2	460	425	4.3	33.0	3.6
3	480	440	7.3	30.9	1.8
4	500	455	10.5	28.6	3.5
5	520	470	16.1	23.6	4.9
6	540	480	17.2	22.6	[a]
Av.					3.3

[a] Briquet broke when tumbled.

INFLUENCE OF THE DEGREE OF PREVOLATILIZATION ON MECHANICAL STRENGTH OF RESULTANT BRIQUET

Data illustrative of the variation in the mechanical strength of briquets made from Will County coal as related to reduction in percent volatile matter (table 44, fig. 43) reveal that the briquets are strong up to 17.6 percent reduction by weight (31.9 percent volatile matter) and that the briquets in which the weight reduction had been 21.0 percent broke in tumbling. This is a general rule substantiated by numerous tests.

TABLE 46.—MECHANICAL STRENGTH OF WILL COUNTY SMOKELESS CYLINDRICAL BRIQUETS CONTAINING 33.1 PERCENT VOLATILE MATTER FROM COAL VOLATILIZED AT 460°C. FOR 5 MINUTES AS AFFECTED BY BRIQUETTING TEMPERATURE
(Figure 45)

Test No.	Briquetting temp., °C.	Tumbling loss (percent)	
		Individual	Average
1	250	4.8	5.0
2		5.1	
3	300	1.9	2.7
4		3.5	
5	350	1.9	1.5
6		1.1	
7	400	1.3	1.2
8		1.6	
9		0.8	

Corresponding representative briquets made from Franklin County coal (table 45, fig. 44) are strong up to 16.1 percent reduction by weight (23.6 percent volatile matter). When reduction by weight reached 17.2 percent they broke in tumbling.

INFLUENCE OF THE TEMPERATURE OF BRIQUETTING ON THE MECHANICAL STRENGTH OF CYLINDRICAL SMOKELESS BRIQUETS

The mechanical strength of smokeless Will County cylindrical briquets (table 46, fig. 45), made from coal prevolatilized for a 5-minute period at a coal temperature of 400° C., as affected by the briquetting tem-

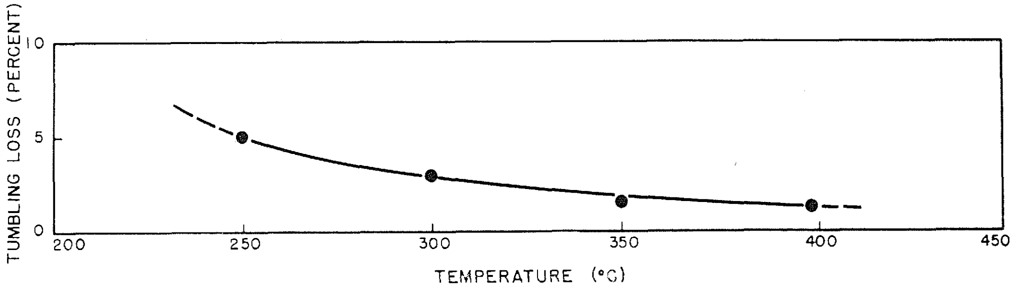

FIG. 45.—Effect of briquetting temperature on mechanical strength of Will County smokeless cylindrical briquets. (Data from table 46)

perature (the temperature to which the coal is lowered and at which the die is maintained) increased with increase of briquetting temperature up to 400° C.; which value is approximately the highest permissible briquetting temperature.

PARTIAL PREVOLATILIZATION

SIGNIFICANCE UPON THE FORMATION AND CHARACTER OF BRIQUETS

Because of the importance of partial volatilization of coal used in the production of briquets made without a binder, it is desirable to discuss briefly the following aspects of the briquetting process: (1) The essential conditions of the process; (2) comparison of this volatilization process with others; (3) the process of removal of the volatile matter; (4) the effect of partial volatilization upon the briquetting properties; (5) the role of temperature and (6) of time in volatilization, and (7) the interrelation of the two; (8) the effect of weathering on volatilization and briquetting; (9) the heating value of the gas liberated by volatilization; (10) the effect of volatilization on the smoke-index of the coals and of Illinois coals specifically; (11) the relation between strength of the briquets and the amount of volatile matter removed; (12) the effect of briquetting temperature on strength of the briquets; (13) the maximum temperature of commercial briquetting; and (14) the relation of results of larger scale to those of small-scale briquetting.

ESSENTIAL CHARACTERISTICS OF PARTIAL VOLATILIZATION AND SUBSEQUENT BRIQUETTING

From the beginning of the investigation more than ten years ago the process of heat-treating the coal before briquetting has been designated "partial volatilization." This process involves establishing conditions for initial production of loose, individually dense coal particles, a subsequent reduction of about 15 percent in dry weight, and the development of a momentary plasticity which eliminates porosity when the coal is subjected to pressure of about 30,000 pounds per sq. in. at a temperature of about 400° C.

COMPARISON OF THIS VOLATILIZATION PROCESS WITH OTHERS

The literature previously cited in this article includes descriptions of processes somewhat similar to the present, by such authors as Bassett, Whitaker and Suydom, Newal and Sinnatt, White, Hobart and Demorest, Dieterle, and St. Jacques. However the processes were characterized generally by the almost instantaneous liberation of the volatile matter from finely pulverized coal (minus 60-mesh or less) with resultant extreme swelling and loss of agglutinating property. Such completely or nearly completely carbonized coal is unsatisfactory for making smokeless briquets unless it is ground, because it has lost its adhesive ability and also because of its usual tendency to swell, in some instances to as much as three times its original volume.

PROCESS OF REMOVAL OF LOW-TEMPERATURE VOLATILE MATTER

In order to retain the original size of a coal particle during partial volatilization, it is necessary to release the volatile gases formed in the interior of the particle at a sufficiently low rate so that they can escape freely to the surface by natural permeability. Otherwise the coal particle becomes bloated due to the accumulation of internal gas pressure. Free escape of the liberated gases from the surface of the particle is also essential, a requirement which seems to be met by repeated agitation resulting from the rotary motion of the cell during volatilization. Without such agitation the particles tend to agglomerate. Such agitation may also result in the maintenance at approximately the same temperature of all the particles of coal during partial volatilization. By observing these conditions it has been found experimentally that even highly coking Eastern coals may be partially volatilized without swelling; however this is not as easily accomplished with these coals as with Illinois coals.

Effect Upon the Briquetting Properties of Illinois Coals

A large amount of accumulated but unpublished evidence shows that the natural briquetting property of partially volatilized coal is essentially the same as that of raw coal. The very fact that Illinois coals which contain up to 25 percent inert materials (such as mineral matter and fusain) may be briquetted without a binder indicates that these coals contain a considerable excess of inherent binding capacity. This conclusion is substantiated by the ease with which partially volatilized Illinois coals may be briquetted without the use of a binder. The fact that low volatile Pocahontas coal with only 17 percent volatile matter may be briquetted by this method is final evidence that only a relatively small percentage of volatile constituents suffices to effect briquetting.

Influence of Temperature

Experimentally there is an approximately linear relationship between the decrease in the percentage of volatile matter remaining in the partially volatilized coal and the increase of temperature used in volatilization. Theoretically the rate of volatilization should increase exponentially with increase of absolute temperature (degrees Kelvin), but the low permeability of the coal tends to restrain the escaping gases. Furthermore the temperature range of volatilization, 698° K. to 823° K. (425° C. to 550° C.) is small. This accounts for the existence of approximately linear relationship between the rate of volatilization and temperature.

Influence of Time

The amount of volatile matter liberated from coal held at a specified volatilization temperature increases with time up to the time when that particular temperature fraction is completely released. Furthermore the character of the volatile matter is determined by the temperature, with the result that volatilization tends to diminish to zero after the particular fraction characteristic of a certain temperature has been liberated.

Interrelation between Time and Temperature

A small reduction in volatile matter (15 percent weight of dry coal) may be obtained by heating at a higher temperature for a shorter time or at a lower temperature for a longer time. As shown in figure 39, this provides a large range of permissible prevolatilization temperature from about 400° to 480° C. and of periods of time from 40 to 8 minutes, respectively. Although in both small-scale laboratory tests and larger scale tests, the period of prevolatilization was usually standardized at 10 minutes, it was found that periods of several hours may be used and followed by successful briquetting. To illustrate an extreme instance: Minus 4-mesh Franklin County coal was partially prevolatilized during an 8-hour period in which it formed the upper layer in a commercial coke oven and then was briquetted without binder.

Effect of Weathering of Illinois Coal on Volatilization and Briquetting

Tests have shown that the natural stockpile weathering, during a three-year period, is not detrimental to the inherent bonding property of Vermilion County coal in making cylindrical briquets. It has also been found that Franklin County coal sludge, even when subjected to a five-year weathering period, retains the inherent bonding ability of fresh coal sludge from the same mine.

Thus the property of Illinois coal which makes possible briquetting without binder is not destroyed by weathering. This is in spite of the fact that, by common knowledge weathering of Illinois fine coal destroys its agglutinating property in the coking process. This indicates that the properties that cause the coherence of particles of coal in a briquet are different from those that produce agglutination and solidity of coke.

Calorific Value of Volatile Gases Liberated

Table 40 reveals that the calorific value of gases liberated in the partial prevolatilization of Illinois coals is more than 600 B.t.u. per cu. ft. which is more than 8000 B.t.u. per pound of gas. With loss of volatile matter amounting to 15 percent of the weight of dry coal, about 300 pounds of volatile matter is liberated per ton of coal (dry weight); thus the total B.t.u. of the liberated gases is more than 2,400,000 B.t.u. It has been estimated[15] that about 1,000,000 B.t.u. would be required to furnish the heat to drive off the desired 15 percent volatile matter and to furnish the power to operate the briquetting equipment. Thus the liberated gases, if utilized only at 50 percent thermal efficiency, would furnish more than the energy required to prevolatilize the coal and to operate the briquetting plant.

Effect of Volatilization on Smoke-Index

Because the smoke ordinances of certain cities specify a definite permissible maximum volatile matter in coal, it was deemed desirable to ascertain the relationship between volatile matter and smoke-index in order to use a specified smoke-index value as a criterion for judging a briquet as smokeless. The City of St. Louis has fixed 23 percent volatile matter as the criterion for natural coals. Figure 40 shows that this corresponds to a smoke-index of 2500 for natural coals, and therefore 2500 may be considered as the critical smoke-index for smokeless briquets.

Prior to these investigations it was thought that it might be necessary to reduce the volatile matter in briquets to that of natural smokeless coals in order to obtain the same smoke-index. However, it was found (fig. 40) that it is necessary to reduce the volatile matter of Will County briquets to only 39 percent from an initial 44 percent and that of Franklin County briquets to only 34 percent from an initial 36 percent to obtain a smoke-index of 2500, which is that of a 23 percent volatile smokeless coal. It has been found also (fig. 40) that the smoke is completely eliminated when the volatile matter in Will County coal is finally reduced to 29 percent. These determinations show that most of the smoke producing constituents of the volatile matter of the coal originate in the fraction released by low-temperature volatilization.

However the same relationships are also valid for other Illinois coals, but the percentage reduction of volatile matter necessary for the elimination of all smoke varies with the coal. Thus Franklin County coal (fig. 41) requires a reduction to 24 percent volatile matter to completely eliminate its tendency to smoke.

Mechanical Strength of Illinois Briquets as Affected by Amount of Volatile Reduction

Throughout the permissible range of volatile reduction (about 15 percent by dry weight), the average strength of the prevolatilized briquet is stronger than that of the raw briquet made from Illinois coal. This is shown by the fact that the average tumbling losses for briquets made from partially volatilized Will County and Franklin County coals are 2.5 and 3.3 percent respectively (tables 44 and 45); whereas the average tumbling loss for briquets made from raw Illinois coals was found to be 5.9 percent.[16]

Effect of Briquetting Temperature on Strength of the Briquets

It was shown earlier in this article that the mechanical strength of a partially prevolatilized briquet increases with an increase of the briquetting temperature. The probable cause of this is that the high-temperature fraction of the volatile matter remains in the briquet, the low-temperature fraction having been eliminated.

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[15] Piersol, R. J., Smokeless briquets: impacted without binder from partially volatilized Illinois coals. Illinois State Geol. Survey Rpt. Inv. No. 41, 1936.

[16] Piersol, R. J., Op. cit.

MAXIMUM TEMPERATURE OF COMMERCIAL BRIQUETTING

The maximum temperature of both laboratory and commercial briquetting, whether with or without binder, is that temperature above which excessive gases are evolved during the briquetting operation. Such gases produce an enormous pressure within the compacted briquet which results in its explosion immediately upon the release of pressure. In order to prevent this condition, the coal which has been subjected to partial volatilization is cooled sufficiently to stop rapid evolution of gas. Commercial attempts to briquet coal at its plastic temperature have failed owing to enormous evolution of gas.

RELATION OF RESULTS OF LARGE-SCALE TESTS TO THOSE OF SMALL-SCALE BRIQUETTING TESTS

In all instances it has been found that the results of larger scale volatilization and briquetting tests are in agreement with those for smaller tests reported in this article.

Once having determined the fundamental nature of the briquetting process by experimentation and mathematical analysis (Article 8), the problem of the commercial scale production of smokeless briquets made without binder from partially volatilized coal becomes primarily an engineering problem of the design of equipment suitable for rapid and economical production of briquets.

However it now appears that the same results in making smokeless briquets may be obtained more economically by partial subsequent volatilization of briquets made at room temperature without an added binder.

SUMMARY

The significant items presented in this article may be briefly stated as follows:

1. The smoke-index of natural coals increases with their increase in volatile matter.
2. For the purpose of smoke abatement control, certain cities arbitrarily specify 23 percent as the maximum permissible volatile matter for natural smokeless coals.
3. Coals which contain 23 percent volatile matter have an average smoke-index of 2500.
4. By this standard, commercially smokeless briquets have a smoke-index of 2500 or less.
5. It has been discovered that the low-temperature fraction of the volatile matter contains all the smoke in bituminous coals.
6. A volatile reduction from 44 to 29 percent for Will County coal and from 36 to 24 percent for Franklin County coal produces zero smoke-index.
7. Briquets from Will County coal partially prevolatilized to 39 percent volatile matter and from Franklin County coal partially prevolatilized to 34 percent volatile matter have a smoke-index of 2500 and therefore are commercially smokeless.
8. For a 10-minute volatilization period, the volatile matter reduction increases linearly with increased temperature, starting at a temperature of 410° to 420° C. for Illinois coals.
9. For a specified volatilization temperature, the volatile matter reduction increases with the increased time of volatilization of Illinois coals.
10. For a specified volatile reduction, the time decreases linearly with increased temperature of volatilization of Illinois coals.
11. Illinois coals contain considerably more volatile matter than is necessary for briquetting without binder.
12. The mechanical strength of briquets without binder, made from Will County coal reduced to 32 percent volatile matter and from Franklin County coal reduced to 25 percent volatile matter, is not detrimentally affected.
13. Before the partially prevolatilized Illinois coal is briquetted, the temperature must be reduced below the temperature that causes excessive liberation of gases in order to prevent explosion of the briquets upon liberation of the briquetting pressure.
14. The mechanical strength of partially prevolatilized briquets increases with briquetting temperature to 400° C.
15. The calorific value of the liberated gases is more than 600 B.t.u. per cu. ft. and about 2,400,000 B.t.u. per ton of coal, which is in excess of the energy requirement to prevolatilize the coal and to operate the briquetting press.

ARTICLE 6—PRELIMINARY STUDY OF CLEANING ILLINOIS COAL SLUDGES BY OIL FLOTATION

INTRODUCTION

Purpose of Investigation

Because the briquetting processes described in this series of articles are particularly well suited to use fine sizes of coal that are commonly difficult to market and because the value of the briquets as domestic fuel is determined to a large extent by their ash value, it is desirable that the fine coal be cleaned to a reasonably low-ash content before briquetting. The purpose of this study was to investigate the possibility of cleaning such sizes of Illinois coal by oil flotation.

Tonnage of Coal Fines

In the almost obsolete practice of delivering run-of-mine Illinois coal to the consumer the fine sizes were not discarded. But with the modern cleaning and preparation of Illinois coal, involving its separation into various screen sizes, the fine size coal is discarded. In the preparation of Illinois stoker coal, usually from 5 to 7 percent of the tonnage hoisted is lost, the discard usually being about minus 10-mesh in screen size. When cleaned by the wet process, the waste product of coal fines is known as coal sludge, sometimes referred to as slurry. When cleaned by the dry process, the waste product of coal fines is known as deduster dust.

Nine Illinois coal operators in 1942 produced about 17,000,000 tons of coal and about 985,000 tons of deduster dust, about 6 percent of their production. In addition, minor production of deduster dust by other operators would make a total deduster dust production slightly in excess of 1,000,000 tons in 1942. In the same year approximately 21,500,000 tons of Illinois coal was cleaned by wet washing. Exact tonnages of the resultant sludge are not available, but a reasonable estimate, based on 5 percent, is a minimum of 1,000,000 tons for the total 1942 Illinois sludge production.

After 1942, the total production of Illinois coal fines, deduster dust, and sludge increased, primarily on account of the war time increased production of Illinois coal. With returning peacetime conditions, the trend toward increased stoker coal production may lead to an eventual annual total of 3,000,000 tons of Illinois deduster dust and sludge.

Fusain in Coal Fines

Due to the pulverant nature of fusain, it tends to concentrate in the coal fines. And since fusain imparts smokeless characteristics to briquets made from coal fines, both deduster dust and coal sludge are important sources of raw material for processing into smokeless briquets.

Cleaning of Coal Fines

However, due to their high ash content, it is necessary to clean many of the Illinois coal fines prior to processing them into smokeless briquets.

Such coal fines may be cleaned to various degrees by float-and-sink in heavy liquids, by centrifuge, by tabling, and by oil flotation.

Although the practice of both wet washing and dry cleaning of coal varies somewhat among different Illinois coal operators, the resultant dust and sludge is essentially a minus 10-mesh product, usually containing more than 25 percent minus 100-mesh fraction; this fraction has about the same ash content as the 10 × 100-mesh fraction.

It is characteristic of oil flotation that it possesses the ability to clean the minus 100-mesh equally as well as the 10 × 100-mesh fraction whereas none of the other three methods of cleaning coal possesses the ability to clean minus 100-mesh coal on a commercial scale.

Dewatering of Coal Fines

Under present commercial conditions, it appears more feasible to clean coal sludge than to clean deduster dust by oil flotation. In the first place, the Illinois sludges normally contain a much higher ash content than the deduster dusts. Ash content in Illinois deduster dust normally ranges from 10 to 18 percent, whereas in Illinois sludges it ranges from 15 to 35 percent. In the second place, since sludges are wet when formed and therefore must be dried to be used, no additional operations are necessitated by oil flotation to make them usable; whereas deduster dust, which is already dry, must be sludged, cleaned, and then redried.

ACKNOWLEDGMENTS

The samples were collected, prior to 1940, by L. C. McCabe, Geologist, C. C. Boley, Associate Mining Engineer, B. C. Parks, Assistant Geologist, and A. E. Spotti, Assistant Geologist, all of the Coal Division of the Survey. The flotation tests were made by Miss Ruth Boyd, Assistant, and P. E. Elarde, Assistant Physicist, both of the Physics Division of the Survey.

OIL FLOTATION

Oil flotation may be defined, in the broad sense, as any process in which oil is used as the means of separating one material from another.

Various Types of Oil Flotation

In an overall classification, oil flotation may be divided into the nonfroth and the froth types. The nonfroth type includes skin flotation, bulk flotation, and agglomeration flotation, and the froth type includes vacuum flotation, pneumatic flotation, and mechanical agitation flotation.

Skin flotation is based on surface tension, the underlying principle being illustrated by a fine steel needle floating on the surface of water. This type of flotation was developed by Bradford[1] and others.

Bulk flotation is based on the buoyancy of oil in water, the oil lifting the load of attached sulfide or other separable material. This type of flotation was developed by Elmore.[2]

Agglomeration flotation is based on the principle that when ore is finely ground the mineral matter may be agglomerated with the oil, forming a pasty agglomerate which sinks to the bottom while most of the other material remains suspended in the water. This type of flotation was developed by Trent.[3]

The skin flotation process requires little or no added flotation oil, but the bulk and agglomeration processes require a very large amount of oil. The skin and bulk flotation processes are of no commercial importance and the agglomeration process has very limited application.

Vacuum flotation is based on the behavior of a mixture of ore and a small amount of oil mixed with water when the pulp is placed under vacuum, which releases the absorbed air, thereby forming bubbles which buoy the attached mineral to the surface in the form of froth. This type of flotation also was developed by Elmore.[4]

Pneumatic flotation is based on passing air upward through the flotation pulp to form a froth. This process was developed by Callow;[5] although, unknown to Callow, the same idea had been covered by Hoover[6] in a British patent.

Mechanical agitation flotation is based on mixing air into the flotation pulp by means of a mechanical stirrer. The equipment to carry out this process is of two general types. In one type, the agitator is on vertical shaft, thereby necessitating individual agitation units for each cell in the flotation machine. This type was developed by Hoover[7] and others. In the

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[1] Bradford, H., Method of saving floating materials in ore separation: U. S. Patent No. 345,941, July 20, 1886.

[2] Elmore, F. E., Process of separating metallic from rocky constituents in ore: U. S. Patent No. 676,679, June 18, 1901.

[3] Trent, W. E., Collecting minerals suspended in water: U. S. Patent No. 1,421,862, July 4, 1922.

[4] Elmore, F. E., Vacuum system of flotation separation of coal, ores, etc.: U. S. Patent No. 1,706,281, March 19, 1929.

[5] Callow, J. M., Ore flotation machine: U. S. Patent No. 1,182,748, May 9, 1916.

[6] Hoover, T. J., Apparatus for flotation process: British Patent No. 10,929, May 3, 1910.

[7] Hoover, T. J., Apparatus for concentrating ores: U. S. Patent No. 953,746, Apr. 5, 1910.

other type, the agitators are attached to a common horizontal shaft, thereby permitting a common agitator shaft for a multiple cell machine. This type was developed by Piersol[8] and others.

At present, only the mechanical agitation and the pneumatic types of flotation machine are used extensively. The former type usually is preferred because it results in a better mixing of the pulp, although the latter type may produce a clean secondary concentrate when used to reclean the primary concentrate obtained by the agitation type of machine.

PRINCIPLE OF OIL FLOTATION

The phenomenon of oil flotation is based on the principle that the surface of certain materials possesses a preferential attraction for oil, whereas that of certain other materials possesses a preferential attraction for water. Metals, sulfides, coal and various other materials tend to be wet by oil; oxides, carbonates, silicates and various similar materials tend to be wet by water.

Mineral matter, which is the ash-forming constituent in coal, is composed principally of clay (kaolinite and other clay materials), calcite (calcium carbonate) and pyrite (iron sulfide). Clay, a complex aluminum silicate, and calcite are wet by water. However the pyrite tends to be wet by oil, unless a depressing agent is used which changes the surface of the pyrite so that it is wet by water rather than by oil.

In the concentration of metallic ores, it is conventional practice to refer to the raw material as "heads," the cleaned product as "concentrates," and the waste product as "tailings." In oil flotation, the mixture of pulverized ore and water is known as flotation "pulp." The same terminology is used herein in describing the oil flotation of coal.

Because the various banded ingredients of coal (clarain, vitrain, durain and fusain) are preferentially wet by oil, the flotation concentrates consist of these ingredients. And because clay and calcite are preferentially wet by water, they form the flotation tailings. Normally the pyrite would be floated off as part of the concentrate, but the use of ferric or ferrous sulphate depresses the pyrite causing it to go down with the tailings. Also fusain may be depressed by the use of starch or glue, if so desired.

Normally it is necessary to use at least two types of flotation oils. The first is a collector and the second is a frother. Kerosene, creosote, and various organic reagents form good collectors. Pine oils, alcohols and various volatile reagents form good frothers.

The buoyancy of air bubbles, rising through pulp, lifts the particles of coal, the oiled surface of the coal adhering to the oily film surface of the bubble. The weight of a particle of coal more than about 10-mesh in size is enough to puncture the bubble, thus limiting the upper size of coal to about 10-mesh for flotation cleaning.

EXTENT OF USE OF OIL FLOTATION

Several hundred million tons of metallic ore are concentrated annually by oil flotation. As yet, the tonnage of coal fines cleaned by oil flotation is relatively small, being somewhat more than a million tons per year. Exact recent tonnages are not available, however, Berthelot[9] records a total European tonnage of 915,000 metric tons for 1926, divided as follows: England, 275,000; Germany, 260,000; Spain, 200,000; Holland, 100,000; and Belgium 80,000. In England alone the tonnage[10] increased to 930,000 in 1927, but suffered a severe reduction later.

In the United States, the Pittsburgh Coal Company uses oil flotation at their Champion Mine in the Pittsburgh District. This process is also being used to clean coal in the Alabama coal fields. And during the war, a considerable quantity of anthracite culm was cleaned by oil flotation.

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[8] Piersol, R. J., Oil flotation machine: U. S. Patent No. 1,335,600, Mar. 30, 1920.

[9] Berthelot, C., Washing of coal by flotation: Chem. et Ind., Special Number, May 1927, pp. 334-353.

[10] Annual reports of the Secretary of Mines, Great Britain.

Cost of Cleaning by Oil Flotation

The cost of flotation varies with the size of plant, the efficiency of operation, and the method of dewatering the cleaned coal. A reasonable estimate of cost is about 50 cents per ton.

For a 25-ton per hour flotation plant at Cumberland, England, Scoular and Dunglinson[11] show a capital investment cost of $27,000 and an operating cost of 10.74 cents per ton.

Guider[12] shows the cost of a 25-ton per hour flotation plant operated by the Clifton and Kersley Coal Company in England to be 41.88 cents per ton, excluding patent royalty, but including interest and depreciation.

Berthelot[9] gives the total cost of 58 cents per ton for treating fine coal in flotation plants located at Charleroi and Bonnier in Belgium.

As this is a preliminary report, the review of the theory and practice of oil flotation purposely is brief. Excellent detail is found in early reference books by Hoover[13] and by Rickard[14] and recent books by Mayer and Schranz,[15] by Wark,[16] and by Rabone.[17] Also the article by Yancey and Taylor[18] gives an excellent summary on the flotation of coal prior to 1933.

EQUIPMENT AND METHOD

The Piersol single-cell laboratory scale flotation machine which was used in this investigation is illustrated in figure 47. The agitator is driven at a speed of 440 revolutions per minute by a ¼-horsepower electric motor. In horizontal cross-section the agitation box is 6 inches square. The capacity of the flotation cell is 1 kilogram of coal diluted with 6 liters of water.

Samples of Coal Tested

Unless otherwise specified, the samples tested consisted of the minus 10-mesh screened fractions of carbon size coal. This size fraction was selected both because this size represents approximately the top size which is feasible to float and also because it corresponds closely to the size of deduster dust and coal sludge. It may be stated, incidentally, that if it is desirable to produce a somewhat coarser sludge (e.g. in washing stoker coal from the Harrisburg district), then sizes coarser than 10-mesh should be cleaned by tabling, by centrifuging, or by other means prior to flotation.

As the samples were collected prior to 1940 and the tests were completed prior to December 1940, the samples do not necessarily represent the present product of preparation practice, therefore it is deemed permissible to identify the samples by mine source rather than simply by district, as is the usual practice in Survey publication.

Procedure of Testing

The kilogram sample of coal was mixed with water and placed in the flotation cell. The various flotation oil mixtures were added to the flotation pulp during agitation. The concentrates were collected, dewatered by vacuum filter, and dried. At the end of the test, the tailings were removed from the flotation cell, dewatered by vacuum filter, and dried. Ash content was determined for heads, concentrates, and tailings, and results are reported herein on a "moisture-free basis."

Yield and Recovery

By definition, the yield is the weight of the concentrates divided by the weight of the heads; and the recovery is the coal (mineral-matter-free or ash-free) in the concentrates divided by the coal in the

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[11] Scoular, J. G., and Dunglinson, B., The washing of fine coal by the froth flotation and concentrating table processes at Oughterside Colliery, Cumberland: Trans. Inst. Min. Eng., vol. 67, pp. 374-379, 1924.

[12] Guider, W., Froth flotation applied to a Baum Washer: Jour. Soc. Chem. Ind. Trans., vol. 46, pp. 238-242, 1927.

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[17] Rabone, Philip, Flotation plant practice: Mining Publications, Ltd., Salesbury House, London, 1939.

[18] Yancey, H. F., and Taylor, J. A., Flotation processes for cleaning fine coal: U. S. Bureau of Mines, Inf. Cir. 6714, May 1933.

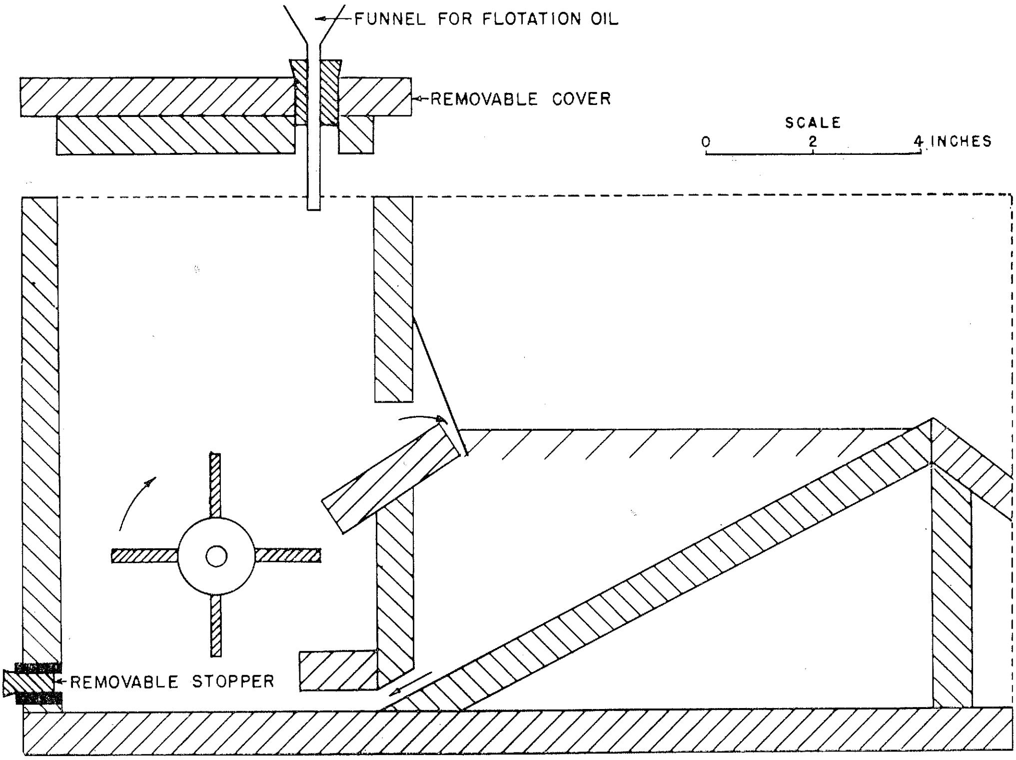

FIG. 46.—Piersol flotation machine.

heads. In practical coal preparation, the non-coal mineral component is generally referred to as ash, although strictly speaking it is mineral matter. The U. S. Bureau of Mines uses a mineral matter-ash ratio of 1.1 ash + 0.1 sulfur, which is reasonably accurate. Thus on an ash-free basis, the percentage of coal in a coal product is 100-A, where A is the percent ash; and on a mineral matter-free basis the percentage of coal in a coal product is 100-(1.1A + 0.1S), where S is the percent sulfur.

Algebraically the concentration ratio may be developed as follows: Let X be the yield and H, C, and T be the percentage of coal in the heads, concentrates, and tailings, respectively. Then

$$CX + T(1 - X) = H \qquad (1)$$

From this, the yield ratio is

$$X = \frac{H - T}{C - T} \qquad (2)$$

Let R be the recovery. Then

$$R = \frac{C}{H} X \qquad (3)$$

from this, the recovery is

$$R = \frac{C}{H} \quad \frac{(H - T)}{(C - T)} \qquad (4)$$

From an ash determination for the heads, concentrates and tailings, it is possible to obtain the percentage recovery of the coal from equation 4 without weighing the concentrates or tailings. Then from the weight of the heads it is possible to obtain the weights of the concentrates and that of the tailings from equation 2.

TABLE 47.—LIST OF FLOTATION OILS USED SHOWING IDENTIFICATION SYMBOL, NAME OF MANUFACTURER, TYPE OF OIL, AND SPECIFIC GRAVITY

Flotation Oil	Company	Symbol	Type	Gravity
Frother 60	American Cyanamid Co.	A	Frother	0.838
Frother B-48	" " "	B	"	0.853
G.N.S. No. 5 Pine Oil	" " "	C	"	0.930
Tarol No. 1	Hercules Powder Co.	D	"	0.985
Yarmor F	" " "	E	"	0.935
Risor Pine Oil	" " "	F	"	0.960
Pure Pine Oil	Northwestern Pine Tar Co.	G	"	0.935
Oil of Pine Tar	" " " "	H	"	1.028
H.T.P. Alcohol B-23	E. I. DuPont de Nemours & Co.	I	"	0.840
Cresylic Acid No. 1	The Barret Co.	J	"	1.016
Flotation Oil No. 4	" " "	K	Modifier	1.024
Kerosene		L	Collector	0.810

EXPERIMENTAL RESULTS

Effect of Various Oils

Various combinations of 12 different oils were used in the tests. Table 47 lists these oils, together with name of companies supplying the oils, and the specific gravity of the oils. All these oils belong to the frother type with the exception of kerosene, which is a collector, and Flotation Oil No. 4 which is a modifier. The purpose of a modifier is to stabilize the bubbles so that they will not burst before the froth is removed.

These oils were used singly and in various combinations in flotation tests on 28 identical 1000-gram samples of Bell and Zoller minus 10-mesh deduster dust, containing 17.8 percent ash. Table 48 shows the results, including the ratio of mixture of oil, the weight of oil per ton of coal, the percentages of ash, in the concentrates and the tailings, the concentration ratio, and the recovery of coal values.

Effect of Various Screen Sizes

A study was made of the effect of various screen sizes on the ash content of the concentrates and the tailings. Two identical 1000-gram samples of Peabody Coal Company minus 10-mesh deduster dust from Mine 14, containing 17.1 percent ash, were used. From one sample, ash analyses of the heads were made for various screen sizes. The other sample was floated, using a flotation oil mixture consisting of 2 parts kerosene and 1 part oil of pine tar. The consumption of oil mixture was at the rate of 1.4 pounds per ton of coal. Ash analyses of both the concentrates and tailings were made for various screen sizes. Table 49 shows the results, including the weights, percentage of ash, concentration ratio, and recovery of various screen sizes for the heads, concentrates, and tailings.

Flotation of Various Illinois Coal Fines

Flotation tests were made on samples of minus-10 mesh coal from 30 different mines, using a flotation oil mixture consisting of 2 parts kerosene and 1 part oil of pine tar. The consumption of oil mixture was at the rate of 1.4 pounds per ton of coal. Table 50 shows the names of the coal companies, the location of the mines by county, and the ash analyses of the heads and the concentrates.

DISCUSSION AND CONCLUSIONS

Interpretation of Results

Inspection of the data shown in table 48 indicates that equally good results can be obtained by numerous combinations of flotation oils. Unless a frothing oil happens to possess an additional collecting characteristic, it is desirable to use a mixture of a frothing and a collecting oil. It is noted

TABLE 48.—EFFECT OF 28 FLOTATION OILS ON MINUS 10-MESH BELL AND ZOLLER COAL COMPANY DEDUSTER DUST

(1000-gram sample; 17.8 percent ash in heads; flotation oil designated by symbol; and ratio of mixtures by parts)

Flotation oil ratio	Pounds per ton	Percent Ash		Yield	Recovery
		Concentrates	Tailings		
A	0.9	9.5	76.5	87.7	96.5
B	1.7	9.3	67.6	85.5	94.3
C	1.9	9.3	70.4	86.1	95.0
D	1.1	8.4	67.0	84.0	93.6
E	0.8	8.8	64.9	83.9	93.1
F	1.4	9.1	63.0	83.8	92.7
G	1.2	10.0	77.8	88.5	96.9
I	1.5	8.4	37.3	67.5	75.2
1A:1C	1.0	9.9	77.1	88.2	96.7
1A:1G	1.0	9.7	77.2	88.0	96.7
1A:1J	1.0	10.5	76.0	88.8	96.7
1A:1L	1.1	10.3	77.5	88.8	96.9
1G:1L	1.3	9.8	76.1	87.9	96.5
1A:2L	0.9	9.2	75.7	87.1	96.2
1B:2L	0.7	9.8	75.4	87.0	95.5
1C:2L	1.1	9.8	76.8	88.0	96.6
1D:2L	1.7	8.6	70.7	85.3	94.8
1E:2L	0.8	9.4	75.6	87.3	96.2
1F:2L	0.9	9.3	75.7	87.2	96.2
1G:2L	1.4	8.3	73.1	85.3	95.2
1H:2L	1.4	8.7	73.0	85.9	95.4
1I:2L	1.0	9.5	74.6	87.3	96.1
1J:2K	1.9	8.7	72.0	85.6	95.1
1A:3L	0.9	9.2	76.1	87.2	96.3
1A:1C:1L	0.8	9.7	77.3	88.0	96.7
1A:1G:1L	0.8	9.7	77.7	88.1	96.8
1A:1J:1K	1.1	8.6	74.4	86.0	95.6
1A:1C:2L	0.8	9.3	75.7	87.2	96.2

TABLE 49.—EFFECT OF SCREEN SIZES ON FLOTATION CLEANABILITY OF PEABODY COAL COMPANY MINE 14 MINUS 10-MESH DEDUSTER DUST

(1.4 pounds per ton coal—2 parts kerosene: 1 part oil of pine tar)

Screen fraction (mesh)	Percent weight			Percent ash			Yield	Recovery
	Heads	Conc.	Tail	Heads	Conc.	Tail		
10x20	4.28	2.67	1.25	16.3	7.4	65.9	84.8	93.8
20x28	12.98	10.54	13.80	14.2	7.4	75.7	90.0	97.2
28x35	16.43	19.10	20.60	17.6	8.5	75.2	86.4	95.9
35x48	15.11	15.40	17.50	19.0	9.9	76.7	86.4	96.1
48x65	12.39	12.91	12.90	18.6	10.8	78.2	88.4	96.9
65x100	9.73	8.40	10.22	18.9	10.8	79.1	88.1	96.9
−100	29.08	30.98	23.73	16.9	9.5	81.0	89.7	97.6

TABLE 50.—FLOTATION CLEANABILITY OF MINUS 10-MESH FRACTION OF CARBON SIZE OF VARIOUS ILLINOIS COALS
(1.4 pounds per ton coal—2 parts kerosene: 1 part oil of pine tar)

Company	County	Percent ash	
		Heads	Conc.
Beckmeyer Coal Company	Clinton	15.6	6.1
Citizens Coal Company	"	17.3	5.9
Penwell Coal Company	Christian	17.1	7.7
Bell & Zoller Coal and Mining Company	Franklin	13.1	5.9
Old Ben Coal Corp. Mine No. 8	"	13.9	5.9
Burnwell Coal Company	Madison	19.9	7.2
East Side Coal Company Mine No. 6	"	19.8	5.8
Lumaghi Coal Company Mine No. 2	"	13.8	6.9
Madison County Coal and Mining Company	"	19.6	6.9
Mt. Olive & Staunton Coal Company	"	19.1	7.2
Mt. Olive & Staunton Coal Company Mine No. 2	"	17.0	5.6
Sunset Hill Coal Company	"	21.8	7.3
Marion County Coal Company	Marion	17.3	6.1
Illinois-Missouri Coal Company	Randolph	24.4	10.2
Ace High Coal Company	St Clair	29.7	9.0
East Side Coal Company	"	20.7	6.3
Golden Rule Coal Company	"	28.9	5.8
Gundlach Coal Company	"	20.5	9.0
Lenzburg Coal Company	"	27.9	7.6
Midway Coal Company	"	25.1	9.3
Mulberry Hill Coal Company	"	34.7	8.2
Pep Coal Company	"	29.7	9.8
Reinheimer Slope Mining	"	30.9	8.6
Summit Coal and Mining Company	"	24.7	7.9
Turkey Hill Coal Company	"	22.9	6.3
Wasson Coal Company	Saline	14.1	4.9
Peabody Coal Company Mine No. 24	Vermilion	10.5	6.1
Centralia Coal Company	Washington	16.6	6.1
Consolidated Coal Company	Williamson	9.7	5.6
Oak Grove Coal Company	"	25.9	7.2
Av.		20.7	7.1

that both frother 60 and pure pine oil act as collectors as well as frothers. The appearance of the resultant froth indicates the proper mixture of flotation oils. A mixture, lean in collecting oil, produces a live froth which carries little or no coal; a mixture, lean in frothing oil, produces a dead froth due to overload of coal.

Although there is but slight preference of choice among several of the oil combinations, the mixture of 2 parts kerosene and 1 part of oil of pine tar was selected for subsequent tests used at the rate of 1.4 pounds per ton of coal. This mixture was chosen because the components are inexpensive and easily obtained.

The higher ash content of certain screen sizes of the heads, as shown in table49, probably denotes a relatively higher nonseparable ash content in such sizes. This is indicated because the relative effect is evident in the ash content of the corresponding screen size of the concentrates.

Also table 49 shows that the ash content of the tailings is somewhat low for the 10 × 20-mesh screen fraction. A visual examination of this size of tailings indicates that it contains about 10 percent of coal particles about 10-mesh in size, which shows that this is about the top size of coal which is feasible to clean by oil flotation.

The relative constancy of the ash content of the screen sizes less than 20-mesh for the tailings is indicated by the fact that a 1.6 specific gravity float-and-sink test shows from 3 to 4 percent float, indicating not more than that amount of coal in the tailings. Likewise microscopic examination of the 1.6 float fraction of tailings from various other coals analyzing about 75 percent ash, indicated that such tailings also contain less than 5 percent coal.

Because of the proved absence of more than this amount of coal in tailings from properly floated coal, it was not deemed worthwhile to make an ash analysis of the tailings from the various coals shown in table 50.

To clarify this point further: The ash content in coal is actually the combustion product resulting from the burning (oxidation) of the mineral matter. The loss of weight of the mineral matter during combustion depends on the proportion of its relative constituents, calcite, kaolinite and pyrite. The value of this weight loss ranges usually from 10 to 15 percent; this being the reason for the assignment of the equivalency of 1.1 ash + 0.1 sulfur to mineral matter.

As there appears to be no easy direct chemical means to determine the mineral matter content of tailings, probably the most convenient method is to weigh the 1.6 float fraction of the tailings and to consider this as the percent coal value and the remainder as mineral matter.

Also it may be pointed out, that since the actual coal values in a 75 percent ash tailings is about 5 percent instead of 25 percent it follows that the actual recovery of coal values averages over 98 percent rather than about 95 percent. This point is merely of academic interest, because commercially a 95 percent recovery is more than satisfactory.

Even quite high-ash coal fines were cleaned to low ash; heads containing from 25 to 35 percent ash were cleaned to less than 10 percent ash, as shown by table 50. Also the average cleanability was excellent; the 30 samples tested averaged 20.7 percent ash for the heads and 7.1 percent ash for the concentrates. The ash content of the concentrates was slightly higher for increasing ash content of the heads. This trend is shown in table 50.

The results herein reported agree with those reported by Olivieri[19] who studied the oil flotation properties of deduster dust produced at the Orient Mine of the Chicago, Wilmington and Franklin Coal Company, the work being a senior thesis, the investigation under the supervision of Harold L. Walker, Head of Department of Mining and Metallurgical Engineering, University of Illinois.

FUTURE INVESTIGATIONS

A pilot plant investigation of the cleanability of Illinois coal fines by oil flotation is the next logical step after the completion of the laboratory scale study. Such an investigation is now in progress. The pilot scale Piersol flotation machine consists of 8 cells, the agitation boxes being 1 foot square; each cell has 8 times the capacity and the 8-cell unit 64 times the capacity of the laboratory machine. The pilot machine may either be operated as a batch unit, with a batch capacity of 125 pounds of coal, or a continuous unit, with a capacity of several tons per hour.

In the pilot scale tests, special attention will be given the effect of various oils on preserving the fusain and discarding the pyrite.

The capacity of the pilot flotation machine also furnishes sufficient samples for pilot scale briquetting and subsequent large-scale smoke tests.

Also pilot plant operation is convenient for a differential flotation study of the various banded ingredients of coal; such ingredients possess well known desirable utilization characteristics.

During the war, the practice was begun at several Illinois mines of reclaiming sludge by steam shovel operation from ponds, the sludge being dried by the atmosphere. This economical method of drying coal flotation concentrates appears feasible.

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[19] Olivieri, John, Froth flotation of fine coal: Thesis for B.S. in Met. Eng., Univ. of Ill., 1940.

SUMMARY

The results of this preliminary investigation may be summarized as follows:

1. The combination of various collecting oils and frothing oils may be used in numerous combinations.
2. The amount of flotation oil required is less than 2 pounds per ton of coal.
3. High-ash coals may be cleaned to low-ash content, the average reduction being from 20.7 percent ash heads to 7.1 percent ash concentrates.
4. The discard is very low in coal values, float-and-sink tests showing less than 5 percent coal values in the tailings.
5. Approximately 10-mesh is the upper size of coal feasible for cleaning by oil flotation.
6. Flotation differs from other methods of cleaning coal because there is no lower size limit.
7. Experience in foreign countries indicates that the operating cost of cleaning coal by oil flotation is about 25 cents per ton, and the total cost including capital cost and depreciation is about 50 cents per ton.

ARTICLE 7—RELATIVE IMPORTANCE OF VOLATILE MATTER AND FIXED CARBON IN HIGH VOLATILE COALS AND BRIQUETS

INTRODUCTION

Although Illinois coal as burned in common hand-fired furnaces is smoky, it can be processed without much difficulty to produce a smokeless fuel. The simplest method, but one which entails much expense and considerable loss, is carbonization. It has also been found that other kinds of treatment will produce an essentially smokeless fuel. For example, if the amount of fusain is greatly increased and the resulting coal is pressed into the form of a briquet, even if a smokeless binder is used, a fuel is formed which burns without smoke in hand-fired stoves and furnaces. Such briquets are at present being produced from southern Illinois deduster dust, which is a "high fusain" product, at the annual rate of about 300,000 tons.

It has also been found that relatively low heating of Illinois coals, enough to bring about mild volatilization with a loss of about one-third of the volatile matter, will also produce a smokeless fuel, which at least under laboratory conditions can be pressed into a briquet without use of an added binder. Not greatly different is the fuel which under commercial scale conditions has recently been produced in the Survey laboratories. This consists of briquets produced from raw coal at room temperature and subsequently subjected to partial volatilization by heat treatment.

As the choice of method of processing coal lies between fairly complete carbonization in the formation of coke and partial carbonization and briquetting, interest attaches to the question of the value of the volatile matter present in the partially volatilized briquets. If the volatile matter is relatively small, or if the volatile matter is of small importance as a source of heat, there is little point in recommending a process that retains the volatile matter as preferable, for this reason, to one that does not. Such smokeless briquets made in the laboratory from prevolatilized coal were available in sufficient quantity to use them in tests, so it was possible to determine the relative heat value of the volatile matter and fixed carbon in such fuel. By study also of the heat value of volatile matter and fixed carbon of raw Illinois coal, burned smokelessly in a fully instrumentized stoker-fed furnace, more was learned of the relative heat value of the volatile matter and fixed carbon in Illinois coals.

Furthermore if it can be shown that volatile matter is an important source of heat when the coal is fully consumed, a fuel which permits the combustion of a large portion of the volatile matter under normal conditions of hand firing in stoves and furnaces is more desirable than a raw coal which burns smokelessly (when hand-fired) only if it is most skillfully handled.

These investigations of the heat value of volatile matter and fixed carbon sought to determine these relationships, both in briquets and in raw coal, thereby determining the extent of loss in heat resulting from prevolatilization or, in the case of the briquets made at room temperature, from subsequent volatilization, and the value of the volatile matter remaining in the briquets.

In connection with these investigations of the heat value of volatile matter and fixed carbon, considerable thought was given to the nature and source of the heat resources in bituminous coal. These investigations consisted first of an inquiry of the relation of the elementary composition of coal to the heat value, and second an examination of the nature of the combustion process in the light of modern concepts. Out of this inquiry there was developed a new formula for calculating the heat value of coal, one based upon the elementary analysis and one based upon the oxygen content of coal and a heat value for pure CH coal material. As these investigations do not contribute to the main problem of briquet formation, the results are discussed later in this article (pp. 126–145).

GROWTH OF SMOKELESS COMBUSTION

In 1944 more than 35 percent of the coal mined in Illinois was burned smokelessly, mainly because most of this coal was consumed in stoker-fed equipment, but partly because minor amounts were processed into pulverized fuel, made into smokeless briquets, or made into coke. In comparison, in 1930, less than 5 percent of the coal mined in Illinois was burned smokelessly. This sharp increase in the amount of Illinois coal burned smokelessly was primarily because of the great increase in the use of domestic stokers, the benefits of which were partly due to mechanical operation and partly to improved combustion as compared with hand-fired apparatus. The demonstration that midwestern coal was a satisfactory fuel for domestic heating apparatus, even in cities maintaining strict smoke control, has done much to enable this coal to maintain a strong market position in the face of the competition of the more expensive but less smoky eastern fuels.

These improvements in combustion conditions have permitted the adoption and the enforcement of rigid smoke ordinances in the metropolitan areas of St. Louis, Chicago, and in other urban communities in the market area of Illinois coal, which action has in turn still further increased the use of domestic and industrial stokers.

IMPORTANCE OF VOLATILE MATTER IN ILLINOIS COAL

The volatile constituents of Illinois coals or derived fuels, pound for pound, have heat value about equal to or even slightly higher than that of the associated fixed carbon. It is therefore important to eliminate the losses resulting from careless methods of combustion, which permit the loss of the heat represented by the volatile matter. The greater the amount of volatile matter present in the fuel, the greater the need for efficient combustion.

The amount of volatile matter in Illinois coals in a moisture-and-mineral-matter-free condition (unit coal[1]) averages about 45.5 percent, the remaining 54.5 percent being fixed carbon. When high volatile coal such as this is burned so as to produce smoke and soot, as much as 45.5 percent of the heat value of the coal (in the case of some coals) may be lost up the chimney. Complete combustion without smoke, on the other hand, will increase the value of the same coal with respect to the heat made available by nearly 85 percent.

The importance of volatile matter in the combustion of our midwestern coals needs to be constantly stressed. The merits and not the deficiencies of the high volatile content, if it is properly handled, need to be emphasized. In order to use efficiently this 45.5 percent of the volatile matter, current efforts toward improvement should be encouraged: (a) The public should be educated toward a better realization of the unnecessary waste involved in smoky combustion; (b) use of domestic stokers should be extended; (c) special types of hand-fired stoves and furnaces adapted for smokeless combustion of high volatile coals should be developed, manufactured and marketed; (d) the possibilities of economically producing smokeless domestic coke should be extensively explored; and (e) fine coals should be prepared by the briquetting method, thus utilizing fuel otherwise very difficult to burn smokelessly or even to burn at all in domestic appliances, and producing smokeless fuel with only small loss of volatile matter during processing.

As the present interest is in the development of the briquetting method of conserving large quantities of fine coal for efficient combustion in domestic hand-fired heating appliances, it is appropriate to point out that at the present time approximately 10 million tons of coal are used in such hand-fired apparatus. Scarcely any of these appliances are so constructed that they will burn this high volatile coal smokelessly under normal methods of firing, and it is practically impossible to burn coal finer than that which is included in the prepared stoker fuel. The amount of such fine coal, including the clean coal smaller than stoker size, the coal represented by the deduster dust, and the coal not removed from the sludge, annually amounts to more than 2,000,000 tons in Illinois. Practically all

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[1] Coal composition throughout this article is in terms of unit coal (moisture-and mineral matter-free) to avoid the confusion that results when extraneous moisture and mineral matter (including sulfur in its various forms) are included in analyses.

this material is a potential domestic smokeless fuel when made available by briquetting practice which takes advantage either of the use of fusain to eliminate the smoke or of some partial devolatilization methods explained in Article 5 of this report.

The importance of the calorific value of the volatile matter in coal and briquets is substantiated by the results of a study of the effect of variation in volatile matter on stoker efficiency, and also by a study of the relative calorific value of volatile matter and fixed carbon in a series of representative Illinois coals. The study is based on analyses representing county averages of mine averages of face sample analyses, assuming that the calorific value for fixed carbon is uniform. The same method is used to examine the relative value of volatile matter and fixed carbon in partially prevolatilized cylindrical laboratory briquets.

RELATIVE CALORIFIC VALUE OF VOLATILE MATTER AND FIXED CARBON

EFFECT OF VARIATIONS IN VOLATILE MATTER CONTENT ON STOKER EFFICIENCY

Experimental verification that the thermal efficiency of coal used in systematic combustion tests in a thoroughly instrumentized stoker-boiler combination is unaffected by variations in the percentage of volatile matter in the coal is conclusive proof that the thermal efficiency of the volatile matter and fixed carbon are at least about the same.

Experimental data by Helfinstine and Boley[2] have been published for a series of combustion tests on 43 representative Illinois coals which contain various percentages of volatile matter. The results (table 51, fig. 47) reveal that the thermal efficiency of stoker coals is unaffected by variations in their percent volatile matter.

Further exploration of the relative heat value of volatile matter and fixed carbon

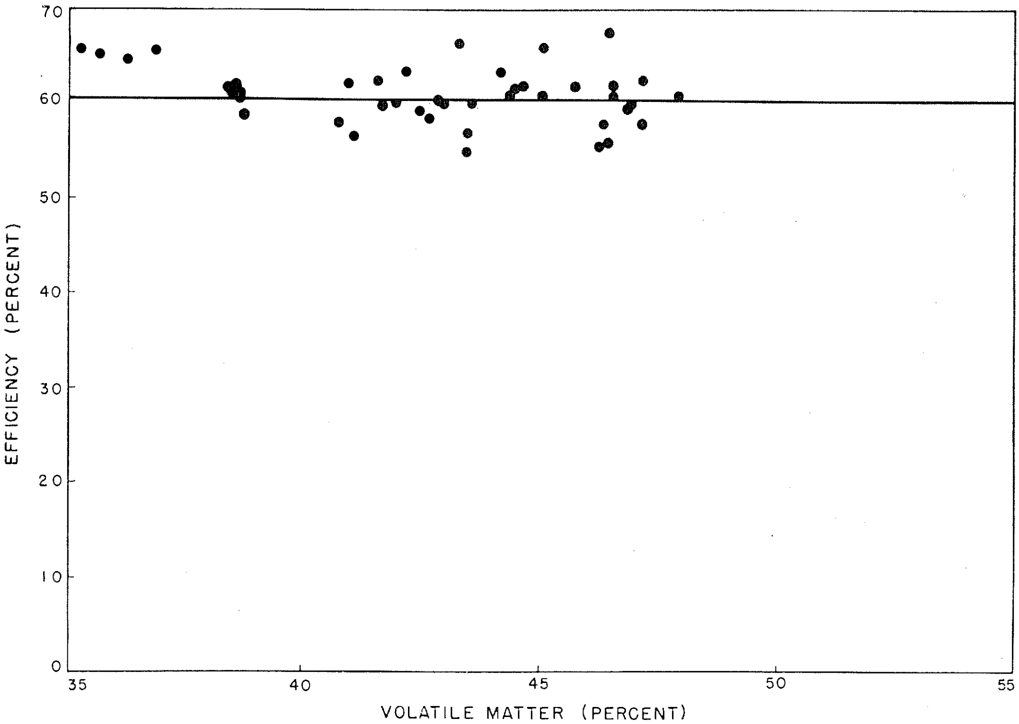

FIG. 47.—Influence of percent volatile matter on efficiency of Illinois stoker coals. (Data from table 51)

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[2] Helfinstine, R. J., and Boley, C. C., Correlation of stoker combustion with laboratory tests and types of fuels. Part II, Results of tests on coals from representative Illinois Mining districts, including a discussion of the effects of preparation: Illinois Geol. Survey Rept. Inv. 120, 1946.

Table 51.—Influence of Percent Volatile Matter on Thermal Efficiency of 43 Illinois Stoker Coals
(Unit coal basis)
(Figure 47)

Coal			Proximate analyses		Calorific value		Thermal Efficiency
Sample No.	County	Seam	Volatile matter (percent)	Fixed carbon (percent)	Input (B.t.u.)	Output (B.t.u.)	
1A	Franklin......	6	35.2	64.8	14580	9590	65.8
2B	LaSalle........	2	41.0	59.0	14760	8390	56.9
2C	"	"	46.9	53.1	14550	8790	60.4
2E	"	"	41.6	58.4	14340	8610	60.0
3A	Vermilion.....	6	44.1	55.9	14560	9280	63.7
3B	"	"	43.2	56.8	14390	9600	66.7
3C	"	"	42.1	57.9	14330	9130	63.7
5A	Macoupin......	"	46.4	53.6	14530	8180	56.3
5B	"	"	46.5	53.5	14210	8710	61.3
5C	"	"	40.9	59.1	14160	8850	62.5
6A	Peoria	5	40.7	59.3	14800	8630	58.3
6B	"	"	41.9	58.1	14530	8760	60.3
6C	"	"	42.8	57.2	14370	8690	60.5
7A	Gallatin.......		38.7	61.3	15170	8940	59.0
7B	"		39.3	60.7	15300	9470	62.0
7C	"		38.6	61.4	15270	9270	60.7
8A	Wabash.......		47.9	52.1	14550	8930	61.4
8B	"		46.5	53.5	14340	8960	62.5
8C	"		46.8	53.2	14360	8620	60.0
9A	St. Clair.......	6	46.4	53.6	14660	8920	60.8
9B	"	"	47.1	52.9	14520	9150	63.0
9C	"	"	43.5	56.5	14480	8750	60.4
10A	Saline.........	5	38.4	61.6	14890	9160	61.5
10B	"	"	38.5	61.5	14850	9240	62.2
10C	"	"	38.6	61.4	14790	9080	61.4
11A	Vermilion.....	7	47.1	52.9	14840	8660	58.4
11B	"	"	46.2	53.8	14870	8300	55.8
11C	"	"	46.3	53.7	14850	8670	58.4
12A	Sangamon.....	5	43.4	56.6	14670	8430	57.4
12B	"	"	42.9	57.1	14540	8760	60.2
12C	"	"	42.4	57.6	14540	8650	59.5
13A	Randolph.....	6	42.6	57.4	14520	8540	58.8
13B	"	"	43.4	56.6	14400	7950	55.2
13C	"	"	41.5	58.5	14410	9020	62.6
14A	Christian......	"	44.3	55.7	14400	8830	61.3
14B	"	"	45.0	55.0	14360	8790	61.2
14C	"	"	44.6	55.4	14360	8950	62.3
15A	Williamson....	"	36.8	63.2	14690	9650	65.7
15B	"	"	35.6	64.4	14600	9530	65.3
15C	"	"	36.2	63.8	14610	9450	64.7
16A	Knox.........	1	45.7	54.3	14770	9200	62.3
16B	"	"	45.0	55.0	14650	9730	66.4
16C	"	"	44.4	55.6	14590	9060	62.0
Av.			42.7	57.3	14600	8930	61.1

is possible by using the calorific value for fixed carbon in the form of volatile-free and ash-free coke, as determined by Mott and Spooner,[3] which is approximately 14,400 B.t.u. per pound. It then follows that the proportionate heat value of the volatile matter is the total calorific value of the particular coal less the proportionate heat value of the fixed carbon. The heat value of the volatile matter per pound can then be determined by dividing the proportionate heat value of the volatile matter by the percent volatile matter.

In line with this procedure, the heat derived from the volatile matter was calculated for 43 samples of the coal used in the combustion tests noted above (table 52, fig. 48). The relations of the calorific value per pound of volatile matter and of fixed carbon at 14,400 B.t.u. per pound may be noted from the tabulated ratios (table 53). These show in general that the ratio $\frac{\text{B.t.u. volatile matter}}{\text{B.t.u. fixed carbon}}$ is slightly more than unity. This does not mean that the proportional calorific value of the volatile matter necessarily exceeds the proportional calorific value of the fixed carbon in any coal. It would only do in those coals in which the percent volatile matter is nearly 50 percent or more. This is not the usual relationship of these values in Illinois coals, being found only in those of relatively low rank.

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[3] Mott, R. A., and Spooner, C. E., The calorific value of carbon in coal: the Dulong relationship: Fuel, p. 226, Vol. 19, No. 10, 1940.

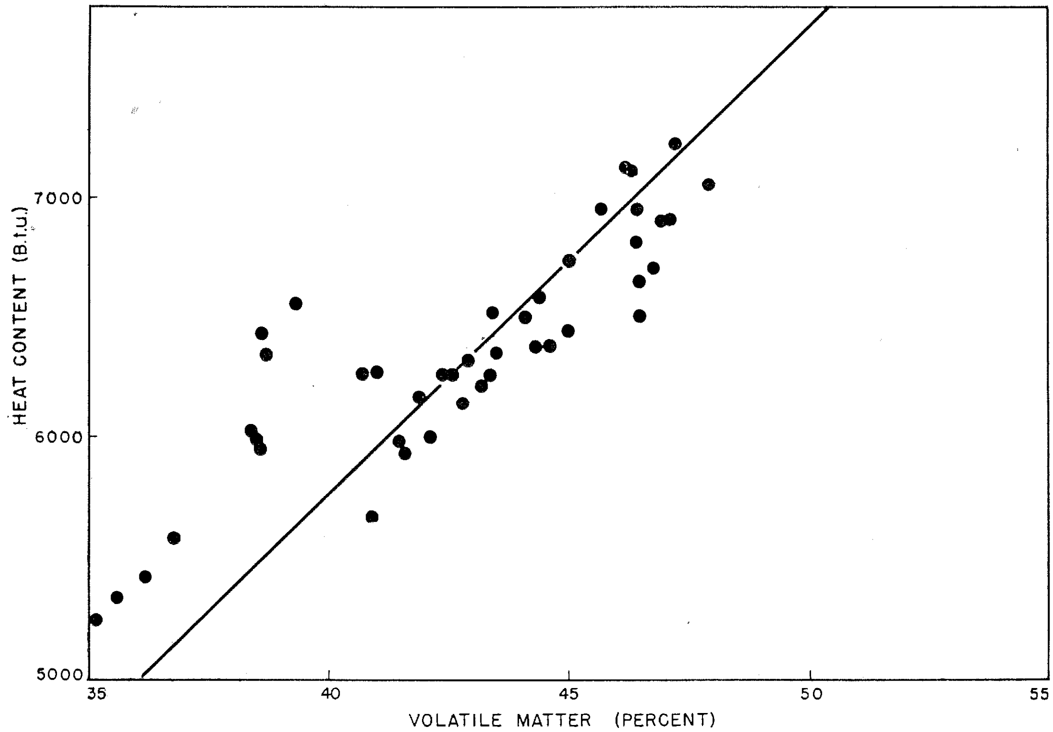

FIG. 48.—Influence of percent volatile matter on heat content of volatile matter in Illinois stoker coals. (Data from table 52)

TABLE 52.—HEAT CONTENT OF VOLATILE MATTER AND OF FIXED CARBON IN 43 ILLINOIS STOKER COALS
(Unit coal basis)
(Fixed carbon 14,400 B.t.u./lb.)
(Figure 48)

Coal sample No.	Proximate analyses		Calorific value (B.t.u.)	Heat content (B.t.u. per lb. of unit coal)	
	Fixed carbon (percent)	Volatile matter (percent)		Fixed carbon	Volatile matter
1A	64.8	35.2	14580	9330	5250
2B	59.0	41.0	14760	8500	6260
2C	53.1	46.9	14540	7650	6890
2E	58.4	41.6	14340	8410	5930
3A	55.9	44.1	14560	8050	6510
3B	56.8	43.2	14390	8180	6210
3C	57.9	42.1	14330	8340	5990
5A	53.6	46.4	14530	7720	6810
5B	53.5	46.5	14210	7700	6510
5C	59.1	40.9	14160	8510	5650
6A	59.3	40.7	14800	8540	6260
6B	58.1	41.9	14530	8370	6160
6C	57.2	42.8	14370	8240	6130
7A	61.3	38.7	15170	8830	6340
7B	60.7	39.3	15300	8740	6560
7C	61.4	38.6	15270	8840	6430
8A	52.1	47.9	14550	7500	7050
8B	53.5	46.5	14340	7700	6640
8C	53.2	46.8	14360	7660	6700
9A	53.6	46.4	14660	7720	6940
9B	52.9	47.1	14520	7620	6900
9C	56.5	43.5	14480	8140	6340
10A	61.6	38.4	14890	8870	6020
10B	61.5	38.5	14850	8860	5990
10C	61.4	38.6	14790	8840	5950
11A	52.9	47.1	14840	7620	7220
11B	53.8	46.2	14870	7750	7120
11C	53.7	46.3	14850	7730	7120
12A	56.6	43.4	14670	8150	6520
12B	57.1	42.9	14540	8220	6320
12C	57.6	42.4	14540	8290	6250
13A	57.4	42.6	14520	8270	6250
13B	56.6	43.4	14400	8150	6250
13C	58.5	41.5	14410	8420	5990
14A	55.7	44.3	14390	8020	6370
14B	55.0	45.0	14360	7920	6440
14C	55.4	44.6	14360	7980	6380
15A	63.2	36.8	14690	9100	5590
15B	64.4	35.6	14600	9270	5330
15C	63.8	36.2	14610	9190	5420
16A	54.3	45.7	14790	7820	6950
16B	55.0	45.0	14650	7920	6730
16C	55.6	44.4	14590	8010	6580
Av.	57.3	42.7	14600	8280	6320

TABLE 53.—RATIO OF CALORIFIC VALUE OF VOLATILE MATTER TO THAT OF FIXED CARBON IN 43 ILLINOIS STOKER COALS
(Unit coal basis)

Coal sample No.	Volatile matter			Calorific ratio V.M. to F C. (F.C. at 14,400 B.t.u. per lb.)
	Percent	Heat content (B.t.u.)	Calorific value (B.t.u.)	
1A	35.2	5240	14900	1.035
2B	41.0	6260	15270	1.061
2C	46.9	6900	14710	1.023
2E	41.6	5930	14250	0.983
3A	44.1	6510	14750	1.025
3B	43.2	6210	14380	0.999
3C	42.1	5990	14230	0.988
5A	46.4	6810	14690	1.020
5B	46.5	6500	13990	0.971
5C	40.9	5650	13830	0.960
6A	40.7	6260	15380	1.068
6B	41.9	6160	14700	1.021
6C	42.8	6140	14340	0.996
7A	38.7	6340	16390	1.138
7B	39.3	6550	16680	1.158
7C	38.6	6430	16650	1.156
8A	47.9	7040	14700	1.021
8B	46.5	6640	14280	0.998
8C	46.8	6700	14310	0.995
9A	46.4	6950	14970	1.040
9B	47.1	6910	14660	1.019
9C	43.5	6350	14590	1.013
10A	38.4	6020	15680	1.089
10B	38.5	5990	15570	1.081
10C	38.6	5940	15400	1.069
11A	47.1	7230	15340	1.065
11B	46.2	7120	15410	1.070
11C	46.3	7120	15380	1.068
12A	43.4	6520	15010	1.043
12B	42.9	6320	14720	1.012
12C	42.4	6250	14740	1.023
13A	42.6	6250	14670	1.019
13B	43.4	6250	14410	1.001
13C	41.5	5980	14420	1.002
14A	44.3	6370	14390	0.999
14B	45.0	6440	14320	0.994
14C	44.6	6380	14300	0.993
15A	36.8	5590	15190	1.055
15B	35.6	5330	14970	1.040
15C	36.2	5420	14990	1.041
16A	45.7	6950	15210	1.056
16B	45.0	6730	14950	1.039
16C	44.4	6580	14820	1.029
Av.	42.7	6330	14900	1.035

TABLE 54.—HEAT CONTENT OF VOLATILE MATTER AND THAT OF FIXED CARBON IN SMOKELESS BRIQUETS MADE FROM DEDUSTER DUST AND PARTIALLY PREVOLATILIZED COALS
(Unit coal basis)
(Figure 49)

Sample	County	Proximate analysis		Calorific value (B.t.u.)	Heat content (B.t.u.)		Calorific value V.M. (B.t.u.)	Calorific ratio V.M. to F.C.	
		F.C. (percent)	V.M. (percent)		F.C.	V.M.		Individual	Average
Deduster dust	Franklin	65.4	34.6	14560	9420	5140	14880	1.033	1.033
Coal prevolatilized to various degrees	Franklin	62.0	38.0	14390	8930	5460	14370	0.998	
	"	66.0	34.0	14290	9500	4790	14310	0.994	
	"	68.6	31.4	14360	9880	4480	14280	0.992	0.980
	"	71.7	28.3	14330	10320	4010	14170	0.984	
	"	74.2	25.8	14260	10680	3580	13450	0.934	
	Will	54.6	45.4	14210	7860	6350	13530	0.940	
	"	63.3	36.7	14310	9110	5200	14140	0.980	
	"	66.0	34.0	14400	9500	4900	14400	1.000	0.972
	"	68.0	32.0	14360	9790	4570	13960	0.968	

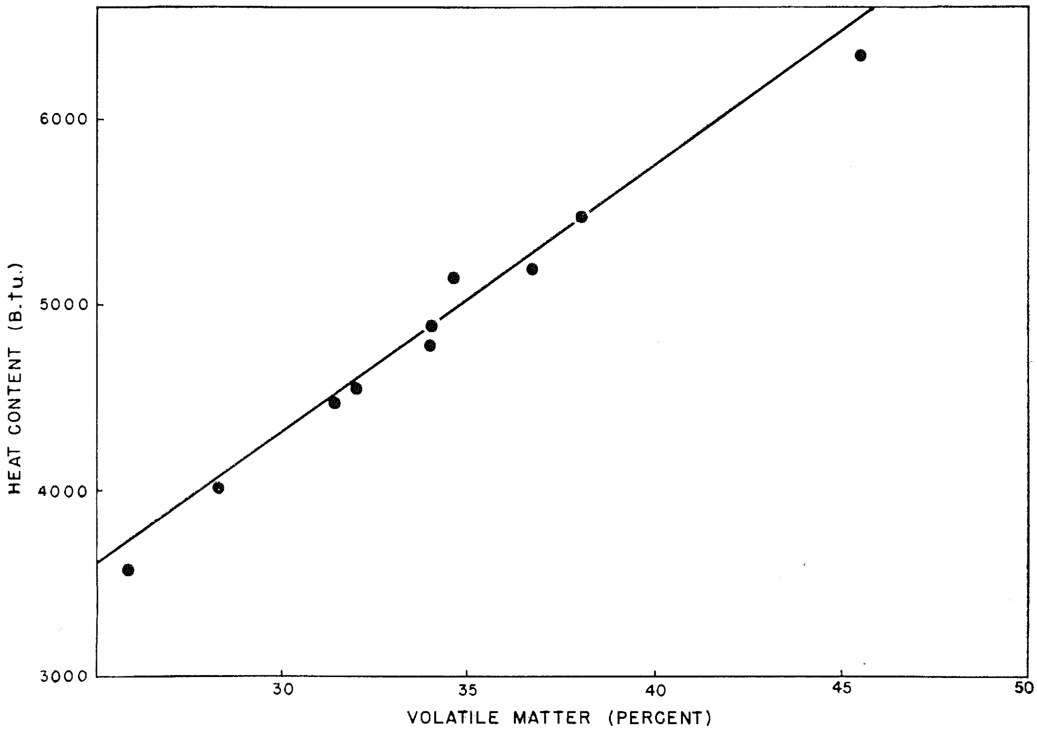

FIG. 49.—Influence of percent volatile matter in smokeless briquets made from Illinois coals. (Data from table 54)

CALORIFIC VALUE OF VOLATILE MATTER AND FIXED CARBON IN RAW ILLINOIS COAL

An examination of data presented by Cady,[4] which summarizes county average proximate analyses of Illinois coals arranged by county and coal bed (table 55, fig. 50) reveals that the ratio of calorific value of the volatile matter per pound to that of fixed carbon on the same basis is also slightly greater than unity and that a linear increase of the heat content (fig. 50) of the volatile matter content takes place with the increase in the percent volatile matter.

HEAT VALUE OF VOLATILE MATTER AND FIXED CARBON IN SMOKELESS BRIQUETS

Study of the analysis of briquets, part of which were made commercially with added binder from deduster dust having high fusain content, and part of which represent experimentally made cylindrical briquets made from partially prevolatilized coal (table 54) reveals similar relationships between the heat value of volatile matter and fixed carbon as is shown by coals used in stoker tests and the analyses of face samples, except that for these fuels the ratio of heat value of the volatile matter to the heat value of the fixed carbon per pound averages slightly less than unity. As in the case of the stoker coal there is the same linear increase (figs. 48 and 49) in the heat content of the percent volatile matter as the volatile matter increases. That is to say, the heat derived from the volatile matter appears always to increase directly as the volatile matter increases, indicating a fairly uniform heat content of the volatile matter irrespective of the rank of the coal.

SIGNIFICANCE OF SIMILARITY IN CALORIFIC VALUE OF VOLATILE MATTER AND FIXED CARBON

Because volatile matter and fixed carbon have essentially the same calorific value, the high volatile content of the midwestern

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[4] Cady, G. H., Classification and selection of Illinois coals: Illinois Geol. Survey Bull. 62, pp. 314-326, 1935.

TABLE 55.—RATIO OF CALORIFIC VALUE OF VOLATILE MATTER TO THAT OF FIXED CARBON FOR 66 ILLINOIS COALS, BASED ON COUNTY AVERAGES

(Unit coal basis)
(Figure 50)

County	Coal bed	Proximate analysis		Calorific value V.M. (B.t.u)	Heat content		Calorific value V.M. (B.t.u.)	Calorific ratio V.M. to F.C.
		V.M. (percent)	F.C. (percent)		F.C. (B.t.u.)	V.M. (B.t.u.)		
Bond	Herrin No. 6	44.1	55.9	14240	8050	6190	14030	0.975
Bureau	LaSalle No. 2	49.4	50.6	14470	7290	7180	14540	1.010
"	Sparland No. 7	45.4	54.6	14530	7860	6670	14690	1.020
Christian	Lower Assumption	47.9	52.1	14760	7500	7260	15150	1.052
"	Upper Assumption	48.0	52.0	14690	7490	7200	15000	1.042
"	Herrin No. 6	46.6	53.4	14390	7690	6700	14380	0.998
Clinton	Herrin No. 6	45.8	54.2	14280	7800	6480	14140	0.982
Edgar	Grape Creek	46.6	53.4	14740	7690	7050	15530	1.051
Franklin	Herrin No. 6	40.5	59.5	14570	8570	6000	14820	1.029
Fulton	Rock Island No. 1	47.5	52.5	14960	7560	7400	15980	1.110
"	Springfield No. 5	46.6	53.4	14520	7690	6830	14660	1.018
Fulton-Peoria	Herrin No. 6	42.2	57.8	14480	8290	6190	14680	1.019
Gallatin	Herrin No. 6	41.0	59.0	15080	8500	6580	16050	1.117
"	Harrisburg No. 5?	39.5	60.5	15070	8710	6360	16100	1.118
Greene	Summum No. 4?	46.2	53.8	14600	7750	6850	14830	1.023
Grundy	LaSalle No. 2	47.7	52.3	14520	7530	6990	14650	1.017
"	Veronica No. 6?	46.9	53.1	14630	7650	6980	14900	1.034
Henry	Rock Island No. 1	47.5	52.5	14510	7560	6950	14630	1.016
"	Colchester No. 2	47.8	52.2	14330	7520	6810	14250	0.990
"	Herrin No. 6	42.4	57.6	14470	8290	6180	14570	1.012
Jackson	Murphysboro No. 1?	39.4	60.6	14820	8730	6090	15470	1.074
"	Herrin No. 6	41.7	58.3	14630	8390	6240	14950	1.038
Jefferson	Herrin No. 6	41.0	59.0	14630	8500	6130	14950	1.031

Knox	Rock Island No. 1	45.9	54.1	14650	7790	6860	14990	1.041
“	Summum No. 4	48.0	52.0	14790	7490	7300	15210	1.056
“	Herrin No. 6	44.0	56.0	14560	8060	6500	14760	1.025
LaSalle	LaSalle No. 2	48.7	51.3	14560	7390	7170	14730	1.023
“	Herrin No. 6?	53.7	46.3	14400	6670	7730	14400	1.000
“	Streator No. 6	49.5	50.5	14660	7270	7390	14920	1.037
Livingston	Grape Creek	45.3	54.7	14960	7880	7080	15640	1.086
Logan	Springfield No. 5	47.4	52.6	14440	7570	6870	14480	1.006
McDonough	Colchester No. 2	44.4	55.6	14640	8010	6630	14940	1.037
McLean	LaSalle No. 2	49.9	50.1	14720	7210	7510	15040	1.045
“	Springfield No. 5	51.2	48.8	14610	7030	7580	14810	1.028
Macon	“ “	46.4	53.6	14390	7720	6670	14380	0.999
Macoupin	Herrin No. 6	47.3	52.7	14250	7490	6760	14300	0.993
Madison	“ “	48.6	51.4	14350	7400	6950	14300	0.993
Marion	“ “	45.1	54.9	14590	7910	6680	14820	1.029
Marshall	LaSalle No. 2	49.4	50.6	14780	7290	7490	15170	1.054
Marshall	Sparland No. 7	48.5	51.5	14630	7420	7210	14870	1.033
Menard	Springfield No. 5	45.8	54.2	14490	7800	6690	14600	1.014
Mercer	Rock Island No. 1	49.9	50.1	14570	7210	7350	14740	1.024
Montgomery	Herrin No. 6	45.9	54.1	14330	7790	6540	14250	0.989
Moultrie	Herrin No. 6?	46.7	53.3	14910	7670	7240	15500	1.076
Peoria	Springfield No. 5	45.8	54.2	14670	7800	6870	14990	1.041
Perry	Herrin No. 6	42.2	57.8	14370	8320	6050	14330	0.995
Randolph	Blair No. 5	44.6	55.4	14450	7980	6470	14510	1.007
Rock Island	Rock Island No. 1	46.2	53.8	14490	7750	6740	14590	1.014
St. Clair	Herrin No. 6	47.8	52.2	14460	7520	6940	14520	1.009
Saline	Harrisburg No. 5	39.3	60.7	14810	8740	6070	15440	1.072
Sangamon	Springfield No. 5	46.7	53.3	14460	7670	6790	14530	1.009
“	Herrin No. 6	47.2	52.8	14360	7600	6760	14320	0.994
Schuyler	Colchester No. 2	46.1	53.9	14970	7760	7210	15590	1.083
“	Springfield No. 5	45.2	54.8	14740	7890	6850	15160	1.053
Shelby	Springfield No. 5	43.8	56.2	14480	8090	6390	14580	1.013
Stark	Herrin No. 6	44.3	55.7	14590	8020	6570	14830	1.029
Tazewell	Springfield No. 5	46.2	53.8	14510	7750	6760	14640	1.016

TABLE 55.—(Concluded)

County	Coal bed	Proximate analysis		Calorific value V.M. (B.t.u.)	Heat content		Calorific value V.M. (B.t.u.)	Calorific ratio V.M. to F.C.
		V.M. (percent)	F.C. (percent)		F.C. (B.t.u.)	V.M. (B.t.u.)		
Vermilion	Grape Creek No. 5	44.5	55.5	14600	7990	6610	14850	1.031
"	Danville No. 7	48.2	51.8	14760	7460	7300	15150	1.052
Warren	Rock Island No. 1	49.0	51.0	14680	7340	7340	14970	1.040
Washington	Herrin No. 6	47.7	52.3	14400	7530	6870	14400	1.000
White	" "	41.8	58.2	14680	8380	6300	15070	1.046
Will	LaSalle No. 2	42.4	57.6	14400	8290	6110	14400	1.000
Williamson	Harrisburg No. 5?	40.1	59.9	14820	8630	6190	15450	1.072
"	Coal No. 6	39.6	60.4	14630	8700	5930	14980	1.040
Woodford	LaSalle No. 2	43.1	56.9	14690	8190	6500	15070	1.047
Av.		45.5	54.5	14590	7820	6770	14850	1.013

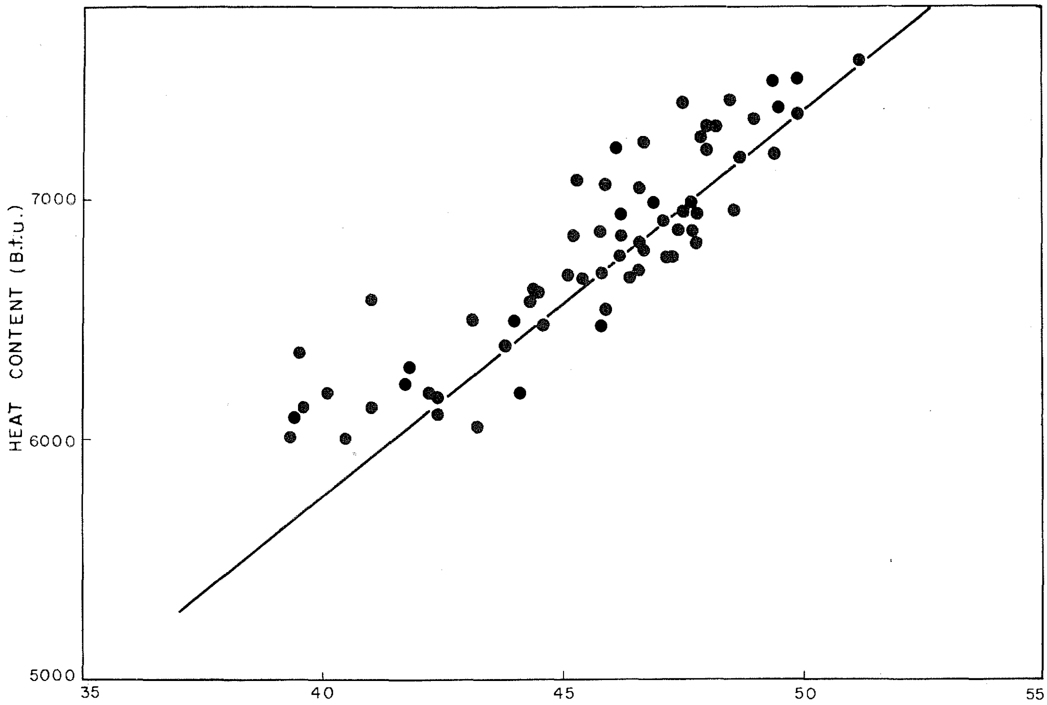

FIG. 50.—Influence of percent volatile matter on heat content of volatile matter in Illinois coals. (Data from table 55)

coals does not materially lessen their calorific efficiency when these coals are completely burned. This means explicitly that heat produced by the smokeless combustion of these coals is in direct proportion to the experimentally determined B.t.u. per pound. Whether or not the useful heat will be so realized depends of course on the mechanical efficiency of the heating apparatus and the quality of its installation, which is aside from the main problem, but which is commonly considerably below 100 percent.

Because of the value of volatile matter as a source of heat in coal, it is important to burn the raw coal smokelessly either by using specially designed equipment or by so processing the coal (with minimum loss of volatile matter) that it will smoke only under unusual operating conditions. Briquetting provides one way of handling coal which would otherwise usually be wasted, and the special processes of briquetting described in this report are those which make possible the production of smokeless briquets of relatively high volatile content from high volatile midwestern coals such as are mined in Illinois.

It has been pointed out that analysis of the briquets made from partially prevolatilized coal indicates that the ratio of the calorific value of the volatile matter to that of the fixed carbon is only slightly less than unity, the same ratio being slightly more than unity for face samples and other fairly freshly mined coal. This loss in the calorific value of the volatile matter in the briquets is reasonably assignable to oxidation, probably resulting from the heating and partial prevolatilization. In standard analytical procedure B.t.u. determinations are made on air-dried samples. If samples are used that have been completely dried at 105° C., a loss of about 200 B.t.u. per pound results.

TABLE 56.—ULTIMATE ANALYSES OF 47 ILLINOIS COALS, BASED ON COUNTY AVERAGES
(Unit coal basis)
(Figure 51)

County	Coal bed	Hydrogen (percent)	Carbon (percent)	Nitrogen (percent)	Oxygen (percent)	Calorific value (B.t.u.)	
						Experimental	Theoretical
Bond	Herrin No. 6	5.5	81.7	1.4	11.4	14240	14450
Bureau	LaSalle No. 2	5.5	80.8	1.5	12.2	14470	14270
"	Sparland No. 7	6.1	81.4	1.2	11.3	14530	14260
Christian	Herrin No. 6	5.9	80.5	1.5	12.1	14390	14370
Clinton	" "	5.7	80.6	1.4	12.3	14280	14360
Edgar	Grape Creek	5.8	82.7	1.5	10.0	14740	14770
Franklin	Herrin No. 6	5.4	82.8	1.8	10.0	14570	14600
Fulton	Springfield No. 5	5.6	82.4	1.6	10.6	14520	14610
Fulton-Peoria	Herrin No. 6	5.7	81.6	1.5	11.2	14480	14470
Greene	Summum No. 4?	5.6	81.9	1.5	11.0	14600	14520
Grundy	LaSalle No. 2	5.7	81.7	1.3	11.4	14520	14540
"	Verona No. 6?	5.8	80.8	1.2	12.2	14630	14400
Henry	Rock Island No. 1	6.1	81.0	1.2	11.7	14510	14590
"	Colchester No. 2	5.9	80.7	1.5	11.9	14330	14440
"	Herrin No. 6	5.7	82.2	1.2	10.9	14470	14660
Jackson	Herrin No. 6	5.8	82.4	1.6	10.2	14630	14720
Jefferson	" "	5.5	82.6	1.8	10.1	14630	14620
Knox	" "	5.6	82.9	1.2	10.3	14560	14700
LaSalle	LaSalle No. 2	5.6	82.4	1.4	10.6	14560	14600
"	Streator No. 6	5.7	81.5	1.4	11.4	14660	14500
Livingston	Grape Creek	6.0	83.9	1.4	8.7	14960	15100
Logan	Springfield No. 5	5.7	82.0	1.5	10.8	14440	14590
Macon	" "	5.7	80.8	1.4	12.1	14390	14360
Macoupin	Herrin No. 6	6.0	79.8	1.4	12.8	14250	14320
Madison	" "	5.9	80.9	1.4	11.8	14350	14480
Marion	" "	5.8	82.2	1.5	10.5	14590	14680
Marshall	Sparland No. 7	5.9	82.2	1.5	10.4	14630	14730

Menard	Springfield No. 5	5.8	82.2	1.4	10.6	14490	14690
Montgomery	Herrin No. 6	5.7	81.1	1.4	11.8	14330	14420
Peoria	Springfield No. 5	5.8	82.4	1.5	10.3	14670	14720
Perry	Herrin No. 6[1]	5.3	81.7	1.8	11.2	14420	14370
"	" " [2]	5.6	81.0	1.4	12.0	14330	14370
Randolph	Herrin No. 6	5.6	81.0	1.4	12.0	14340	14350
St. Clair	Herrin No. 6	5.6	81.7	1.5	11.2	14460	14570
Saline	Harrisburg No. 5	5.6	83.8	1.8	8.8	14810	14790
Sangamon	Harrisburg No. 5	5.7	81.7	1.5	11.1	14460	14530
"	Herrin No. 6	5.7	80.9	1.5	11.9	14360	14390
Shelby	Springfield No. 5	5.9	81.4	1.7	11.0	14480	14580
Stark	Herrin No. 6	5.7	82.3	1.3	10.7	14590	14640
Tazewell	Springfield No. 5	5.7	82.3	1.5	10.5	14510	14640
Vermilion	Grape Creek No. 5	5.6	82.0	1.7	10.7	14600	14550
"	Danville No. 7	5.8	82.1	1.5	10.6	14760	14660
Washington	Herrin No. 6	5.9	80.6	1.6	11.9	14400	14430
White	Herrin No. 6	5.7	83.0	1.7	9.6	14680	14780
Will	LaSalle No. 2	6.1	80.7	1.4	11.8	14400	14540
Williamson	Coal No. 6	5.6	82.9	1.7	9.8	14630	14720
Woodford	LaSalle No. 2	5.6	82.9	1.5	10.0	14690	14710
Av.		5.73	81.80	1.47	11.0	14520	14570

[1] East of DuQuoin anticline.
[2] West of DuQuoin anticline.

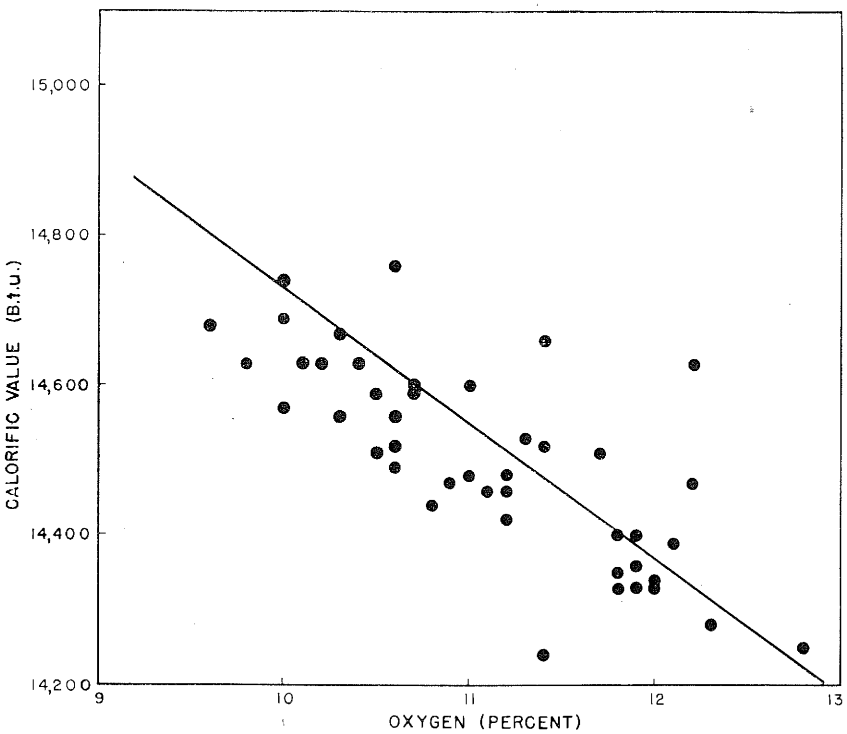

FIG. 51.—Influence of oxygen on calorific values of Illinois coals, unit coal basis. (Data from table 56)

RELATION OF ELEMENTARY COAL COMPOSITION TO THE HEAT VALUE OF THE COAL

I. FORMULA FOR CALCULATING CALORIFIC VALUE FROM ELEMENTARY ANALYSES

In connection with the study of the relative importance of volatile matter and fixed carbon as sources of heat, considerable thought was given to the part played by the heat-producing components in bituminous coal, particularly the atomic elements composing the hydrocarbons of the volatile matter. These are included in the items reported in the ultimate analysis, that is hydrogen, carbon, and oxygen with minor amounts (about 1.5 percent) of nitrogen.

On the basis of certain premises and deductions explained beginning on p. 130 it appeared that calorific value of a bituminous coal can be determined from the calorific value of the natural elements by use of the following formula.

$$Q = 453.6 (H + C/3 - O/12.5) \qquad (1)$$

where Q is calorific value in units of B.t.u. per pound; the hydrogen H, the carbon C, and oxygen O, are all in units of percent weight.

Using the proposed formula (1) the theoretical calorific value of 47 Illinois coals calculated from ultimate values on a unit coal basis (table 56) agree within the range of accepted experimental error with experimentally determined values. The difference between the calorific value of Illinois coals calculated from the percentages of hydrogen, carbon, oxygen, and sulfur and their experimental calorific value depends upon the amount of deviations in the experimental determination of the percentage of each of these elements and of the calorific value. The maximum variation may be as much as 300 B.t.u. per pound when all the individual deviations are of the same algebraic sign.

II. EFFECT OF OXYGEN ON THE CALORIFIC VALUE OF COAL

From the proposed formula it is apparent that an increase in the amount of oxygen in coal—the one element that is subject to increase through extraneous influences and from extraneous sources—will effect a decrease in the heat value of coals. The data (table 56, fig. 51) show that such a relationship holds true for Illinois coals.

III. Pure CH-coal

Regarding oxygen (and nitrogen) essentially as impurities in the elementary constitution of coal, just as moisture and ash may be so regarded in the proximate constitution, it may be useful to think of true or pure coal material as being composed entirely of carbon and hydrogen. In such a calculation it is necessary to make suitable allowance for the loss of hydrogen that would attend the removal of oxygen. The remaining effective or available hydrogen may be considered as the percentage hydrogen less 0.08 percentage oxygen. With the ineffective hydrogen removed there is then left a residuum of pure CH-coal composed only of carbon and effective hydrogen. Thus the formulas for pure CH-coal are as follows:

$$C_p = \frac{C}{C + H - 0.08 \times O} \qquad (2)$$

and

$$H_p = \frac{H}{C + H - 0.08 \times O} \qquad (3)$$

and

$$Q_p = \frac{Q}{C + H - 0.08 \times O} \qquad (4)$$

when the subscript refers to pure CH-coal values.

For Illinois coals the CH-coal calorific values and the percentages of carbon and effective hydrogen on a pure CH-coal basis (table 57) reveal a remarkable constancy for each of these values, as has been previously pointed out.[5] The averages 94.4 percent carbon, 5.6 percent hydrogen, and 16,800 B.t.u. represent what are believed to be universal constants for bituminous coals.

IV. Calculation of Unit Coal Heat Value from the Universal Constant Heat Value (CH-coal)

The CH-coal values designated in the preceding section are basic and from them it it possible to derive the more commonly known values such as unit coal values and the various conventional forms in which the ultimate analysis is presented. The assumption that nitrogen and oxygen as well as moisture and ash are impurities "diluting" the coal substance is consistent. Unit coal values are derived by a simple calculation which makes allowance for the known contents of oxygen and the use of 1.5 percent as representing the prevailing nitrogen content. The method of calculation from unit coal to the conventional analytical bases is too well known to require explanation here.

Using the average or universal constant heat value of 16,800 B.t.u. as a basis for calculation it is possible to determine unit heat value for any coal if the content of oxygen and nitrogen are known. Since on the unit coal basis the percentage of C is

$$C = 100 - (H + N + O) \qquad (5)$$

equation 4 becomes

$$Q_p = \left[\frac{Q}{100 - (H + N + O) + H - 0.08 \times O}\right] \times 100 \qquad (6)$$

This reduces to

$$Q_p = \left[\frac{Q}{100 - N - 1.08 \times O}\right] \times 100 \qquad (7)$$

Also table 57 shows that the precentage nitrogen (unit coal basis) is quite constant and is approximately 1.5 percent for Illinois coals. Substitute the value for nitrogen equation 7 becomes

$$Q_p = \left[\frac{Q}{98.5 - 1.08 \times O}\right] \times 100 \qquad (8)$$

Since the pure CH-coal calorific constant is 16,800 B.t.u. equation 8 may be written as follows:

$$Q = 168\,[98.5 - 1.08 \times O] \qquad (9)$$

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[5] Piersol, R. J., Theoretical physics and pioneering research in Illinois minerals: Trans. Illinois State Acad. Science, pp. 88-93, vol 38, 1946.

TABLE 57.—CARBON, EFFECTIVE HYDROGEN, AND CALORIFIC VALUE OF PURE CH-COAL FOR 47 ILLINOIS COALS, BASED ON COUNTY AVERAGES

County	Coal bed	Carbon (percent)	Effective hydrogen (percent)	Calorific value (B.t.u.)
Bond	Herrin No. 6	94.7	5.3	16550
Bureau	LaSalle No. 2	94.7	5.3	16940
“	Sparland No. 7	94.0	6.0	16780
Christian	Herrin No. 6	94.2	5.8	16840
Clinton	“ “	94.5	5.5	16670
Edgar	Grape Creek	94.3	5.7	16810
Franklin	Herrin No. 6	94.7	5.3	16610
Fulton	Springfield No. 5	94.6	5.4	16660
Fulton-Peoria	Herrin No. 6	94.4	5.6	16760
Greene	Summum No. 4	94.6	5.4	16850
Grundy	LaSalle No. 2	94.5	5.5	16790
“	Verona No. 6	94.4	5.6	17090
Henry	Rock Island No. 1	94.0	6.0	16840
“	Colchester No. 2	94.2	5.8	16730
“	Herrin No. 6	94.5	5.5	16630
Jackson	Herrin No. 6	94.3	5.7	16580
Jefferson	“ “	94.6	5.4	16760
Knox	“ “	94.6	5.4	17090
LaSalle	LaSalle No. 2	94.5	5.5	16710
“	Streator No. 6	94.4	5.6	16990
Livingston	Grape Creek	94.1	5.9	16770
Logan	Springfield No. 5	94.4	5.6	16590
Macon	“ “	94.5	5.5	16820
Macoupin	Herrin No. 6	94.1	5.9	16810
Madison	“ “	94.2	5.8	16740
Marion	“ “	94.2	5.8	16720
Marshall	Sparland No. 7	94.2	5.8	16760
Menard	Springfield No. 5	94.3	5.7	16630
Montgomery	Herrin No. 6	94.5	5.5	16690
Peoria	Springfield No. 5	94.3	5.7	16790
Perry	Herrin No. 6	94.9	5.1	16750
“	“ “	94.6	5.4	16730
Randolph	“ “	94.6	5.4	16740
St. Clair	“ “	94.6	5.4	16740
Saline	Harrisburg No. 5	94.5	5.5	16700
Sangamon	“ “	94.4	5.6	16720
“	Herrin No. 6	94.5	5.5	16770
Shelby	Springfield No. 5	94.3	5.7	16590
Stark	Herrin No. 6	94.4	5.6	16740
Tazewell	Springfield No. 5	94.4	5.6	16650
Vermilion	Grape Creek No. 5	94.5	5.5	16830
“	Danville No. 7	94.3	5.7	16960
Washington	Herrin No. 6	94.2	5.8	16840
White	“ “	94.4	5.6	16690
Will	LaSalle No. 2	94.0	6.0	15770
Williamson	Coal No. 6	94.5	5.5	16660
Woodford	LaSalle No. 2	94.5	5.5	16750
Av.		94.41	5.59	16760

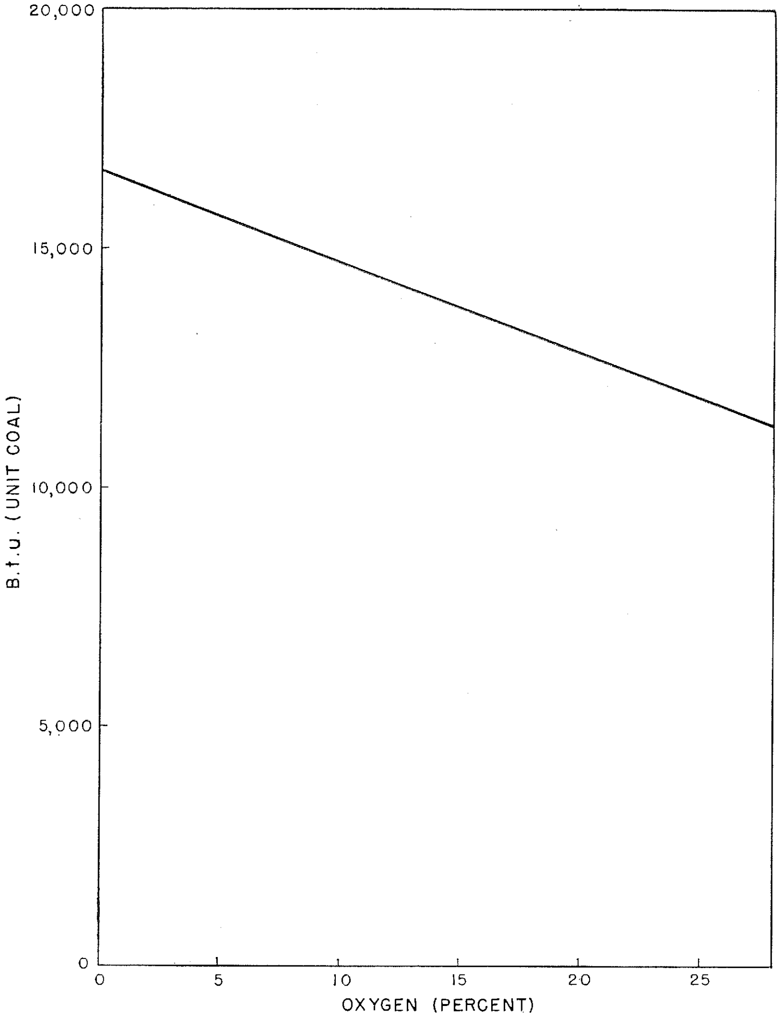

FIG. 52.—Relation of calorific value of coal to percent oxygen (unit coal basis). (Data from table 58)

FUNDAMENTAL NATURE OF THE CH-CONCEPT

The pure CH-coal concept is even more fundamental than the Parr unit coal concept in that it shows that all bituminous coals on an oxygen-free basis, are identical in their content of carbon, hydrogen, and in their calorific value.

SIGNIFICANCE OF CH-CONCEPT IN COALIFICATION

The existence of universal constants for pure CH-coal of bituminous and lower rank indicates geological conditions of thermal equilibrium during coalification through these ranks. In the formation of anthracite on the other hand, hydrogen is liberated and the valence electrons, discussed beginning p. 130, are shifted to a lower level with a resulting change in the constants for pure CH-coal in these high rank coals.

WAXES AND RESINS EXTRANEOUS TO CH-COAL

With respect to the botanical components of bituminous coal, the writer is of the opinion that such materials as resins and waxes, which do not appear amenable to typical coalification, probably represent extraneous matter not having the constitution of pure CH-coal.

OXYGEN CONTENT AND VOLATILE MATTER-FIXED CARBON RATIO

The calorific ratio of the volatile matter to fixed carbon is found to be higher than unity for any coal containing less than 11.3 percent oxygen (solution of equation 9). Since about two thirds of Illinois coals have an oxygen content less than 11.3 percent (table 56) they therefore possess a calorific ratio of the volatile matter to the fixed carbon higher than unity. The remaining third of the coal has only a slightly higher oxygen content with the result that no Illinois coal has a unit coal calorific value more than 160 below that of fixed carbon, that is less than 14,240 B.t.u. per pound (about 0.98 calorific ratio).

A NEW FORMULA FOR THE CALCULATION OF THE CALORIFIC VALUE OF COAL

The formula 1 introduced in the opening paragraph (p. 126) has its origin in considerations based upon modern physical concepts of the nature of combustion. Physicists discovered early in this century that valence electrons are the binding force that holds atoms together in the form of molecules; that the strength of the bond depends on the energy level of the valence electrons in the outer orbits of the atom; that this energy level of the valence electron is changed with the formation of a new molecule; and, finally that the heat of combustion of organic substances is the effect of energy liberated because of the changes in energy levels of the valency electrons.

In about 1900, J. J. Thomson[6] proposed the planetary structure of the atom, composed of a relatively large central positive nucleus (sun) about which the relatively small negative electrons (planets) revolve in almost circular orbits and also suggested that the electrons in the outer orbits comprise the valence electrons. Shortly thereafter Bohr[7] showed that the electrons revolve in orbits of definite energy levels and that the atom liberates energy when an electron is displaced to a lower energy orbit from a higher energy orbit. Energy liberated in chemical reactions due to the interdisplacement of valence electrons was investigated by G. N. Lewis,[8] Langmuir,[9] Sidgwick,[10] Pauling,[11] and others. Kharasch[12] made a quantitative study of energies liberated in the interdisplacement of carbon, hydrogen, and oxygen valence electrons during the combustion of aliphatic and aromatic organic compounds.

DEVELOPMENT OF A CALORIFIC FORMULA FOR COAL

Because of greater convenience in its use the following discussion is given in terms of the metric system, heat values being expressed in unit of calories per gram instead of B.t.u. per pound. If the reader prefers to think in terms of B.t.u. he may use the conversion factor which is 1.8 (1 calorie per gram equals 1.8 B.t.u. per lb.).

For aromatic hydrocarbons, the molecular structure of which is believed to be predominately that of bituminous coal, Kharasch[12] has shown experimentally that the change in energy levels resulting from combustion is 25±1 kg. cal. each per mole per valence electron, for hydrogen and carbon, and minus 16± 1 kg. cal. per mole per effective valence electron for oxygen. The exact value of these changes in energy levels depends on the molecular structure of the aromatic compound. Since the coefficients of carbon and hydrogen are identical, but that of oxygen is different, the exact values may be calculated by simultaneous equations from the ultimate analyses and the heats of combustion of two hydrocarbons

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[6] Thomson, J. J., Electricity and matter: Yale Univ. Press, 1904.

[7] Bohr, Niels H. B., The theory of spectra and atomic constitution: Macmillan, 1922.

[8] Lewis, G. N., Valence and the structure of atoms and molecules: Chemical Catalog Co., 1923.

[9] Langmuir, I., Isomorphism, isoterism, and covalence: Jour. Amer. Chemical Soc. Vol. 41, No. 368, p. 1543, 1919.

[10] Sidgwick, N. V., Some physical properties of the covalent link in chemistry: Cornell Univ. Press, 1933.

[11] Pauling, L., The nature of the chemical bond: Cornell Univ. Press, 1939.

[12] Kharasch, M. S., The electronic conception of valence and heats of combustion of organic compounds: Jour. Phys. Chem. Vol. 29, p. 625, 1924.

Heats of combustion of organic compounds, Bureau of Standards, Jour. Research, Vol. 2, No. 2, p. 359, 1929.

TABLE 58.—UNIT COAL CALORIFIC VALUES FOR 47 ILLINOIS COALS, BASED ON COUNTY AVERAGES

County	Coal bed	Oxygen (percent)	Unit coal calorific value (B.t.u.)		
			A[a]	B[a]	C[a]
Bond	Herrin No. 6	11.4	14240	14450	14480
Bureau	LaSalle No. 2	12.2	14470	14270	14330
"	Sparland No. 7	11.3	14530	14660	14500
Christian	Herrin No. 6	12.1	14390	14370	14350
Clinton	" "	12.3	14280	14360	14300
Edgar	Grape Creek	10.0	14740	14770	14730
Franklin	Herrin No. 6	10.0	14570	14600	14730
Fulton	Springfield No. 5	10.6	14520	14610	14620
Fulton-Peoria	Herrin No. 6	11.2	14480	14470	14520
Greene	Summum No. 4	11.0	14600	14520	14550
Grundy	LaSalle No. 2	11.4	14520	14540	14480
"	Verona No. 6	12.2	14630	14400	14330
Henry	Rock Island No. 1	11.7	14510	14590	14420
"	Colchester No. 2	11.9	14330	14440	14390
"	Herrin No. 6	10.9	14470	14660	14570
Jackson	" "	10.2	14630	14720	14700
Jefferson	" "	10.1	14630	14620	14830
Knox	" "	10.3	14560	14700	14680
LaSalle	LaSalle No. 2	10.6	14560	14600	14620
"	Streator No. 6	11.4	14660	14500	14480
Livingston	Grape Creek	8.7	14960	15100	14970
Logan	Springfield No. 5	10.8	14440	14590	14570
Macon	" "	12.1	14390	14360	14350
Macoupin	Herrin No. 6	12.8	14250	14320	14380
Madison	" "	11.8	14350	14480	14410
Marion	" "	10.5	14590	14680	14640
Marshall	Sparland No. 7	10.4	14630	14730	14660
Menard	Springfield No. 5	10.6	14490	14690	14620
Montgomery	Herrin No. 6	11.8	14330	14420	14410
Peoria	Springfield No. 5	10.3	14670	14720	14680
Perry	Herrin No. 6	11.2	14420	14370	14520
"	" "	12.0	14330	14370	14370
Randolph	" "	12.0	14340	14350	14370
St. Clair	" "	11.2	14460	14570	14520
Saline	Harrisburg No. 5	8.8	14810	14790	14950
Sangamon	" "	11.1	14460	14530	14530
"	Herrin No. 6	11.9	14360	14390	14390
Shelby	Springfield No. 5	11.0	14480	14580	14550
Stark	Herrin No. 6	10.7	14590	14640	14610
Tazewell	Springfield No. 5	10.5	14510	14640	14640
Vermilion	Grape Creek No. 5	10.7	14600	14550	14610
"	Danville No. 7	10.6	14760	14660	14620
Washington	Herrin No. 6	11.7	14400	14430	14420
White	" "	9.6	14680	14780	14810
Will	LaSalle No. 2	11.8	14400	14540	14410
Williamson	Coal No. 6	9.8	14630	14720	14770
Woodford	LaSalle No. 2	10.0	14690	14710	14730
Av.		11.0	14520	14570	14550

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[a] (A) Determined experimentally, (B) Calculated from calorific formula and (C) Calculated from universal CH-coal constant and percent oxygen.

which have different composition and the same molecular arrangement. Since all bituminous coals and coals of lower rank apparently possess the same molecular arrangement, this method reveals that the exact values for such coals are given by the formula as follows:

$$Q_k = 25.2\ V_h + 25.2\ V_c - 16.1\ V_o \qquad (10)$$

where Q_k is the heat of combustion in kg. cal. per mole and V_h, V_c, and V_o are the number of valence electrons per atom for hydrogen, carbon, and oxygen, respectively.

Since hydrogen and carbon have one and four valence electrons, respectively, and oxygen has two effective valence electrons, equation 10 becomes

$$Q_k = 25.2 \times H + 25.2 \times 4 \times C - 16.1 \times 2 \times O \qquad (11)$$

and since the atomic weights of hydrogen, carbon, and oxygen are 1, 12, and 16, respectively, becomes

$$Q = 252\ (H + C/3 - O/12.5) \qquad (12)$$

where Q is expressed in calories per gram rather than B.t.u. per lb., and H, C, and O are in units of percent weight.

The conversion from equation 11 to equation 12 proceeds as follows:

For hydrogen:

$$\frac{25.2 \text{ kg. per mole} \times 1 \text{ (valency)}}{1 \text{ (atomic weight)}} = 25.2 \text{ kg. cal.}$$

per gram hydrogen or 252 cal. per gram material percent hydrogen

(1 kg. equals 1000 grams, 1 percent 1000 is 10).

For carbon:

$$\frac{25.2 \text{ kg. cal. per mole} \times 4 \text{ (valency)}}{12 \text{ (atomic weight)}} \times 10 \text{ (conversion factor)}$$

$$= \frac{252}{3} \text{ cal. per gram material percent carbon.}$$

For oxygen:

$$\frac{16.1 \text{ kg. cal. per mole} \times 2 \text{ (valency)}}{16 \text{ (atomic weight)}} \times 10 \text{ (conversion factor)} = \frac{252}{12.5} \text{ per gram material percent oxygen.}$$

It has been previously stated that the established experimental calorific value of carbon in its free state (coke) is 8000 cal. per gr. (14,400 B.t.u. per lb.) which is 80 cal. Thus for charcoal, coke, and anthracite, the energy constant in equation 12 is reduced from 252 to 240; the heat of combustion of free carbon in these fuels is 8000 calories per gram (14,400 B.t.u. per pound).

PROOF OF VALIDITY OF PROPOSED CALORIFIC FORMULA

The heat energy liberated, or absorbed, in the shift of a valence electron from one energy level to another is determined experimentally. Therefore the coefficient 252 in equation 12 is an experimental constant. The proof of the accuracy of this constant in the proposed calorific formula may be shown by the agreement between the calculated and the experimental heats of combustion for a series of coals representative of various stages of coalification. Table 59 shows such a comparison for 316 American coals, selected by Fieldner[13] as representative of various ranks of coal. These analyses are reported on moisture-free basis and therefore require a sulfur correction; adding such a correction, equation 12 becomes

$$Q = 252\ (S/10 + H + C/3 - O/12.5) \qquad (13)$$

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[13] Fieldner, A. C., Selvig, W. A., and Frederic, W. H., Classification chart of typical coals of the United States: U. S. Bur. of Mines, Rept. Inv. 3296, 1935.

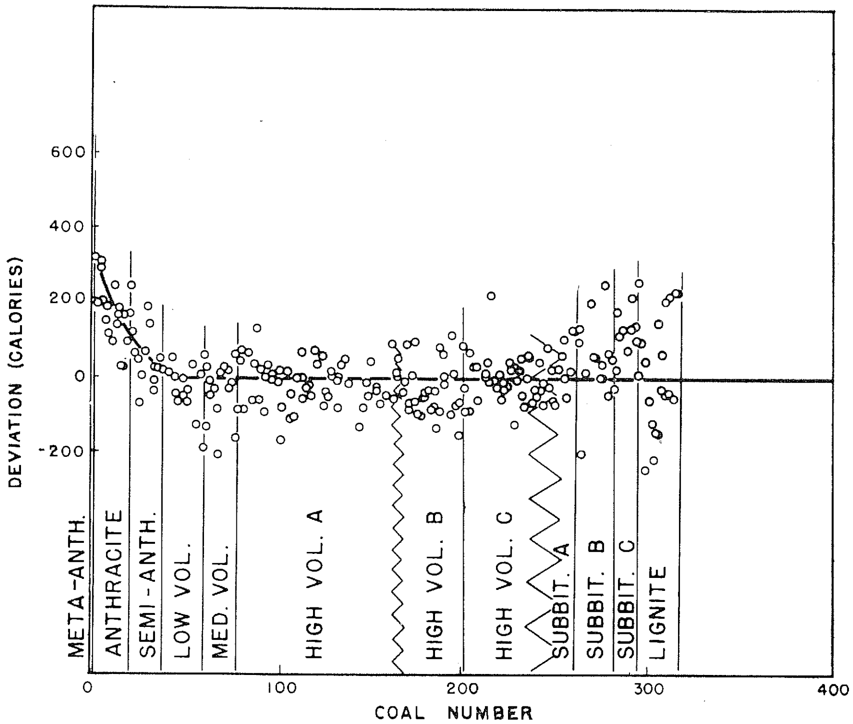

FIG. 53.—Deviation between calculated and experimental heats of combustion of 316 coals representing various ranks of coals. (Data from table 59)

Figure 53 shows graphically the deviation between the calculated and the experimental calorific values for these coals.

Plotting the deviation between the calculated and the experimental calorific values for the bituminous coals (but omitting the anthracite coals) with increasing amounts of hydrogen, carbon, oxygen, and sulfur is

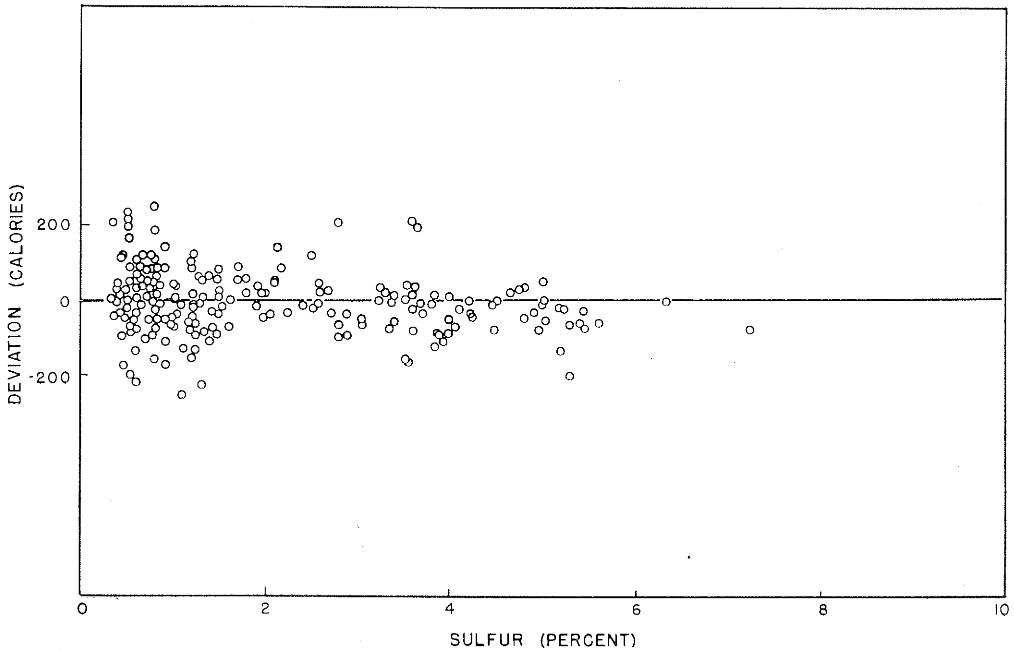

FIG. 54.—Deviation between calculated and experimental heats of combustion of 316 coals as affected by percent sulfur. (Data from table 59)

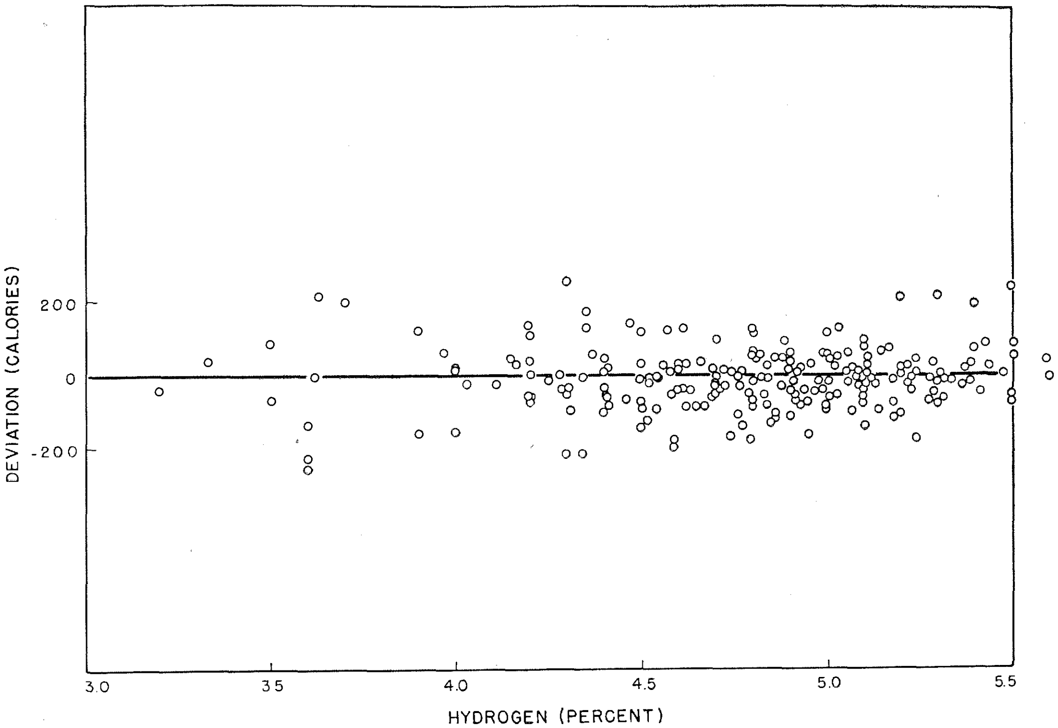

FIG. 55.—Deviation between calculated and experimental heats of combustion of 316 coals as affected by percent hydrogen. (Data from table 59)

a preferred method of mathematical analysis to show the accuracy of their respective coefficients; the results, shown in figures 54, 55, 56, 57, reveal that the coefficients are accurate. Also figure 58 shows that increasing amounts of ash in the coals do not affect the deviation.

The calorific formula (equation 13) ap-

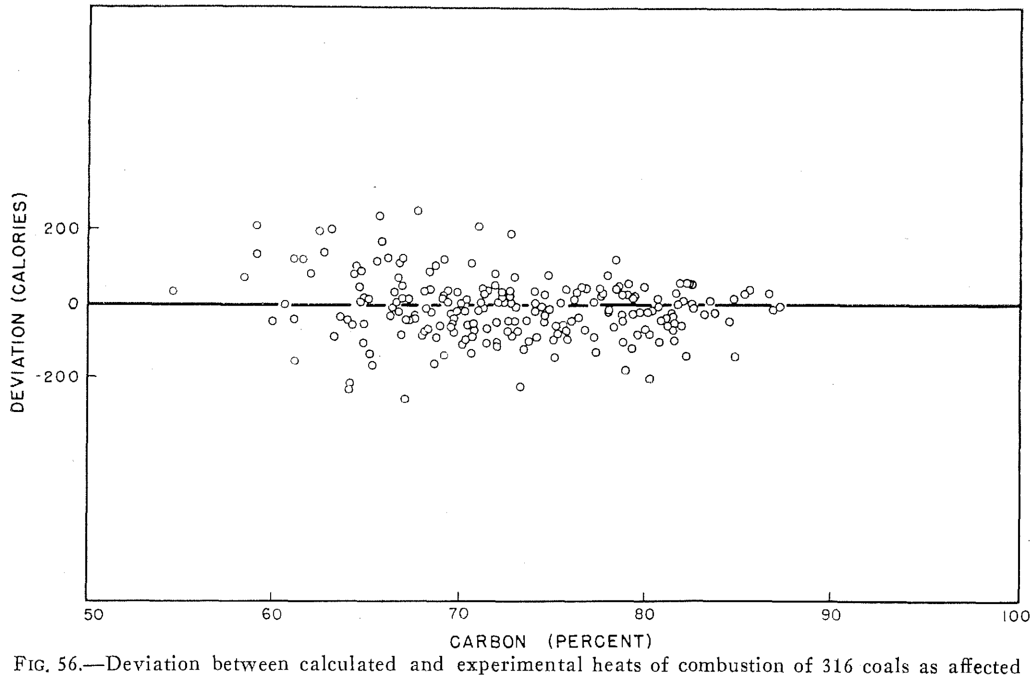

FIG. 56.—Deviation between calculated and experimental heats of combustion of 316 coals as affected by percent carbon. (Data from table 59)

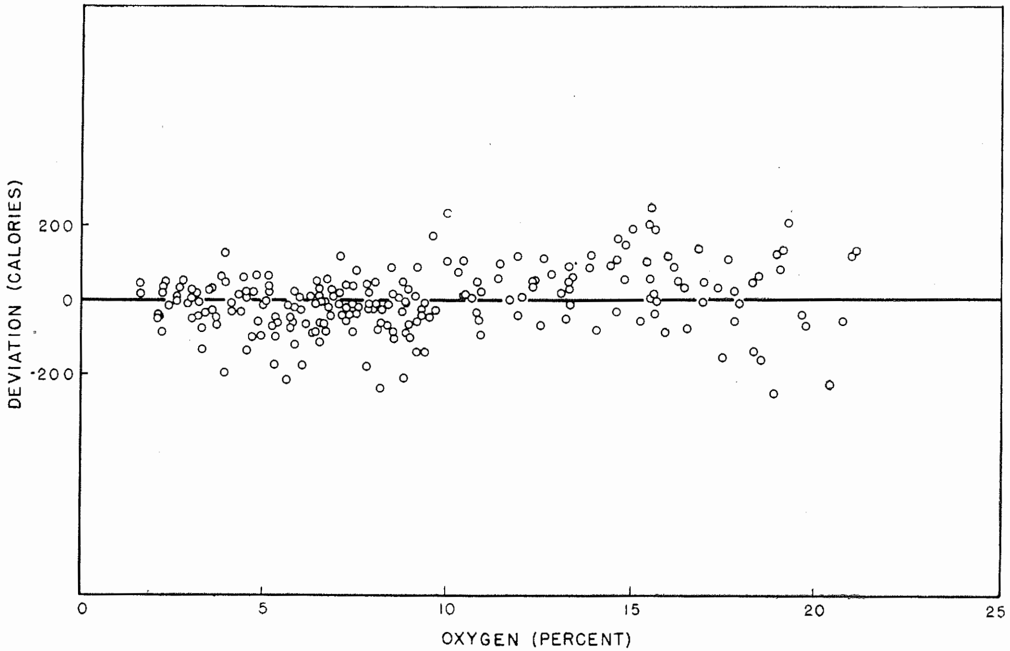

FIG. 57.—Deviation between calculated and experimental heats of combustion of 316 coals as affected by percent oxygen. (Data from table 59)

plies to bituminous coal equally well for analyses reported on a dry basis, on a dry ash-free basis, and on a dry mineral matter-free basis. This is because the various values remain in approximately the same ratio for these methods of reporting. However, this formula does not apply to any one of the types of moist basis. This is because the combining ratio of hydrogen and oxygen in water is 1/8 whereas the ratio of the coefficient for hydrogen and oxygen in this formula is 1/12.5.

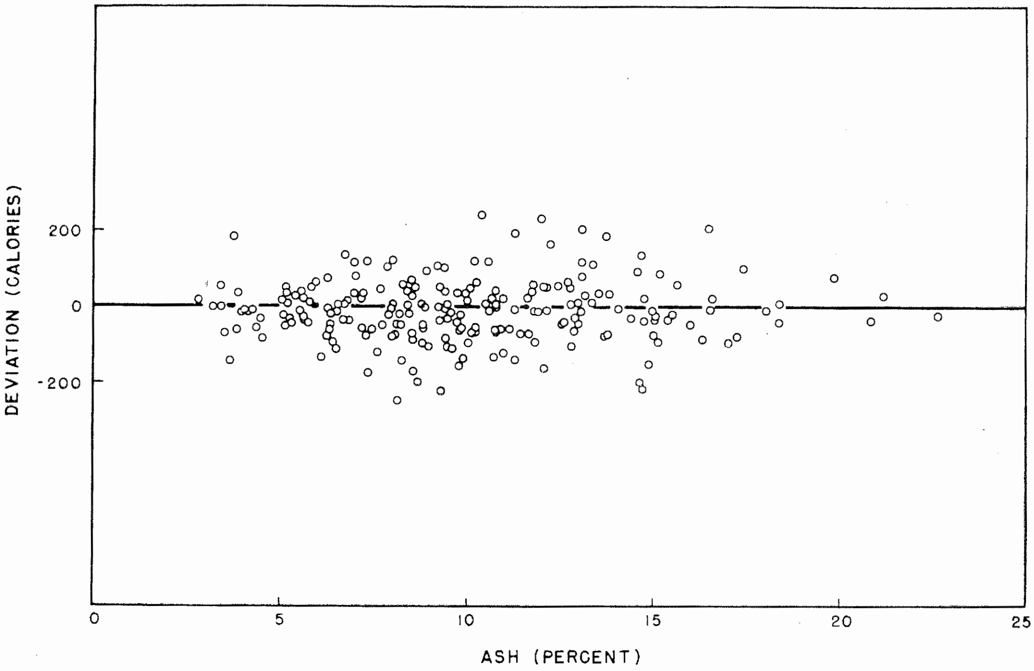

FIG. 58.—Deviation between calculated and experimental heats of combustion of 316 coals as affected by percent ash. (Data from table 59)

TABLE 59.—COMPARISON OF CALCULATED AND EXPERIMENTAL HEATS OF COMBUSTION OF 316 AMERICAN COALS, REPRESENTING VARIOUS RANKS OF COAL
(Analyses on moisture-free basis)
(Figures 53-58)

No.	Rank	State	A	S	H	C	O	Exp. Cal.	f	Calcu. Cal.	Dev. ±
1	*Meta-anth.*	R. I.	21.77	0.35	0.47	74.05	3.11	5960	24.93	6280	+320
2	"	"	14.41	0.87	0.46	82.39	1.75	6460	27.87	7020	+560
3	Anth.	Pa.	9.3	0.5	1.9	86.0	1.5	7500	30.50	7690	+190
4	"	"	10.5	0.5	1.5	86.3	0.5	7340	30.28	7630	+290
5	"	Colo.	15.08	0.61	2.26	78.87	1.79	7010	28.47	7170	+160
6	"	Pa.	11.4	0.5	1.9	83.8	1.8	7300	29.74	7490	+190
7	"	"	10.9	1.4	2.1	83.3	1.8	7380	29.87	7530	+150
8	"	"	9.9	0.4	2.0	85.4	1.6	7460	30.38	7660	+200
9	"	"	8.6	0.8	2.6	83.3	4.1	7480	30.12	7590	+110
10	"	"	10.2	0.4	2.1	83.6	2.6	7410	29.80	7510	+100
11	"	"	8.9	0.6	2.7	84.6	1.4	7590	30.85	7770	+180
12	"	"	10.0	0.8	3.0	83.3	2.4	7480	30.66	7730	+250
13	"	"	13.2	0.5	2.1	81.2	2.1	7190	29.05	7320	+130
14	"	Colo.	9.1	0.7	3.0	86.1	0.7	7830	31.71	7980	+160
15	"	Pa.	6.03	0.58	2.52	88.30	1.64	7850	31.88	8030	+180
16	"	"	7.4	0.6	2.7	85.0	3.3	7740	30.83	7770	+ 30
17	"	"	7.23	0.43	2.23	87.91	1.51	7760	31.45	7920	+160
18	"	"	11.94	0.48	2.22	81.65	2.91	7350	29.26	7370	+ 20
19	"	"	12.9	0.8	2.9	80.0	2.2	7340	29.47	7430	+ 90
20	"	Wash.	12.79	1.00	2.60	81.30	1.29	7310	29.70	7480	+170
21	"	N. M.	10.08	0.82	1.36	85.42	1.24	7270	29.81	7510	+240
22	"	Pa.	10.6	0.6	3.1	83.0	1.7	7620	30.69	7730	+110
23	"	"	11.4	1.2	3.2	80.7	2.2	7510	30.04	7570	+ 60
24	Semi-anth.	"	10.0	0.7	3.3	82.7	2.2	7700	30.76	7750	+ 50
25	"	"	12.09	0.84	3.37	80.59	2.13	7540	30.14	7590	+ 50
26	"	"	10.7	0.6	3.6	80.1	3.0	7660	30.12	7590	− 70
27	"	Ark.	16.03	1.78	3.46	81.97	1.79	7770	30.82	7770	0
28	"	Wash.	19.49	—	—	—	—	6810	—	—	—
29	"	Ark.	12.37	2.04	3.65	78.29	2.25	7440	29.77	7500	+ 60
30	"	Va.	25.1	0.6	3.2	68.4	2.3	6360	25.88	6520	+160

31	Semi-anth.	Va.	19.3	0.7	3.4	73.7	2.0	6880	27.88	7030	+150
32	Low-Vol. Bit.	Ark.	10.3	—	—	—	—	7670	—	—	—
33	“	Pa.	6.24	1.07	4.29	84.64	2.13	8210	32.44	8170	− 40
34	“	“	7.89	0.67	4.25	83.35	2.39	8060	31.91	8040	− 20
35	“	W. Va.	5.1	0.6	4.2	86.7	2.2	8270	32.98	8310	+ 40
36	“	Md.	10.6	2.6	4.0	79.4	2.2	7680	30.55	7700	+ 20
37	“	“	11.79	2.59	4.15	78.60	1.59	7590	30.48	7680	+ 90
38	“	Pa.	7.17	1.90	4.41	83.48	1.80	8120	32.29	8140	+ 20
39	“	Ark.	8.05	—	—	—	—	8070	—	—	—
40	“	Ga.	8.07	—	—	—	—	8120	—	—	—
41	“	W. Va.	7.66	—	—	—	—	8050	—	—	—
42	“	“	3.40	0.49	4.58	87.27	2.63	8450	33.51	8440	− 10
43	“	Ark.	8.04	—	—	—	—	8000	—	—	—
44	“	W. Va.	5.5	0.8	4.4	85.7	2.3	8240	32.87	5280	+ 40
45	“	“	3.98	0.73	4.54	86.98	2.61	8420	33.39	8410	− 10
46	“	Md	4.3	1.0	4.3	81.6	3.0	7960	31.36	7900	− 60
47	“	“	10.1	1.6	4.2	79.7	3.3	7800	30.67	7730	− 70
48	“	W. Va.	1.1	4.6	4.6	81.7	3.2	8030	32.03	8070	+ 40
49	“	“	7.89	0.70	4.34	82.60	2.93	8000	31.71	7990	− 10
50	“	Pa.	7.72	1.99	4.79	82.08	2.15	8060	32.18	8110	+ 50
51	“	Md.	8.5	1.1	4.5	80.4	3.7	7910	31.11	7840	− 70
52	“	Pa.	8.06	2.09	4.63	81.62	2.24	8050	31.87	8030	− 20
53	“	Wash.	22.69	0.78	4.11	66.40	4.12	6580	25.99	6550	− 30
54	“	W. Va.	6.06	—	—	—	—	8200	—	—	—
55	“	Wash.	16.64	0.51	4.16	73.12	3.56	7100	28.30	7130	+ 30
56	“	Va.	13.74	—	—	—	—	7490	—	—	—
57	“	Pa.	6.05	1.26	4.51	83.23	3.35	8230	32.11	8090	−140
58	“	Va.	3.4	—	—	—	—	8480	—	—	—
59	“	Okla.	6.53	0.79	4.28	83.58	3.10	8050	31.97	8060	+ 10
60	“	Colo.	8.70	0.53	4.59	80.38	3.95	8040	31.11	7840	−200
61	“	Pa.	10.11	1.31	4.37	79.98	2.77	7740	30.94	7800	+ 60
62	Mod. vol. Bit.	Md.	10.7	2.7	4.6	77.8	3.0	7680	30.56	7700	+ 10
63	“	W. Va.	3.59	0.60	4.77	84.93	4.54	8400	32.78	8260	−140
64	“	Pa.	8.13	1.07	4.52	80.97	2.91	7930	31.39	7910	− 20
65	“	Md.	8.2	1.2	4.4	81.0	3.7	7920	31.22	7870	− 50
66	“	W. Va.	5.46	0.54	4.62	85.38	2.74	8260	32.91	8290	+ 30
67	“	Md.	11.0	2.1	4.6	77.8	3.0	7660	30.50	7690	+ 30
68	“	“	11.8	4.1	4.5	76.0	2.2	7570	30.06	7570	0
69	“	Mont.	14.75	0.60	4.34	73.48	5.66	7380	28.44	7170	−210
70	“	Pa.	7.00	1.51	4.77	82.23	3.2	8080	32.09	8090	+ 10

Table 59.—(Continued)

No.	Rank	State	A	S	H	C	O	Exp. Cal.	f	Calcu. Cal.	Dev. ±
71	High Vol. A bit.	Ala.	4.95	—	—	—	—	8300	—	—	—
72	"	Pa.	11.64	2.75	4.56	76.13	3.53	7510	29.93	7540	+ 30
73	"	Wash.	18.09	0.40	3.67	72.83	3.24	6950	27.73	6990	+ 40
74	"	Ala.	5.00	1.50	5.02	83.67	3.24	8240	32.80	8270	+ 30
75	Mod. Vol. bit.	Pa.	9.23	2.72	4.61	78.91	3.40	7820	30.91	7790	− 30
76	"	"	6.66	1.41	4.88	82.13	3.58	8120	32.11	8090	− 30
77	"	Va.	9.28	1.47	4.72	78.76	3.91	7710	30.81	7760	+ 50
78	"	W. Va.	8.52	0.91	4.80	78.99	5.28	7930	30.80	7760	−170
79	"	Wash.	8.75	0.43	5.07	78.93	4.72	7920	31.04	7520	−100
80	"	Colo.	13.53	0.54	4.88	74.23	5.08	7330	29.26	7370	+ 40
81	High Vol. A bit.	Tenn.	8.61	0.82	4.80	79.17	5.06	7720	30.87	7780	+ 60
82	"	Ala.	17.03	1.48	4.31	70.51	5.32	7010	27.53	6940	− 70
83	"	Tenn.	9.40	—	—	—	—	7630	—	—	—
84	"	"	12.17	0.53	4.72	76.47	4.82	7470	29.88	7530	+ 60
85	"	Pa.	7.58	—	—	—	—	8000	—	—	—
86	"	Tenn.	7.27	1.28	5.06	81.04	3.83	7960	31.89	8040	+ 80
87	"	Wash.	11.65	0.51	4.69	75.89	5.25	7530	29.62	7460	− 70
88	"	Tenn.	8.50	1.05	4.90	79.05	5.03	7770	30.95	7800	+ 30
89	"	Ala.	10.18	0.77	5.03	78.49	3.91	7670	30.96	7800	+130
90	"	Tenn.	15.01	0.81	4.59	72.88	5.69	7230	28.50	7180	− 50
91	"	W. Va.	10.25	0.99	4.74	76.86	5.67	7730	30.01	7570	−160
92	"	Ala.	2.79	0.82	5.20	84.85	4.49	8340	33.20	8370	+ 30
93	"	"	6.43	1.24	5.14	80.83	4.94	8110	31.80	8010	−100
94	"	Pa.	10.75	1.30	4.76	76.75	4.96	7690	30.07	7580	−110
95	"	Va.	5.65	0.53	5.44	81.71	5.07	8120	32.33	8150	+ 30
96	"	W. Va.	5.78	1.22	4.93	82.09	4.33	8060	32.06	8080	+ 20
97	"	Va.	3.87	1.53	5.11	83.84	4.06	8290	32.89	8290	0
98	"	Okla.	6.46	0.89	5.32	80.59	4.87	8040	31.88	8030	− 10
99	"	Va.	6.36	—	—	—	—	8030	—	—	—
100	"	W. Va.	5.20	0.74	5.18	81.54	5.81	8070	31.97	8060	− 10
101	"	Okla.	5.19	0.51	5.12	80.23	7.23	7920	31.33	7890	− 30
102	"	Colo.	7.32	0.47	5.24	77.36	7.82	7850	30.45	7670	−180
103	"	Ala.	15.19	1.17	4.30	68.93	8.86	6820	26.69	6730	− 90
104	"	Mo.	9.46	3.83	5.05	75.65	4.52	7620	30.29	7630	+ 10
105	"	Pa.	5.67	—	—	—	—	8000	—	—	—

106	High vol. A. bit.	Pa.	8.41	1.32	5.11	77.40	6.29	7680	30.54	7700	+ 20
107	"	Kan.	10.99	3.93	4.84	73.26	5.87	7470	29.18	7350	−120
108	"	Pa.	7.43	1.20	5.01	78.39	6.50	7800	30.74	7750	− 50
109	"	W. Va.	6.45	0.92	5.18	79.39	6.49	7980	31.21	7860	−120
110	"	Va.	3.18	—	—	—	—	8180	—	—	—
111	"	Pa.	6.49	2.59	5.06	80.26	4.11	8010	31.74	8000	− 10
112	"	Wash.	10.79	0.47	5.08	74.59	7.44	7410	29.39	7410	0
113	"	Va.	5.93	0.61	5.15	82.41	4.43	8080	32.33	8150	+ 70
114	"	Wash.	9.83	1.04	5.28	76.00	5.79	7690	30.25	7620	− 70
115	"	W. Va.	5.57	1.05	5.23	80.88	5.71	8060	31.83	8020	− 40
116	"	Wash.	15.40	0.47	5.12	69.59	7.35	7040	27.78	7000	− 40
117	"	Ala.	5.60	0.44	5.13	78.70	8.18	7770	30.75	7750	− 20
118	"	Kan.	9.56	5.20	4.77	74.83	4.34	7560	29.88	7530	− 30
119	"	Mo.	10.76	5.29	4.80	72.69	5.29	7400	29.14	7340	− 60
120	"	Ky.	3.33	0.57	5.49	82.26	6.71	8110	32.43	8170	+ 60
121	"	"	4.42	1.39	5.22	81.50	5.96	8100	32.05	8080	− 20
122	"	W. Va.	7.18	0.84	5.07	79.49	5.84	7830	31.18	7860	+ 30
123	"	Okla.	5.28	—	—	—	—	7850	—	—	—
124	"	Ky.	5.15	0.73	5.22	80.71	6.54	7960	31.67	7980	+ 20
125	"	W. Va.	8.57	0.72	5.11	77.73	6.41	7650	30.58	7710	+ 60
126	"	Colo.	16.32	0.55	4.65	70.83	6.27	7090	27.81	7010	− 80
127	"	Wash.	12.57	0.36	5.42	73.10	6.84	7420	29.28	7380	− 40
128	"	Tenn.	3.77	1.14	5.50	81.22	6.61	8060	32.15	8100	+ 40
129	"	Ky.	3.15	1.01	5.48	81.83	6.60	8140	32.33	8150	+ 10
130	"	Tenn.	6.26	1.63	5.28	79.35	5.61	7930	31.44	7920	− 10
131	"	Ky.	4.22	0.86	5.34	79.89	7.88	7930	31.43	7920	− 10
132	"	"	6.31	0.80	5.31	78.13	7.64	7780	30.82	7770	− 10
133	"	W. Va.	6.30	1.34	5.00	77.35	8.39	7700	30.24	7620	− 80
134	"	Wash.	12.86	0.39	5.08	73.08	6.55	7300	28.96	7300	0
135	"	Tenn.	10.72	3.25	5.11	74.81	4.67	7470	30.00	7560	+ 90
136	"	W. Va.	7.11	0.76	4.96	78.80	6.75	7720	30.77	7750	+ 30
137	"	N. M.	12.28	1.00	4.81	72.54	8.03	7120	28.45	7170	+ 80
138	"	N. M.	14.99	0.63	4.89	70.47	7.47	7020	27.84	7020	0
139	"	Tenn.	8.05	4.11	5.37	76.53	4.18	7830	30.96	7800	− 30
140	"	Ill.	8.55	—	—	—	—	7580	—	—	—

TABLE 59.—(Continued)

No.	Rank	State	A	S	H	C	O	Exp. Cal.	f	Calcu. Cal.	Dev. ±
141	High vol. A bit.	W. Va.	5.71	—	—	—	—	8060	—	—	0
142	"	Ky.	12.22	3.74	4.76	71.38	6.39	7160	28.41	7160	0
143	"	Tenn.	6.77	2.01	5.38	77.22	6.72	7740	30.78	7760	+ 20
144	"	Wash.	13.07	0.40	5.61	70.13	9.38	7130	28.28	7130	0
145	"	Ohio	9.9	5.2	5.1	70.7	8.2	7330	28.53	7190	−140
146	"	Okla.	10.61	6.34	5.08	72.77	3.75	7480	29.67	7480	0
147	"	Ohio	9.45	3.60	4.93	74.28	6.38	7530	29.54	7440	− 90
148	"	Ky.	5.03	2.41	5.39	78.12	7.16	7860	31.09	7830	− 30
149	"	Okla.	10.25	5.40	5.10	72.75	4.83	7490	29.50	7430	− 60
150	"	N. M.	9.96	3.63	5.39	72.94	6.55	7410	29.54	7440	+ 30
151	"	W. Va.	7.42	1.92	5.29	76.19	7.78	7600	30.26	7630	+ 30
152	"	N. M.	10.82	—	—	—	—	7370	—	—	—
153	"	"	15.07	0.85	4.99	69.80	8.03	6990	27.70	6980	− 10
154	"	Tenn.	10.72	4.25	5.10	73.21	5.27	7480	29.50	7430	− 50
155	"	Ohio	8.94	—	—	—	—	7470	—	7580	+110
156	"	W. Va.	7.25	3.36	5.18	75.42	7.40	7660	30.07	—	—
157	"	"	8.93	—	—	—	—	7600	—	—	—
158	"	Nev.	7.33	—	—	—	—	5440	—	—	—
159	"	Ohio	10.92	5.05	5.03	70.67	7.18	7240	28.52	7190	− 50
160	"	Iowa	11.15	—	—	—	—	8060	—	—	—
161	"	Ky.	14.0	—	—	—	—	7100	—	—	—
162	High vol. B. bit.	Texas	19.89	2.17	5.51	62.06	9.17	6430	25.69	6470	+ 40
163	"	Ky.	3.46	1.25	5.32	80.06	8.34	7990	31.46	7930	− 60
164	"	Okla.	8.75	4.01	5.24	74.21	5.94	7520	29.90	7530	+ 10
165	"	Ohio	8.33	2.11	5.01	75.93	7.22	7520	29.95	7550	+ 30
166	High vol. A bit.	"	9.44	4.54	5.23	72.80	6.67	7420	29.42	7410	− 10
167	High vol. B bit.	Ill.	8.09	—	—	—	—	7620	—	—	—
168	"	Colo.	9.77	0.46	4.97	73.82	9.50	7320	28.87	7270	− 50
169	"	Ohio	6.3	3.8	5.3	74.3	8.9	7510	29.74	7490	− 20
170	"	Utah	8.40	1.20	5.43	74.95	8.49	7430	29.85	7520	+ 90
171	"	Ohio	8.8	2.9	5.0	73.9	8.1	7470	29.27	7380	− 90
172	"	Okla.	10.77	2.07	4.91	72.66	8.25	7290	28.68	7230	− 60
173	"	Wash.	12.79	0.38	5.31	69.46	10.70	6960	27.64	6960	0
174	"	Wash.	15.2	0.52	4.89	64.42	14.40	6270	25.26	6370	+100
175	"	"	13.77	5.60	4.91	68.51	6.13	7070	27.82	7010	− 60

176	High vol. B bit.........	Ohio............	8.9	3.9	5.2	70.3	10.3	7210	28.20	7110	−100
177	“	“	7.6	2.8	5.1	73.3	9.9	7380	29.02	7310	− 70
178	“	“	9.6	1.4	4.9	72.2	10.6	7230	28.26	7120	−110
179	“	“	6.3	0.8	5.1	75.8	10.5	7520	29.61	7460	− 60
180	“	Utah............	6.30	0.73	5.29	75.26	10.88	7500	29.58	7450	− 50
181	“	Ky..............	7.76	—	—	—	—	7490	—	—	—
182	“	Colo............	5.59	0.48	5.23	76.20	10.82	7550	29.81	7510	− 40
183	“	Ohio............	10.0	1.4	5.0	71.6	10.8	7190	28.15	7090	−100
184	“	Cal.............	4.48	4.48	5.92	70.94	10.70	7430	29.16	7350	− 80
185	“	Wyo............	5.63	1.49	5.12	74.81	11.87	7410	29.24	7370	− 40
186	“	Ill..............	8.25	1.24	4.50	75.33	9.22	7440	28.99	7300	−140
187	“	Colo............	6.45	0.78	5.04	75.16	10.88	7480	29.30	7380	−100
188	“	Utah............	11.24	0.71	5.17	71.05	10.27	7010	28.10	7080	+ 70
189	“	Idaho...........	12.80	0.58	5.51	76.71	10.81	7570	30.28	7630	+ 60
190	“	Mont............	15.04	2.53	4.03	67.67	9.76	6590	26.06	6570	− 20
191	“	Okla............	14.09	4.22	4.52	66.49	9.23	6650	26.36	6640	− 10
192	“	Ill..............	15.33	—	—	—	—	6900	—	—	—
193	“	Ky..............	9.44	3.89	4.76	71.65	8.65	7250	28.34	7140	−110
194	“	Wash............	17.5	1.2	5.1	64.6	10.0	6430	25.95	6540	+110
195	“	Ill..............	9.25	1.01	4.92	74.06	9.09	7290	28.98	7300	+ 10
196	“	Wash............	12.14	—	—	—	—	6900	—	—	—
197	“	Mo.............	13.76	5.46	4.84	68.20	6.66	7030	27.59	6950	− 80
198	“	Ind.............	12.04	3.55	4.95	68.79	9.59	7080	27.46	6920	−160
199	“	Kan.............	17.28	4.09	4.41	67.05	6.00	6800	26.69	6730	− 70
200	“	Ill..............	15.33	—	—	—	—	6900	—	—	—
201	“	Ind.............	14.41	4.90	4.71	67.16	7.49	6840	26.99	6800	− 40
202	“	Ky..............	9.51	2.91	4.86	72.21	8.96	7260	28.50	7180	− 80
203	High vol. C bit.........	Colo............	12.5	0.7	4.8	69.5	11.4	6770	27.13	6840	+ 70
204	“	Utah............	12.8	6.9	4.4	65.0	9.9	6650	25.97	6540	−110
205	“	Ind.............	7.74	—	—	—	—	7470	—	—	—
206	“	Ind.............	10.52	3.58	5.22	71.33	7.93	7220	28.72	7240	+ 20
207	“	Mont............	14.87	3.30	4.74	64.97	10.91	6500	25.86	6520	+ 20
208	“	Mo.............	12.88	4.00	4.73	69.13	8.25	6990	27.51	6930	− 60
209	“	Ind.............	11.29	3.23	4.82	70.37	8.77	7040	27.90	7030	− 10
210	“	Iowa............	11.86	—	—	—	—	7110	—	—	—

TABLE 59.—(Continued)

No.	Rank	State	A	S	H	C	O	Exp. Cal.	f	Calcu. Cal.	Dev. ±
211	High vol. C bit.	Ill.	11.9	3.7	4.7	70.2	8.1	7020	27.82	7010	− 10
212	“	Colo.	7.94	1.03	5.08	72.60	12.05	7150	28.42	7160	+ 10
213	“	Mo.	13.20	3.53	4.89	69.76	7.44	6990	27.90	7030	+ 40
214	“	“	9.88	4.46	4.81	72.05	7.64	7240	28.67	2220	− 20
215	“	Ky.	13.1	2.8	4.7	71.1	8.1	6850	28.04	7070	+220
216	“	Utah	7.6	—	—	—	—	7180	—	—	—
217	“	Kan.	15.56	5.01	4.52	66.94	6.73	6760	26.79	6750	− 10
218	“	Mo.	12.93	5.19	5.09	67.68	7.88	6970	27.54	6940	− 30
219	“	Wyo.	18.40	5.44	4.72	61.34	9.34	6320	24.96	6290	− 30
220	“	N. M.	7.8	0.8	5.2	73.3	11.7	7250	28.77	7250	0
221	“	Ohio	9.7	0.8	4.8	71.7	12.5	7090	27.78	7000	− 90
222	“	Ind.	7.93	1.23	5.01	74.98	9.18	7420	29.39	7410	− 10
223	“	“	20.90	2.27	4.33	63.75	7.53	6370	25.21	6350	− 20
224	“	Mont.	8.4	3.6	4.7	69.6	10.0	6940	27.46	6920	− 20
225	“	Ill.	13.8	4.6	4.9	68.2	8.9	6890	27.38	6900	+ 10
226	“	“	11.4	3.4	4.7	70.5	8.7	7000	27.84	7020	+ 20
227	“	Colo.	6.94	0.47	5.24	72.39	13.19	7110	28.36	7150	+ 40
228	“	Mo.	11.27	3.85	4.85	69.43	9.37	7070	27.62	6960	−110
229	“	Wyo.	4.1	1.2	5.0	74.8	13.3	7320	28.99	7300	− 20
230	“	Ill.	13.35	4.66	4.69	67.42	8.50	6770	26.95	6740	+ 20
231	“	Mont.	9.72	0.70	4.86	71.38	12.28	6940	27.74	6990	+ 50
232	“	Ill.	11.2	4.4	4.7	69.7	9.2	7020	27.63	6960	− 60
233	“	Iowa	8.53	7.14	4.62	63.49	7.50	6610	25.89	6520	− 90
234	“	Ill.	8.2	—	—	—	—	7340	—	—	—
235	“	“	11.86	3.37	4.98	70.00	8.44	7060	27.97	7050	− 10
236	Sub-bit. A	Mont.	5.8	0.6	4.8	72.2	12.4	6990	27.94	7040	+ 50
237	High vol. C bit.	Ill.	10.8	5.0	4.8	68.6	8.8	6870	27.47	6920	+ 50
238	“	Mo.	8.01	3.58	4.95	72.27	9.89	7280	28.61	7210	− 70
239	Sub. bit. A	Wyo.	5.1	0.6	4.9	74.7	13.2	7300	28.81	7260	− 40
240	High vol. C bit.	Mo.	11.77	3.53	4.81	69.65	8.96	7010	27.66	6970	− 40
241	Sub. bit. A	Mont.	13.3	1.1	4.5	66.4	13.3	6440	25.68	6470	+ 30
242	High vol. C bit.	Mo.	12.98	4.22	4.93	67.45	9.30	6870	27.09	6830	− 40
243	Sub-bit. A	Mont.	9.5	1.9	4.8	68.6	13.3	6770	26.80	6750	− 20
244	High vol. C bit.	Iowa	12.76	4.96	4.67	68.07	8.49	6930	27.18	6850	− 80
245	“	Cal.	14.0	—	—	—	—	6280	—	—	—

246	Sub-bit. A	Wash.	12.7	0.7	5.4	66.8	12.8	6660	26.72	6730	+ 70
247	High vol. C bit.	Ill.	14.8	2.9	4.4	68.4	8.8	6780	26.79	6750	− 30
248	Sub-bit.	Colo.	10.0	2.0	4.6	69.4	10.8	6790	27.07	6820	+ 30
249	“	Wash.	8.0	1.2	5.5	69.8	14.0	7070	27.77	7000	− 70
250	“	Wyo.	6.2	0.6	5.3	70.7	15.9	7000	27.66	6470	− 30
251	“	Wyo.	7.9	—	—	—	—	6920	—	—	—
252	“	Ariz.	12.9	0.8	4.9	67.1	13.1	6610	26.30	6630	+ 20
253	High vol. C bit.	Utah	5.1	1.7	5.0	72.0	14.8	7000	27.99	7050	+ 50
254	Sub-bit. A	Wash.	14.6	0.6	5.1	64.8	13.3	6380	25.70	6480	+100
255	High vol. C bit.	Mo.	12.14	5.02	4.55	68.31	8.86	6840	27.11	6830	− 10
256	High vol. C bit.	Iowa	12.9	3.4	4.2	70.5	8.2	6960	27.38	6900	− 60
257	Sub-bit. A	Wash.	11.38	—	—	—	—	6580	—	—	—
258	High vol. C bit.	Iowa	18.4	3.6	4.4	65.2	6.9	6510	25.94	6540	+ 30
259	Sub-bit. A	Wyo.	13.4	2.5	5.0	65.7	12.1	6480	26.18	6600	+120
260	“	Colo.	7.9	0.6	4.8	70.7	14.6	6760	27.26	6870	+110
261	Sub-bit B	Wyo.	7.0	0.9	4.9	72.0	13.9	6940	27.88	7030	+ 90
263	“	Mont.	7.3	0.7	4.8	69.3	16.9	6580	26.62	6710	+130
264	“	Iowa	14.7	5.3	4.3	64.3	8.8	6650	25.56	6440	−210
265	“	Cal.	14.28	—	—	—	—	6040	—	—	—
266	“	Colo.	6.62	0.33	4.75	71.33	15.47	6880	27.32	6880	0
267	“	Wyo.	3.31	—	—	—	—	7160	—	—	—
268	“	Idaho	12.80	—	—	—	—	6310	—	—	—
269	“	Wyo.	3.7	0.8	5.4	73.9	15.0	7090	28.91	7280	+190
270	“	“	3.8	0.4	4.9	72.4	17.0	6960	27.71	6980	+ 20
271	“	Colo.	5.46	0.40	4.63	71.53	16.42	6810	27.20	6850	+ 40
272	“	Idaho	20.36	—	—	—	—	7280	—	6850	—
273	“	Ore.	12.86	—	—	—	—	6030	—	—	—
274	“	Colo.	.42	0.5	4.7	71.3	17.9	6880	27.09	6830	—
275	“	Wyo.	5.6	0.6	5.6	69.3	17.7	6860	27.34	6980	+ 30
276	“	Wash.	12.0	0.5	5.5	65.8	15.0	6380	26.28	6620	+240
277	“	Wyo.	16.6	0.7	4.5	60.7	16.4	5920	23.49	5920	—
278	“	“	7.15	0.92	4.58	70.79	15.24	6670	27.05	6820	+150
279	“	Wash.	7.69	0.55	5.03	66.99	18.33	6480	25.94	6540	+ 60
280	“	Colo.	5.29	0.49	4.66	71.68	16.28	6830	27.30	6880	+ 50

TABLE 59.—(Concluded)

No.	Rank	State	A	S	H	C	O	Exp. Cal.	f	Calcu. Cal.	Dev. ±
281	Sub-bit. B..............	Wyo............	6.8	0.6	5.1	67.0	19.6	6570	25.92	6530	− 40
282	"	"	13.0	1.3	4.0	64.7	15.6	6150	24.45	6160	+ 10
283	Sub-bit. C..............	Mont............	12.23	1.52	4.35	65.95	14.61	6200	25.31	6380	+180
284	"	Wyo............	9.4	0.5	4.5	68.8	15.4	6460	26.05	6610	+150
285	"	"	10.3	—	—	—	—	6340	—	—	—
286	"	Colo............	8.02	0.46	4.61	67.02	18.87	6300	25.49	6420	+120
287	"	Wyo............	9.2	0.8	4.2	66.9	17.6	6210	25.17	6340	+130
288	"	Mont............	16.2	—	—	—	—	5840	—	—	—
289	"	Wash............	15.7	1.4	4.9	58.5	18.4	5740	23.07	5810	+ 70
290	"	Colo............	6.96	0.41	4.57	66.25	21.04	6180	25.01	6300	+120
291	"	Wash............	11.3	3.6	5.3	63.2	15.5	6220	25.49	6420	+200
292	"	Mont............	14.7	0.9	4.2	59.2	19.1	5530	22.49	5670	+140
293	"	Wyo............	8.9	0.8	4.7	68.5	16.1	6470	26.32	6630	+160
294	"	"	10.4	0.8	4.3	67.8	15.5	6230	25.74	6490	+260
295	Lignite.................	N. D............	10.7	2.0	4.2	66.5	15.6	6380	25.32	6380	0
296	"	"	13.1	1.7	3.5	62.0	19.0	5660	22.82	5750	+ 90
297	"	"	12.68	—	—	—	—	6020	—	—	—
298	"	Mont............	21.21	0.78	3.33	56.57	17.35	5220	20.87	5260	+ 40
299	"	N. D............	8.1	1.1	3.6	67.3	18.9	6460	24.63	6210	−250
300	"	Mont............	7.1	—	—	—	—	5340	—	—	—
301	"	Texas............	11.43	1.43	4.46	64.84	16.53	6340	24.89	6270	− 70
302	"	N. D............	10.7	1.1	3.6	65.3	18.3	6180	24.02	6050	−130
303	"	"	9.3	1.4	3.6	64.2	20.4	6150	23.51	5920	−230
304	"	Texas............	14.9	0.8	4.0	61.3	17.5	5970	23.11	5820	−150
305	"	N. D............	6.68	2.13	4.47	63.79	16.79	6060	24.60	6200	+140
306	"	"	9.8	1.2	3.9	65.5	18.5	6300	24.37	6140	−160
307	"	"	12.10	1.80	3.97	64.69	15.55	6130	24.47	6170	+ 40
308	"	S. D............	12.6	3.7	3.2	64.1	15.6	6010	23.69	5970	− 40
309	"	"	13.72	3.65	3.70	62.49	15.57	5760	23.64	5960	+200
310	"	N. D............	8.82	0.79	4.21	64.41	20.66	6130	24.11	6080	− 50

311	Lignite.................	Ark..............	16.03	0.81	4.29	59.98	17.77	5830	22.94	5780	− 50
312	“	N. D.............	16.54	0.35	3.63	59.23	19.28	5290	21.86	5510	+220
313	“	“	9.9	1.0	3.5	65.0	19.7	6040	23.69	5970	− 70
314	“	Mont............	10.51	1.22	4.35	61.71	21.06	5760	23.36	5890	+130
315	“	“	11.5	—	—	—	—	5560	—	—	—
316	“	“	13.1	0.5	3.9	61.2	20.2	5610	22.73	5730	+120

Note: Analytical data from Fieldner, Selvig, and Frederic. Ultimate analyses are not available for coals Nos. 28, 32, 39, 40, 41, 43, 54, 56, 58, 71, 83, 85, 99, 105, 110, 123, 140, 141, 152, 155, 157, 158, 160, 161, 167, 181, 192, 196, 205, 210, 216, 234, 245, 251, 257, 261, 265, 267, 268, 272, 273, 285, 288, 297, 300, and 315. Also available ultimate analyses for coals for closely similar samples were substituted for the following coals, Nos. 29, 1331; 31, 19358; 53, 9604; 70, 20346; 73, 10412; 78, 1262; 80, 14060; 82, 4252; 84, 21019; 86, 22164; 90, 3102; 91, 1297, 94, 2187; 103, 3211; 107, 1567; 108, 3532; 109, 1213; 111, 17456; 126, 537; 129, 21566; 133, 15671; 136, 17465; 138, 3331; 142, 19175; 147, 2083; 170, 17604; 172, 1138; 191, 1470; 201, 1495; 206, 21876; 223, 3979; 230, 21906; 233, 1434; 244, 1437; 301, 2562; 307, 2243; 310, 4276; and 311, 2726.
Calories are calculated from the formula q = 252.f where f = S/10 + H + C/3 — 0.08.0.

ARTICLE 8—MATHEMATICAL ANALYSIS OF BRIQUETTING PHENOMENA

INTRODUCTION

PURPOSE OF INVESTIGATION

When the studies on briquetting without a binder were initiated in 1931, the work was set up as an "Investigation of the physical properties of coal under three variables—temperature, pressure and time." Exploratory investigations in these three fields discovered that under favorable conditions of temperature, pressure, and time the formation of briquets was possible. This possibility has been explored systematically.

SCOPE OF ARTICLE

In order that the significance of the mathematical analysis may be appreciated, the article first describes the equipment and procedure used and the experimental results achieved, thereafter presenting the mathematical basis of the procedure adopted and pointing out the general agreement between theory and practice. Consideration is given (a) to the equipment and procedure for both slow briquetting (5 to 30 minutes) in a hydraulic press and rapid briquetting (0.01 second) in an impact press; (b) to the graphical relationships between density, pressure, temperature, and time in the experimental slow briquetting of various coals in a hydraulic press; and (c) to the mathematical development, in the calculus of briquetting, of relationships between density, pressure, temperature, and the time for briquetting these coals by each of the two methods, that is by the hydraulic press (slow) and by impact (rapid). The article closes with a mathematical analysis of pressure distribution in the Piersol press.

PRACTICAL APPLICATION OF RESULTS

The practical significance of the analysis lies in its usefulness in determining the energy required to produce given quantities of briquets and in designing the briquetting equipment. It becomes evident that the amount of the mechanical energy required decreases with increase in temperature or with increase in time. When the briquetting is done rapidly the power consumption is found to be less than 10 horsepower hours per ton of briquets. A theoretical graph was calculated for the relationship at a briquetting time of 0.008 second; this graph was then substantiated experimentally, thereby sustaining the accuracy of the mathematical analysis. Such substantiation justified the use of the results of the calculus of briquetting for the engineering design of the rotary press which is described in Article 1. Details of this design are available to those interested, upon application to the Survey.

COALS USED IN THE INVESTIGATION

Nine different samples of coal or coal components were tested in this investigation. The samples, and proximate analysis (dry basis) are: (1) Crushed St. Clair County lump coal, 9.2 percent ash, 43.1 percent volatile matter, 47.7 percent fixed carbon; (2) crushed Will County lump coal, 5.3 percent ash, 43.9 percent V.M., and 50.8 percent F.C.; (3) crushed Franklin County lump coal, 7.1 percent ash, 35.9 percent V.M., and 57.0 percent F.C.; (4) crushed Pocahontas (West Virginia) lump coal, 5.0 percent ash, 17.7 percent V.M., and 77.3 percent F.C.; (5) Franklin County deduster dust, 10.8 percent ash, 30.0 percent V.M., and 59.2 percent F.C.; (6) a blend of 75 percent crushed St. Clair County lump coal and 25 percent hand-picked fusain, 7.9 percent ash, 35.2 percent V.M., and 56 percent F.C. (fusain 4.0 percent ash 11.3 percent V.M., and 84.7 percent F.C.; (7) crushed hand-picked vitrain, 8.1 percent ash, 39.3 percent V.M., and 52.6 percent F.C.; (8) crushed hand-picked clarain, 10.3 percent ash, 36.9 percent V.M., and 52.8 percent F.C.; and (9) crushed hand-picked durain, 7.5 percent ash, 40.3 percent V.M., and 52.2 percent F.C.

EQUIPMENT AND PROCEDURE

As stated previously the experimental data and the theory presented in this article are concerned both with relatively slow briquetting in the hydraulic press and very rapid briquetting in a falling-weight impact press. The equipment and procedure used in each type of test is described separately.

Equipment for Slow Briquetting

HYDRAULIC PRESS

The 50,000-pound hand-operated Riehle hydraulic press was used to secure steady pressures. Four different calibrated hydraulic gauges gave accurate pressure with full-scale reading at various pressure ranges.

FURNACE

The heating cells used for preheating the coal were 1.5 inches in diameter and 4 inches long, with one end removable. The electric rotary furnace, in which these cells were heated, had a rotating oven, 8 inches in diameter and 8 inches long. The furnace was equipped with rheostats, ammeters, calibrated thermocouples and milliammeters for accurate temperature regulation.

BRIQUETTING DIES

The briquetting dies were made from heat-treated alloy steel. The inside of the die cylinders and the die plungers were hand polished; the clearance between plunger and cylinder was 0.001 inch or less. The briquetting dies were fitted into a housing which was wound with heating wire; rheostats were used to maintain the temperature of the die at any specified value.

DEPTH GAUGES

Two Ames depth gauges, with dial hands which read directly in units of 0.001 inch, were used to determine the height of the briquet at any instant during various stages of compression.

Equipment for Rapid Briquetting

TURNER IMPACT PRESS

The Turner impact press consisted of a 500-pound hammer with free movement in vertical guides; the hammer was lifted electromagnetically to a desired height up to 6 feet by means of a motor; and an electric switch released the hammer for gravity drop.

ROTARY ELECTRIC PREHEATER

The same preheater was used for heating the coal prior to briquetting in both the impact press and the hydraulic press.

BRIQUETTING DIES

Also the same briquetting dies were used for briquetting in the impact press as in the hydraulic press. However, the dies were clamped, by means of iron straps, to the base of the impact press in order to prevent bouncing of the dies after impact.

CHRONOMETER

A motor-driven rotating drum chronometer served as a timing device; a stylus attached to the falling hammer drew a line on smoked paper placed around the rotating drum.

Procedure for Slow Briquetting

PREPARATION OF COAL SAMPLES

For the 1.5-inch die, the coal was ground to a minus 40 mesh in order to secure uniform samples. For 1-inch die and smaller dies, all the samples, with the exception of Franklin County vitrain, were ground to minus 100 mesh; the vitrain was already ground to minus 200 mesh when received.

BRIQUETTING

Approximately 45-gram samples were used in the 1.5-inch die; 15-gram samples in the 1-inch die; and proportionately smaller samples in the ½-inch and the ⅜-inch dies; these samples were heated in the rotary oven for 10 minutes to the desired temperature; then the sample was transferred to the die maintained at the same temperature as that of the coal; and the desired pressure was applied immediately and held constant for the specified period of time.

DENSITY DETERMINATION

The density of a briquet is its weight per unit volume (grams per cc.). The weight of the briquet was determined after its removal from the die, by means of an analytical balance. The volume of the briquet at any stage during briquetting was calculated from its cross-sectional area and its experimentally determined height within the die, which was measured as follows: the empty die was placed in the press with the lower end of its bottom plunger in contact with the lower press plate and with the lower and the upper ends of its top plunger in contact with the upper end of its bottom plunger and the upper parallel press plate, respectively; then the datum reading (zero thickness of briquet) was obtained by means of the average value of the two Ames depth gauges placed in a vertical position between the press plates and on either side of the die. The datum readings were obtained for various press pressures and die temperatures in order to compensate for the elastic compressibility of the die plungers. Finally the height of the briquet of any thickness was determined as the average reading of the depth gauges less the datum reading for the same pressure and die temperature.

INTERNAL PRESSURE

The procedure in measuring the internal pressure of a briquet during compression at an elevated temperature was based on the secondary pressure of the briquet against the die plungers after its external pressure had been lowered to zero by the rapid opening of the press for the least possible distance; then the value of the internal pressure was recorded as that of the pressure gauge reading after the pressure came to an equilibrium value.

PROCEDURE FOR RAPID BRIQUETTING

PREPARATION OF COAL SAMPLES

The coal was prepared in exactly the same manner as that described for slow briquetting.

BRIQUETTING

The briquetting procedure was identical to that for slow briquetting except that the pressure was obtained by the impact blow of a falling hammer instead of by the hydraulic press.

DENSITY DETERMINATION

The density of the briquet at any instant during its impaction by a falling weight was determined in a manner similar to that used for slow compaction in a hydraulic press except for the method of measurement of its height which was as follows: The hammer was raised to a predetermined distance above the top plunger of the briquetting die, the chronometer started, the hammer released, and the graph of its position and its time marked by stylus on the smoked paper; this graph also recorded the rebound of the hammer after impact of the die and the final position of the hammer resting upon the plunger of the die. The briquet was removed from the die; its height was measured; its density was calculated from its weight and the cross-sectional area of the die. This height served as the datum height for the above final position of the stylus when the hammer was resting upon the plunger of the die; from this information and from the stylus graph the height of the briquet and its resultant density were determined for any time during its impaction.

EXPERIMENTAL RESULTS

FOUR STAGES OF COMPRESSION

The results obtained by the laboratory equipment and procedure indicated that compression of the coal in the formation of the experimental cylindrical briquets proceded through four stages: (1) settling stage, (2) crushing stage, (3) plastic stage, and (4) elastic stage. This behavior of the coal during briquetting is regarded as fundamental, and its actuality is supported by the following representative data:

Four stages of compression were evident in the compaction for 30 minutes of 1.5-inch diameter briquets made from 40-mesh St. Clair County coal at various pressures up to 28,300 pounds per sq. in., and at temperatures of 150°, 300°, and 400° C. (fig. 59 and table 60). Four similar stages are apparent also when 100-mesh coal from the

TABLE 60.—RELATIONSHIP BETWEEN LOGARITHM OF THE DENSITY AND LOGARITHM OF THE TOTAL PRESSURE OF 1.5-INCH BRIQUETS MADE FROM MINUS 40-MESH ST. CLAIR COUNTY COAL AT VARIOUS TEMPERATURES FOR 30 MINUTES

(Figure 59)

150°C					300°C					400°C				
Test No.	Total pressure (lb. per sq. in.)	Log total pressure (lb. per sq. in.)	Density	Log density	Test No.	Total pressure (lb. per sq. in.)	Log total pressure (lb. per sq. in.)	Density	Log density	Test No.	Total pressure (lb. per sq. in.)	Log total pressure (lb. per sq. in.)	Density	Log density
406......	6.43	0.808	0.669	$\bar{1}.825$	401......	6.43	0.808	0.681	$\bar{1}.833$	400......	6.43	0.808	0.726	$\bar{1}.861$
403......	17.8	1.250	0.670	$\bar{1}.826$	402......	17.8	1.250	0.703	$\bar{1}.847$	405......	6.43	0.808	0.764	$\bar{1}.883$
407......	17.8	1.250	0.674	$\bar{1}.829$	389......	51.0	1.708	0.735	$\bar{1}.866$	404......	17.8	1.250	0.833	$\bar{1}.921$
379......	51.0	1.708	0.689	$\bar{1}.838$	388......	118.0	2.072	0.754	$\bar{1}.877$	390......	51.0	1.708	0.943	$\bar{1}.975$
378......	132.0	2.121	0.708	$\bar{1}.850$	387......	226.0	2.354	0.787	$\bar{1}.896$	392......	226.0	2.354	1.025	0.011
377......	202.0	2.305	0.721	$\bar{1}.858$	386......	495.0	2.695	0.855	$\bar{1}.932$	393......	495.0	2.695	1.081	0.034
370......	226.0	2.354	0.734	$\bar{1}.866$	385......	1346.0	3.129	0.932	$\bar{1}.969$	394......	1346.0	3.129	1.157	0.063
371......	495.0	2.695	0.787	$\bar{1}.896$	384......	2692.0	3.430	1.010	0.004	395......	2690.0	3.430	1.220	0.086
372......	808.0	2.907	0.822	$\bar{1}.915$	383......	6057.0	3.782	1.149	0.060	396......	6057.0	3.782	1.276	0.106
373......	1077.0	3.032	0.845	$\bar{1}.927$	382......	10100	4.004	1.211	0.083	399......	13460.0	4.129	1.337	0.126
374......	1346.0	3.129	0.865	$\bar{1}.937$	452......	28300	4.452	1.332	0.125	453......	28300	4.452	1.350	0.130
375......	1883.0	3.275	0.897	$\bar{1}.953$										
376......	2692.0	3.430	0.927	$\bar{1}.967$										
380......	6057.0	3.782	1.023	0.010										
381......	10100.0	4.004	1.100	0.041										
451......	28300.0	4.452	1.274	0.105										

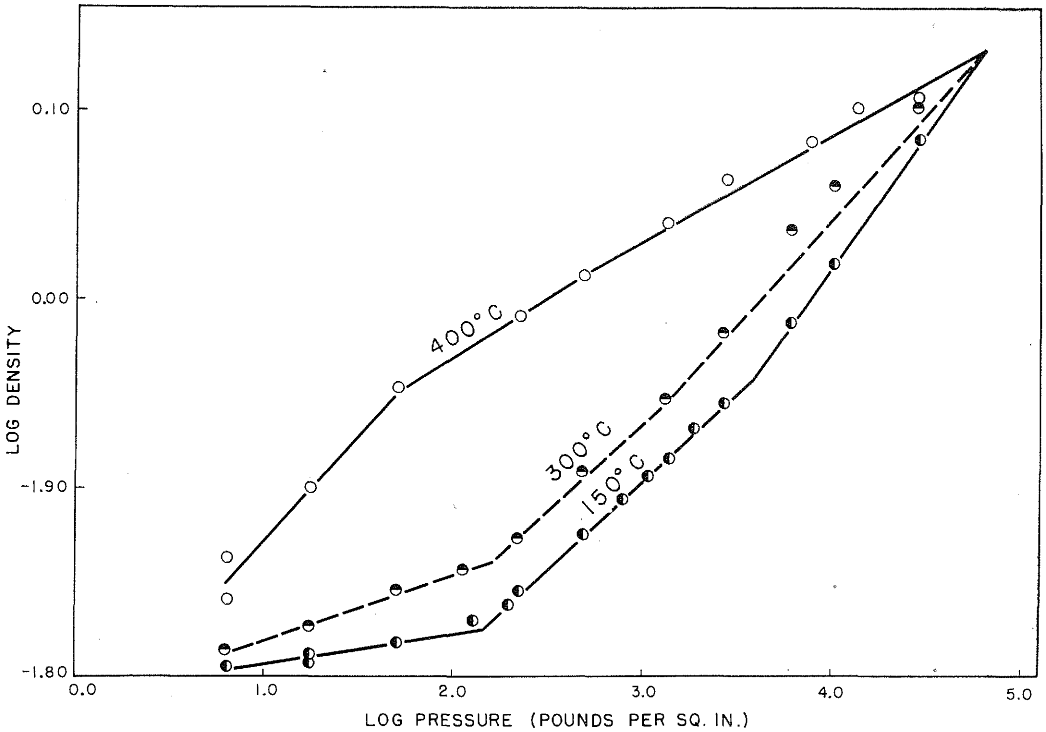

FIG. 59.—Relationship between logarithm of the density and logarithm of the total pressure for St. Clair County 1.5-inch briquets processed at various temperatures for 30 minutes. (Data from table 60)

same source was compressed at various pressures up to 66,800 pounds per sq. in. to make 1-inch diameter briquets.

These two examples illustrate the character of the compression phenomena and are chosen from a large number that are available.

It is more or less incidental but a matter of much importance in the briquetting process, in connection with preheating the coal for 10 minutes prior to briquetting, that there was no tendency for the coal grains to swell or cohere at temperatures below 400° C. Nor at such temperatures was volatile matter liberated in appreciable amounts, although undoubtedly some was freed. Briquetting at temperatures of 400° C. or less will, therefore, not be disturbed by detrimental effects of swelling and of volatile matter discharge, as these phenomena begin at about 425° C.

The general character of the phenomena that take place during the successive four stages are described in detail because these provide the basis for the mathematical analysis of the briquetting process.

SETTLING STAGE

The settling stage of compaction takes place at very low pressures, usually less than 100 pounds per sq. in. The first break in the curves (fig. 59) represents the top pressure values for this zone; the value of which seems to decrease with increase of temperature. The compaction due to settling may be illustrated by the action of increasing the bulk density of a granular material by means of vibration. What occurs is that the grains slide into the arrangement which results in minimum pore space between the grains; for spheres this condition is provided by cannon-ball formation. This phenomenon is so commonly characteristic of settling granular matter that its occurrence in this case seems to be required.

CRUSHING STAGE

The evidence that the coal composing the briquets is actually subjected to crushing is abundantly indicated by the appearance of the coal grains on the polished surface of a sliced briquet. Although some such frac-

Table 61.—Relationship between Logarithm of the Density and Logarithm of the Total Pressure of 1-inch Briquets Made from Minus 100-mesh St. Clair County Coal at Various Temperatures for 30 Minutes

(Data for Figure 60)

20°C

Test No.	Total pressure (lb. per sq. in.)	Log total pressure (lb. per sq. in.)	Density	Log density
529......	42.1	1.624	0.646	—
461......	10000.0	4.000	1.009	—
462......	10000.0	4.000	1.011	—

300° C

Test No.	Total pressure (lb. per sq. in.)	Log total pressure (lb. per sq. in.)	Density	Log density
538......	8.06	0.906	0.621	$\bar{1}.793$
539......	19.68	1.294	0.678	$\bar{1}.831$
532......	42.1	1.624	0.703	$\bar{1}.847$
438......	121.0	2.083	0.740	$\bar{1}.869$
570......	121.0	2.083	0.745	$\bar{1}.872$
437......	362.0	2.559	0.796	$\bar{1}.901$
436......	980.0	2.991	0.894	$\bar{1}.951$
569......	3240	3.511	1.044	0.019
435......	3240	3.511	1.050	0.021
434......	10000	4.000	1.163	0.066
430......	30000	4.477	1.335	0.125
433......	30000	4.477	1.332	0.125
466......	46800	4.670	1.355	0.132
449......	66800	4.825	1.379	0.140

150°C

Test No.	Total pressure (lb. per sq. in.)	Log total pressure (lb. per sq. in.)	Density	Log density
537......	19.68	1.294	0.645	$\bar{1}.810$
530......	42.10	1.624	0.649	$\bar{1}.812$
423......	344.0	2.537	0.747	$\bar{1}.873$
422......	980.0	2.991	0.818	$\bar{1}.913$
447......	980.0	2.991	0.817	$\bar{1}.912$
424......	3079.0	3.488	0.917	$\bar{1}.962$
446......	3240.0	3.511	0.928	$\bar{1}.968$
445......	10000	4.000	1.064	0.027
425......	10170	4.007	1.066	0.028
410......	16060	4.206	1.140	0.057
444......	30000	4.477	1.276	0.106
448......	66800	4.825	1.395	0.145

350° C

Test No.	Total pressure (lb. per sq. in.)	Log total pressure (lb. per sq. in.)	Density	Log density
542......	8.06	0.906	0.651	$\bar{1}.814$
543......	19.68	1.294	0.682	$\bar{1}.834$
533......	42.10	1.624	0.730	$\bar{1}.863$
459......	980	2.991	1.002	0.001
460......	980	2.991	0.987	$\bar{1}.994$

250°C

Test No.	Total pressure (lb. per sq. in.)	Log total pressure (lb. per sq. in.)	Density	Log density
540......	8.06	0.906	0.620	$\bar{1}.792$
541......	19.68	1.294	0.645	$\bar{1}.810$
531......	42.10	1.624	0.669	$\bar{1}.825$
455......	980	2.991	0.871	$\bar{1}.940$
456......	980	2.991	0.873	$\bar{1}.941$

400° C

Test No.	Total pressure (lb. per sq. in.)	Log total pressure (lb. per sq. in.)	Density	Log density
544......	8.06	0.906	0.648	$\bar{1}.812$
545......	19.68	1.294	0.746	$\bar{1}.873$
421......	42.1	1.624	0.940	$\bar{1}.973$
419......	217.0	2.336	1.057	0.024
443......	362.0	2.559	1.087	0.036
418......	408.0	2.611	1.064	0.027
439......	980.0	2.991	1.155	0.063
417......	1591.0	3.202	1.171	0.069
416......	2385	3.377	1.195	0.077
440......	3240	3.511	1.222	0.087
415......	3820	3.582	1.211	0.083
412......	16060	4.206	1.326	0.123
413......	24080	4.382	1.357	0.133
442......	30000	4.477	1.340	0.127
450......	66800	4.825	1.361	0.134

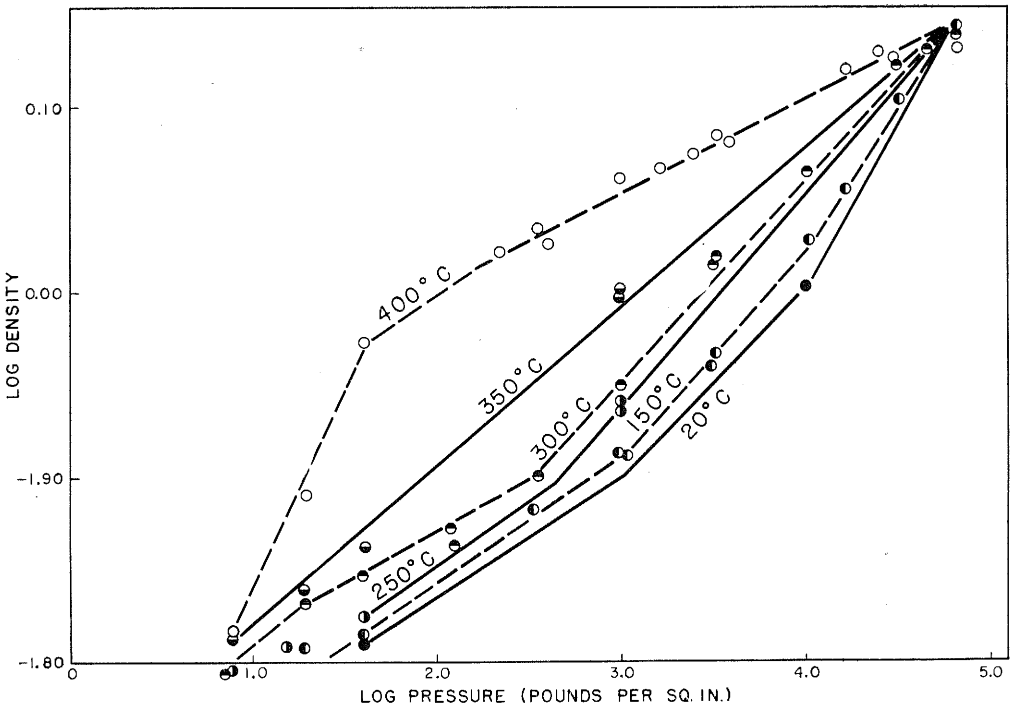

FIG. 60.—Relationship between logarithm of the density and logarithm of the total pressure for St. Clair County 1-inch briquets processed at various temperatures for 30 minutes. (Data from table 61)

ture may have taken place during the settling stage it seems probable that it would tend to follow that stage and thereby eliminate angular protuberances, as suggested in the preceding paragraph.

PLASTIC STAGE

The fact of the relative softness of coal leads to the probability that eventually, as pressure increases, areas of differential pressure within the mass not overcome by crushing will tend to produce flow in the coal, thereby closing all pores both internal and interstitial. The plastic stage is believed to start when the coal has attained a density of less than unity (figs. 59 and 60 for position of second break in the briquetting curves) and ends when all pore space is eliminated. The rate of this adjustment increases as temperature and/or pressure increases.

The actuality of this phenomenon cannot be, or at least has not been, demonstrated by observation at any stage of magnification of polished or thin sections of briquets but it is believed to be demonstrated by the coal's attainment of a state of permanent physical compaction beyond which no further permanent compaction is possible, any additional compaction being of an elastic character from which the coal returns to the permanent condition of compaction, as explained in the following section.

The reader is cautioned against confusing the concept of plasticity—here used as a physical concept—with the concept of "plasticity of coal" which is a condition of fluidity produced by high temperatures such as exist in coke ovens.

ELASTIC STAGE

The stage of elastic deformation starts after pressure and temperature have eliminated all pore space from the coal and with increasing pressure it continues, theoretically, until internal metamorphism produces a permanent fixture of the deformation and forms a higher rank coal which may have the characteristics of anthracite. The density of the coal increases due to its compression as the pressure increases, but theoretically so long as it remains in this stage of elastic deformation measurement shows that the density of the coal always elastically returns to its pore-free density upon release of pressure.

It should be explained that in dealing with pressures of wide range, that is from less than 10 to more than 50,000 pounds per sq. in., plotted logarithmically, the scale in the low range is much exaggerated. However the relative accuracy of observation is the same for low as for high pressures, and, for this reason, small variations in low pressure are not overemphasized in the logarithmic compression graphs.

The fact that anthracite coal has a density greater than that which it has been possible to impose upon bituminous coal, even under the very high pressures that have been applied, suggests the possibility that some still higher pressure may make it possible to produce anthracitization of bituminous coal and the permanent fixation of the high density characteristic of anthracite.

Phenomena of Elastic Deformation

The critical character of the phenomena that takes place within the stage of elastic deformation calls for some consideration of the coefficient of the compressibility of the coal and its significance.

COEFFICIENT OF COMPRESSIBILITY

Compressibility curves (fig. 61, table 62) at a temperature of 250° C. in the stage of elastic deformation for pressures up to 215,000 pounds per sq. in. in a die ½ inch in diameter have been prepared for Franklin, Will, and St. Clair counties coal, for Pocahontas coal, and for hand-picked specimens of vitrain and clarain from St. Clair County coal. In this graph the six curves are essentially parallel. It is evident that the density increases almost linearly with the pressure within this pressure range. At still higher pressures, however, as is shown later, the lines curve downward.

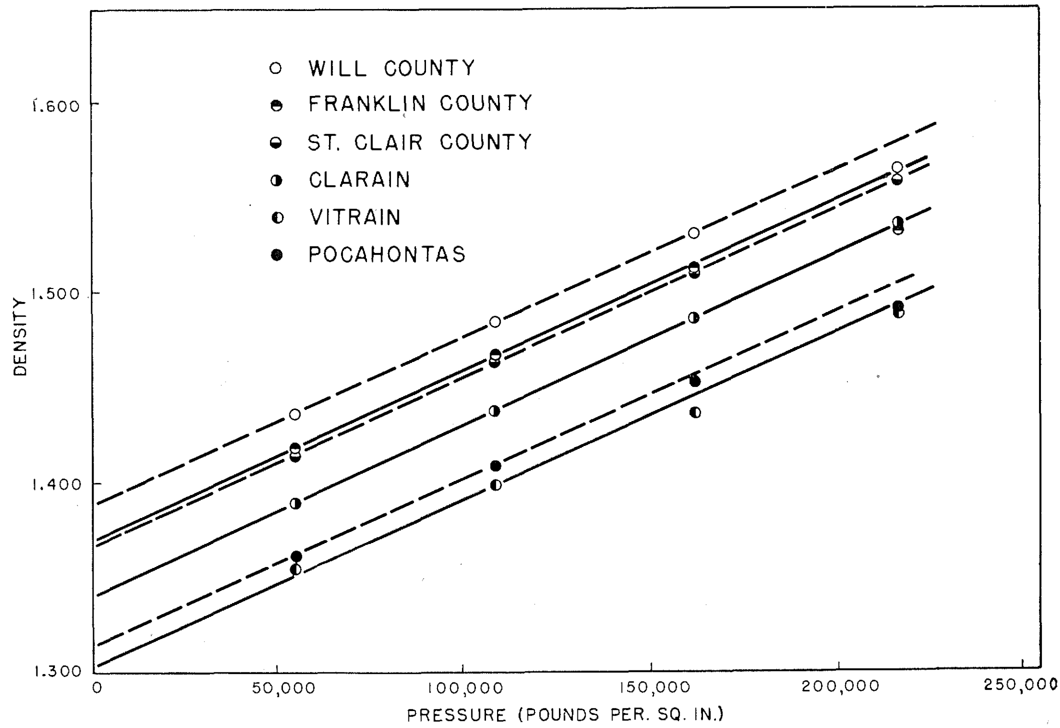

FIG. 61.—Coefficient of compressibility in the elastic zone for briquets made from various coals at 250° C., ½-inch die. (Data from table 62)

TABLE 62.—COEFFICIENT OF COMPRESSION (C.C.) OF VARIOUS COALS AT 250°C.
(Data for Fig. 61)

Pressure		Density[a]					
Lb. per sq. in.	Atmosphere	A	B	C	D	E	F
0	0	1.391	1.372	1.320	1.342	1.315	1.304
50800	3460	1.439	1.420	1.416	1.391	1.362	1.355
116000	7890	1.488	1.469	1.466	1.439	1.411	1.399
152000	10340	1.536	1.517	1.513	1.488	1.455	1.438
230000	15660	1.568	1.536	1.563	1.541	1.496	1.492
Coef. of comp. $\times 10^{-6}$......		80	68	99	82	77	80

[a] A Will County
B Franklin County
C St. Clair County
D Clarain
E Vitrain
F Pocahontas

The coefficient of compressibility of an elastic substance is normally expressed in units of contraction in unit volume per atmosphere (the pressure of one atmosphere is 14.7 pounds per sq. in.) or algebraically the coefficient of compressibility, cc, is

$$cc = (V_0 - V)/V_0\,P \qquad (1)$$

where V is the volume at pressure P, and V_0 is the volume to which the material elastically expands when the pressure is removed. Since the volume of a material varies inversely with its density D, the equation 1 may be written

$$cc = (1/D_0 - 1/D)\ 1/D_0 \times P \qquad (2)$$

This reduces algebraically to the more convenient form

$$cc = (D - D_0)/D \times P \qquad (3)$$

from which it becomes apparent that differences in density and differences in volume are equally appropriate in evaluating compression phenomena.

EFFECTS OF VARIATIONS IN PRESSURE AND TEMPERATURES ON COMPRESSION

LOWER PRESSURES

For pressures ranging from 0 to 15,660 and a temperature of 250° C. the coefficients of compressibility (table 62) range from 68 x 10^{-6} to 99 x 10^{-6} for the six coals listed above. At temperatures 250° and 400° C. in the same pressure range the coefficients of compressibility of hand-picked clarain, which has essentially the character of a finely banded bright coal, increased with the increase in temperature (fig. 62, table 63). This is a common characteristic of hydrocarbons: The accepted values for the coefficients of compressibility of paraffin for the pressure range from 20 to 100 atmospheres (294 to 14,700 pounds) and temperatures of 64° and 100° C. are 84 x 10^{-6} and 107 x 10^{-6} respectively. Thus within a relatively moderate pressure range there is general increase in compression.

HIGHER PRESSURES

As pressures increase up to 31,300 atmospheres (460,110 pounds per sq. in.) by steps the coefficient of compressibility tends to decrease up to at least 230,000 pounds per sq. in. on a ⅜-inch diameter die using St. Clair County coal (figs. 61 and 62). This decrease is not pronounced but it becomes increasingly evident at still higher pressures (fig. 63, table 64).

TEMPERATURE EFFECTS

The determination of the general character of the effect of high pressure upon the compressibility of coal was followed by experimental inquiry concerning the effect of variations in temperature upon compressibility. Investigations at temperatures of 150°, 300°, and 400° C. (fig. 64) indicated that irrespective of temperature the plastic compression as shown in graphs, tended to converge toward a common point, whereas at still higher pressures no such convergence was discovered. In general, also the slope

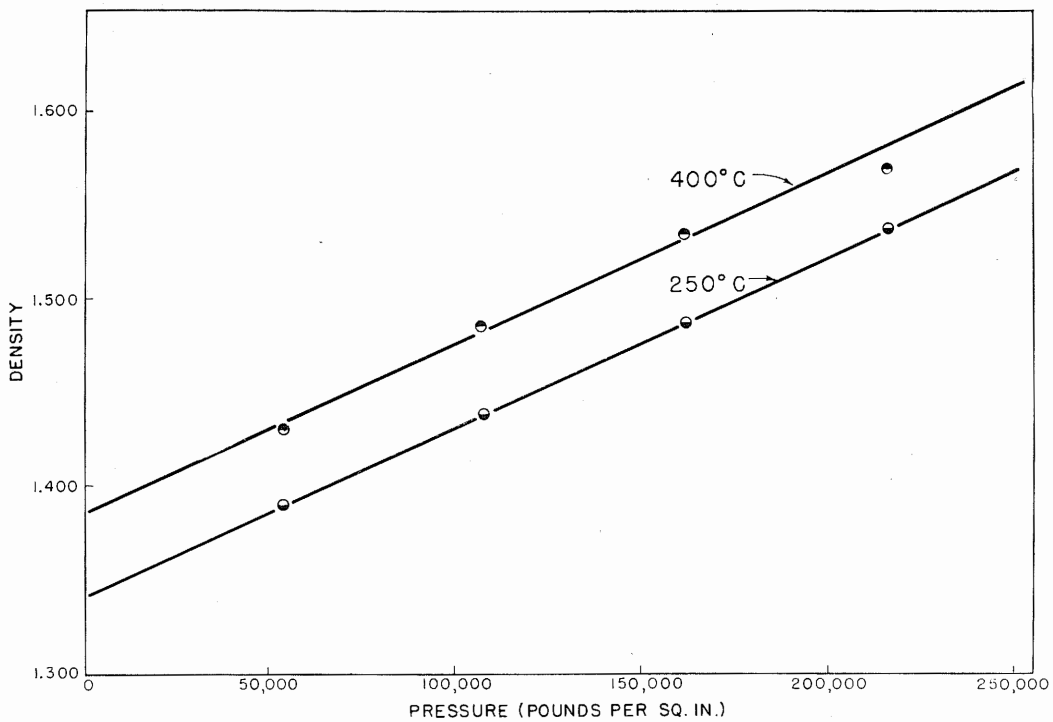

Fig. 62.—Coefficient of compressibility in the elastic zone for briquets of hand-picked clarain, ½-inch die. (Data from table 63)

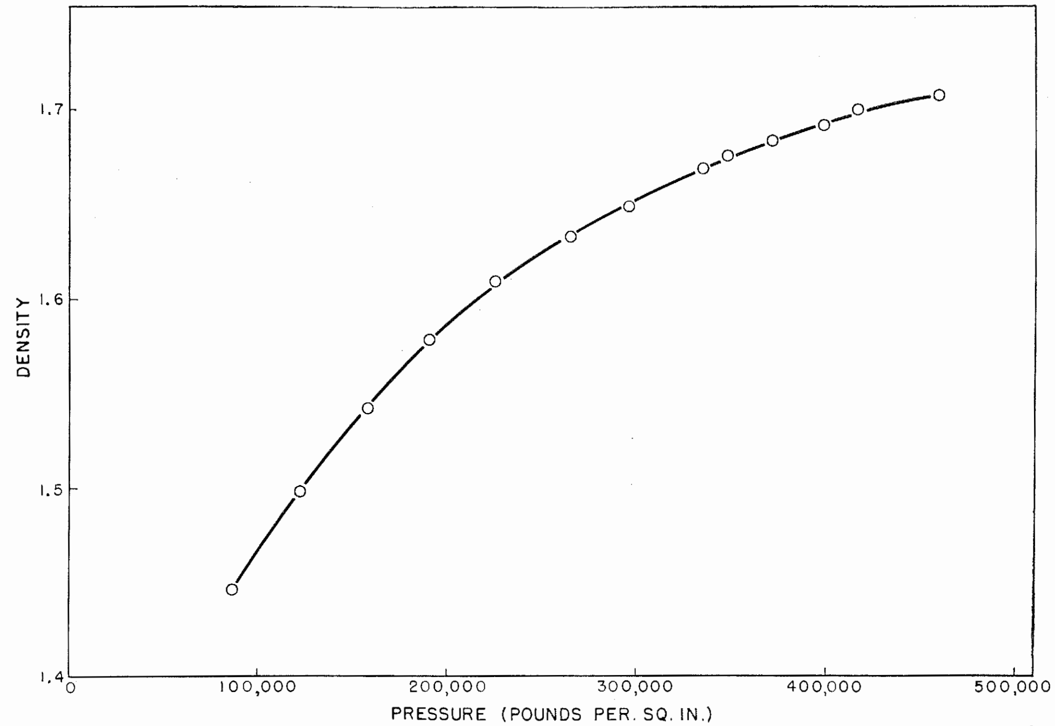

Fig. 63.—Coefficient of compressibility in the elastic zone for briquets of St. Clair County coal at 300° C. and very high pressure, ⅜-inch die. (Data from table 64)

TABLE 63.—INFLUENCE OF TEMPERATURE ON COEFFICIENT OF COMPRESSIBILITY OF HAND-PICKED CLARAIN
(Data for Fig. 62)

Pressure		Temperature	
Lb. per sq. in.	Atmosphere	250°C.	400°C.
0	0	1.342	1.342
50800	3460	1.391	1.433
116000	7890	1.439	1.486
152000	10340	1.488	1.537
230000	15660	1.541	1.572
Coef. of comp. $\times 10^{-6}$		82	93

TABLE 64.—COEFFICIENT OF COMPRESSIBILITY OF ST. CLAIR COUNTY COAL AT VERY HIGH PRESSURE IN 3/8-INCH DIE AT 300°C.
(Data for Figs. 63 and 64)

Pressure		Density	Coef. of Comp. $\times 10^{-6}$
lb. per sq. in.	Atmosphere		
0	0	1.320	
87000	5900	1.445	147
123000	8400	1.498	143
159000	10800	1.542	121
191000	13000	1.578	112
226000	15400	1.609	101
296000	20100	1.632	95
335000	22800	1.648	88
347000	23600	1.669	88
372000	25300	1.675	84
399000	27100	1.683	81
417000	28400	1.700	79
460000	31300	1.706	72

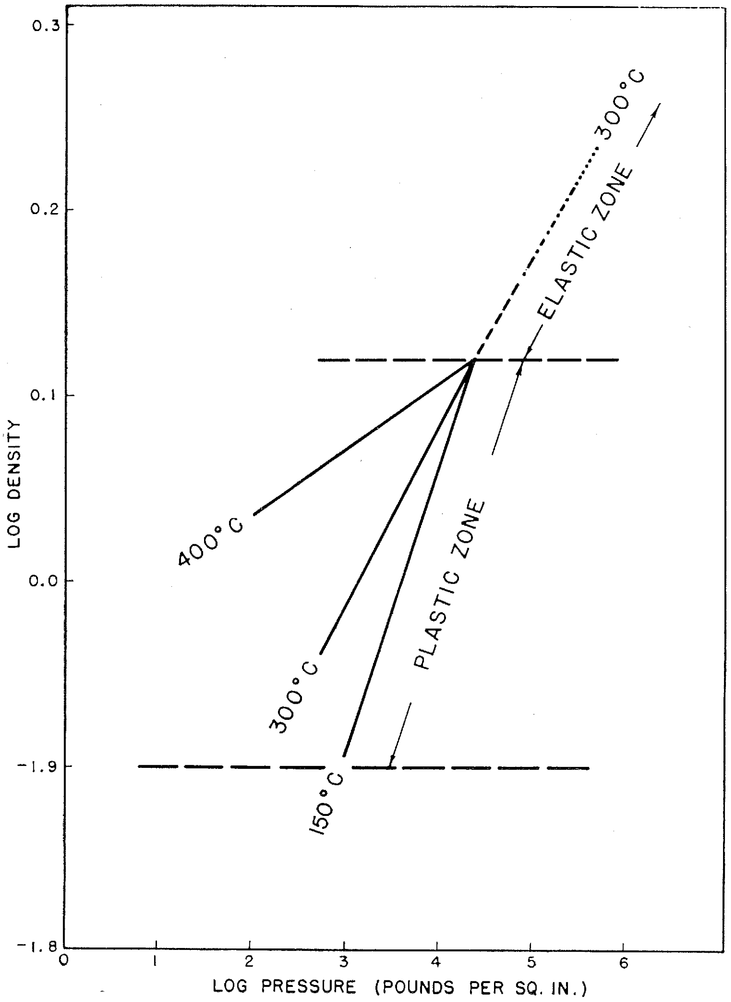

FIG. 64.—Elastic and plastic zones for St. Clair County briquets.
(Data from table 64)

of the coefficient of compressibility curve at the higher pressures was found to be approximately that of the line representing the compressibility at 300° C. at lower temperatures, below the point of convergence. This agreement may have no particular significance, because if no further convergence takes place above the point of first convergence, whatever line is taken to represent the direction of the slope of compressibility will be the extension of some line below the point of convergence.

Significance of Curves

The convergence of the straight-line compression curve (representing the effect of increasing pressures up to a very high amount) indicate that for each coal there is a critical pressure at which the type of compression changes in such a way that thereafter temperature is no longer a factor in the character of the change. This point toward which the coefficient of compression lines converge is regarded as the threshold between plastic and elastic compression or the point where the coal loses all pore space. Except for one line, which happens to be that representing a temperature of about 300° C., the direction of all lines representing changes in the character of compression shows a definite bend at the boundary between the stages of plastic and of elastic compression. Whether or not the interpretation of the phenomenon demonstrated is due to plastic flow or to pore space elimination or to some other cause, it is evident that a change in physical character of the coal takes place at this point.

Compression in Stage of Elastic Deformation

In the range of pressures above the point of convergence of the curves of compressibility, further compression is regarded as representing the elastic stage. In several series of tests, briquets were compressed and released from compression without being removed from the die with pressures up to 230,000 pounds per sq. in. The graphs of various cycles were found to be identical; in each instance after compression the briquet expanded elastically to its pore-free density when this pressure was removed. Possibly at sufficiently high pressure (perhaps in the order of 600,000 to 700,000 pounds per sq. in.) the coal would undergo a molecular rearrangement that would result in a permanent retention of the imposed density, as suggested in an earlier paragraph.

The preceding data on phenomena that are characteristic of coal compression were selected as typical from a large amount of available research results.

SPECIAL PHENOMENA OF STAGE OF PLASTIC DEFORMATION

Internal pressure.—In a cylindrical briquet the dynamic pressure is applied by a top movable plunger and the fixed side wall of the die. When gaseous pressure is created inside a plastic, such pressure tends to cause the plastic to swell owing to the formation of air cells within the plastic. When hot pulverized coal is confined under pressure in a tightly fitting die, the internal gases create an outward pressure as the briquet is being formed, counteracting the externally applied pressure; the pressure which is effective in the formation of the briquet is therefore the difference between the externally applied pressure and such internal pressure as may exist.

A study of the internal pressure for 1-inch St. Clair County cylindrical briquets, formed at temperatures of 150°, 300°, and 500° C., and at external pressures ranging from 1000 to 46,800 pounds per sq. in. (fig. 65, table 65), reveals that the internal

Table 65.—Relationship between Internal Pressure and Temperatures for Various External Pressures for 1-inch Briquets Made from St. Clair County Coal
(Data for Fig. 65)

External pressure (lb. per sq. in.)	Temperature °C.		
	150	300	400
1000	290	390	400
3200	710	720	730
10000	1080	1100	1110
30000	2160	2460	2480
46800	3360	3770	3800

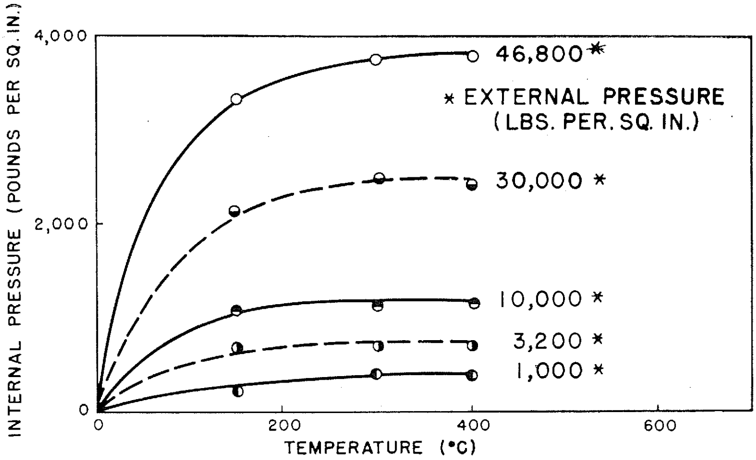

FIG. 65.—Relationship between internal pressure and temperatures for various external pressures for St. Clair County briquets. (Data from table 65)

pressure within this temperature range increases only slightly with increase of temperature above steam temperature (100° C.), but that with increase of external pressure in general there is rapid increase in internal pressure.

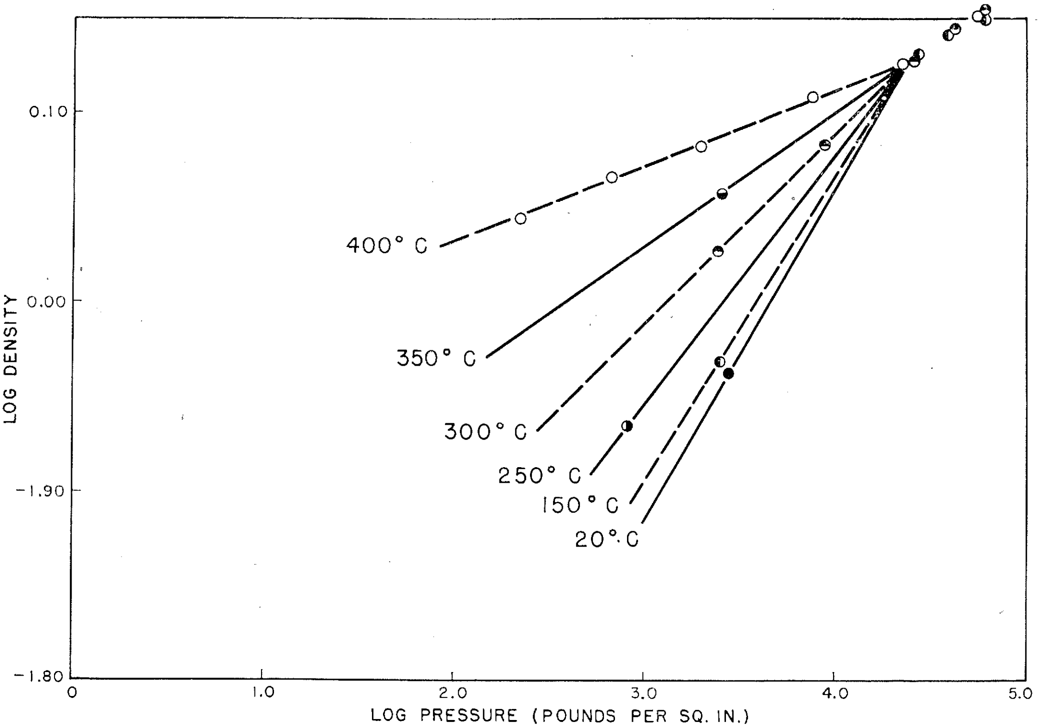

FIG. 66.—Relationship between logarithm of the density and logarithm of the pressure for St. Clair County briquets processed at various temperatures for 30 minutes. (Data from table 66)

TABLE 66.—RELATIONSHIP BETWEEN LOGARITHM OF THE DENSITY AND THE LOGARITHM OF THE PRESSURE OF 1-INCH BRIQUETS MADE FROM MINUS 100-MESH ST. CLAIR COUNTY COAL AT VARIOUS TEMPERATURES AND TIMES

(Data for Figs. 66, 67, 68, and 69)

Temp. °C.	Test No.	Total Pressure (lb. per sq. in.)	Internal Pressure (lb. per sq. in.)	Effective Pressure (lb. per sq. in.)	Log Effective Pressure (lb. per sq. in.)	5 Min.		10 Min.		20 Min.		30 Min.	
						Density	Log density	Density	Log density	Density	Log density	Density	Log density
400........	443	362	138	229	2.3598	0.958	$\bar{1}$.9814	1.028	0.0120	1.064	0.0239	1.158	0.0637
400........	439	980	307	673	2.8280	1.034	0.0145	1.088	0.0366	1.124	0.0508	1.162	0.0652
400........	440	3240	1240	2000	3.3010	1.119	0.0488	1.163	0.0656	1.184	0.0734	1.209	0.0824
400........	454	10000	2220	7780	3.8910	1.251	0.0973	1.256	0.0990	1.263	0.1014	1.269	0.1035
400........	442	30000	5940	24060	4.3813	1.308	0.1166	1.312	0.1189	1.317	0.1196	1.318	0.1199
400........	450	66800	6100	60700	4.7832	1.379	0.1395	1.380	0.1399	1.384	0.1411	1.384	0.1411
350........	468	3240	725	2515	3.4005	1.079	0.0330	1.103	0.0426	1.122	0.0500	1.141	0.0573
300........	435	3240	790	2450	3.3892	1.022	0.0095	1.034	0.0145	1.044	0.0187	1.060	0.0253
300........	434	10000	1140	8860	3.9474	1.189	0.0752	1.201	0.0795	1.203	0.0803	1.210	0.0828
300........	433	30000	2800	27200	4.4346	1.314	0.1186	1.317	0.1196	1.318	0.1199	1.322	0.1212
300........	466	46800	2670	44130	4.6447	1.391	0.1433	1.393	0.1440	1.395	0.1446	1.396	0.1449
300........	449	66800	2130	64670	4.8107	1.419	0.1520	1.421	0.1526	1.423	0.1532	1.429	0.1550
250........	455	980	160	820	2.9138	0.826	$\bar{1}$.9169	0.842	$\bar{1}$.9253	0.856	$\bar{1}$.9325	0.860	$\bar{1}$.9345
150........	446	3240	695	2545	3.4057	0.856	$\bar{1}$.9624	0.920	$\bar{1}$.9638	0.923	$\bar{1}$.9652	0.926	$\bar{1}$.9666
150........	444	30000	2130	27870	4.4451	1.348	0.1297	1.351	0.1306	1.352	0.1310	1.353	0.1313
150........	465	46800	3340	43460	4.6381	1.370	0.1367	1.372	0.1374	1.374	0.1380	1.369	0.1396
150........	448	66800	2730	64070	4.8067	1.395	0.1446	1.398	0.1455	1.403	0.1471	1.404	0.1474
20........	469	3240	440	2800	3.4472	0.905	$\bar{1}$.9566	0.908	$\bar{1}$.9581	0.911	$\bar{1}$.9595	0.915	$\bar{1}$.9614

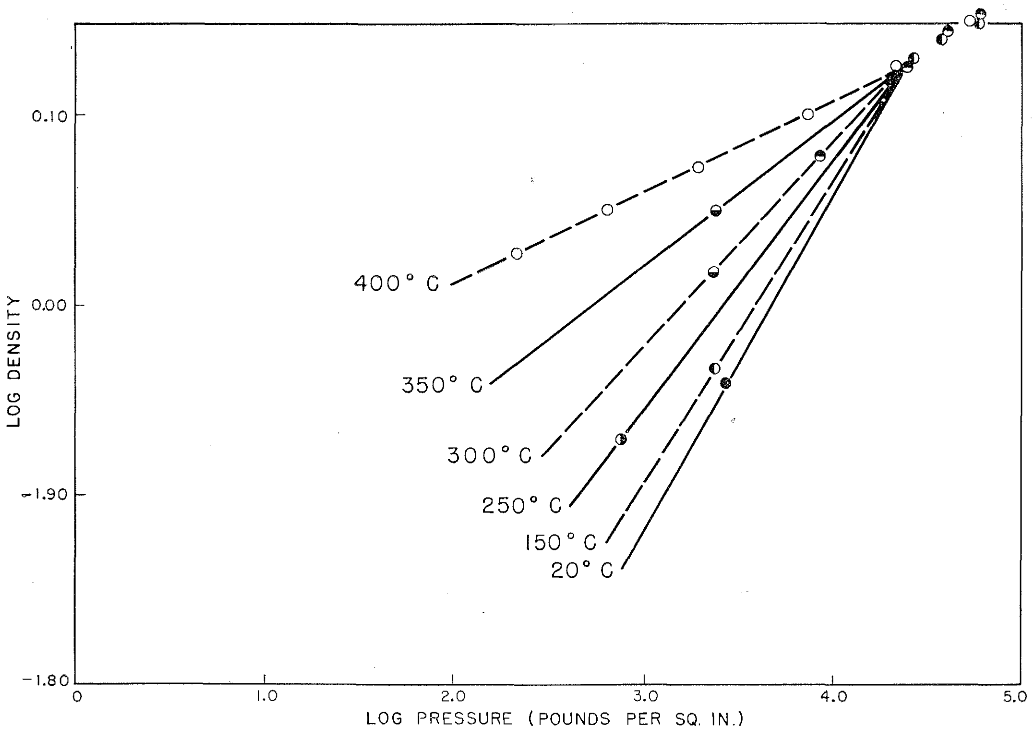

FIG. 67.—Relationship between logarithm of the density and logarithm of the pressure for St. Clair County briquets processed at various temperatures for 20 minutes. (Data from table 66)

CRITICAL PRESSURE AND PORE-FREE DENSITY

EXPERIMENTAL RESULTS WITH ST. CLAIR COUNTY COAL

The continuation of pressure to amounts beyond that necessary to eliminate space (plastic deformation) does not contribute materially to the formation of dense briquets because such extra-compressed briquets immediately expand elastically to their pore-free density when the pressure is removed. St. Clair County coal was subjected to briquetting pressures from 362 to 66,800 pounds per sq. in., at temperatures of 20°, 150°, 250°, 300°, 350°, and 400° C. (table 66). The resulting briquet density was determined while subjected to these conditions for periods of time of 5, 10, 20 and 30 minutes. The effective briquetting pressure was calculated as the total pressure less the internal pressure. Effective pressures and densities were determined in corresponding logarithmic values for convenience in preparing graphs to illustrate the relationships (figs. 66, 67, 68 and 69). The figures show a straight-line relationship between the logarithm of the density and the logarithm of the effective pressure for the various temperatures and periods of time. Furthermore each family of curves (fig. 66) meets at a common point. At this point the density is 1.320 and the pressure is 25,100 pounds per sq. in. This density is herein designated the critical density and the pressure the critical pressure. The critical density is the pore-free density of the briquet.

It may be observed also that curves based on a variety of conditions of temperature and of briquetting periods (figs. 67, 68 and 69) likewise meet at the same critical density and at the same critical pressure.

MATHEMATICAL ANALYSIS

The equation of any one family of lines may be expressed algebraically

$$\log D \times \log D_c = N [\log P \times \log P_c] \tag{4}$$

where D and D_c are any density and the

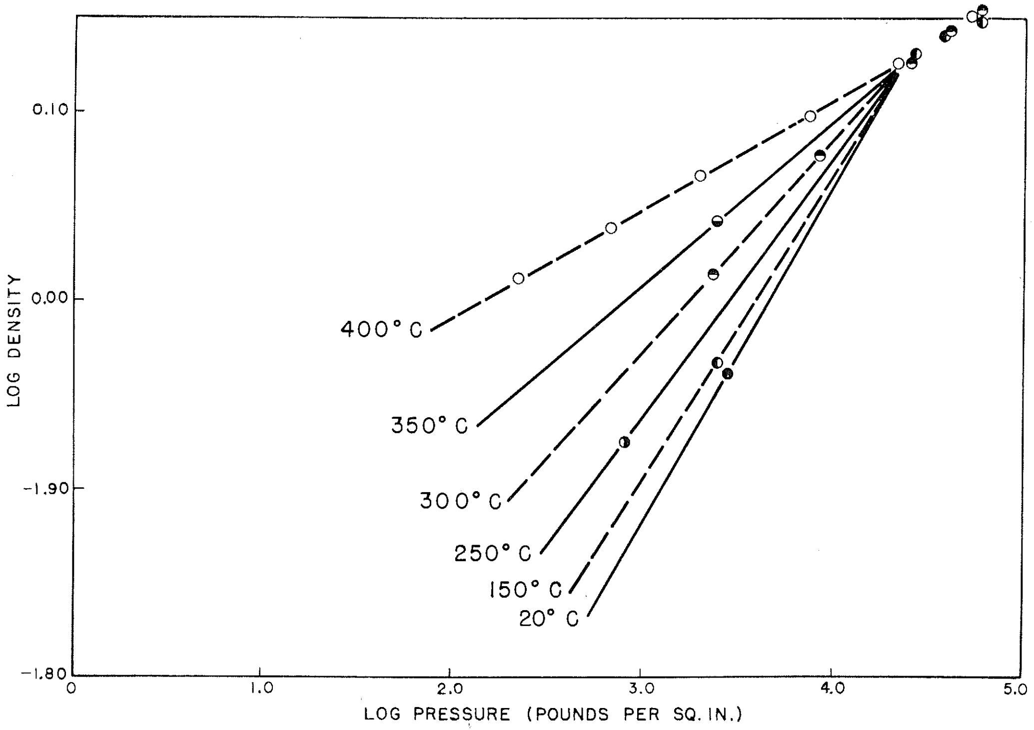

FIG. 68.—Relationship between the logarithm of the density and logarithm of the pressure for St. Clair County briquets processed at various temperatures for 10 minutes. (Data from table 66)

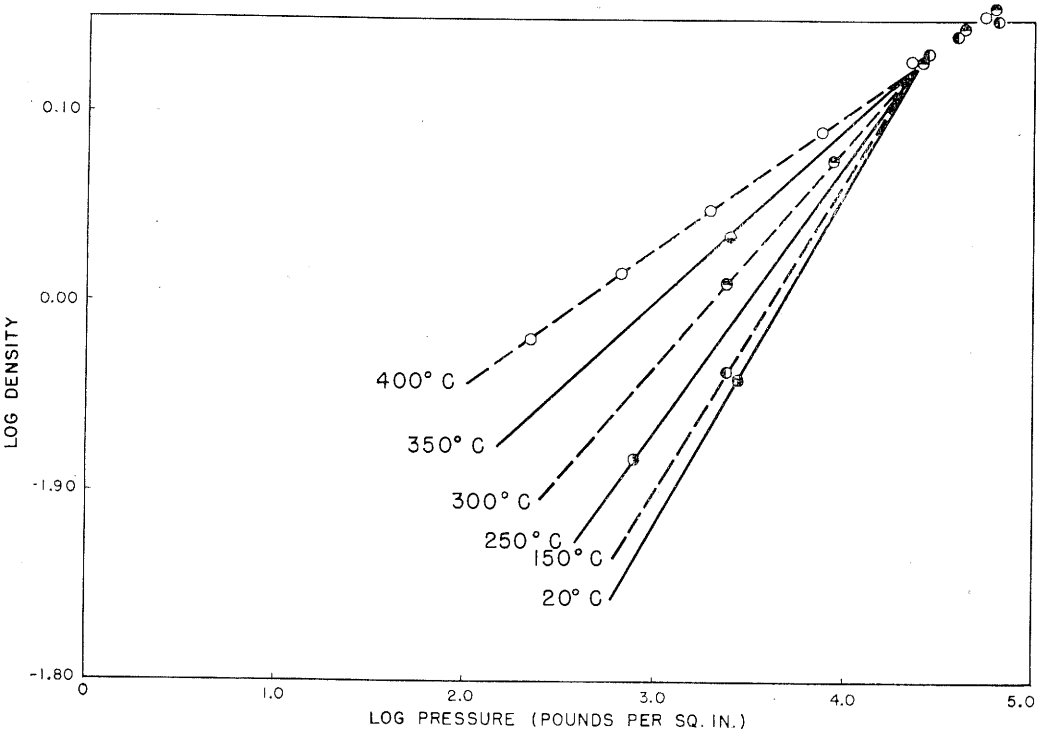

FIG. 69.—Relationship between logarithm of the density and logarithm of the pressure for St. Clair County briquets processed at various temperatures for 5 minutes. (Data from table 66)

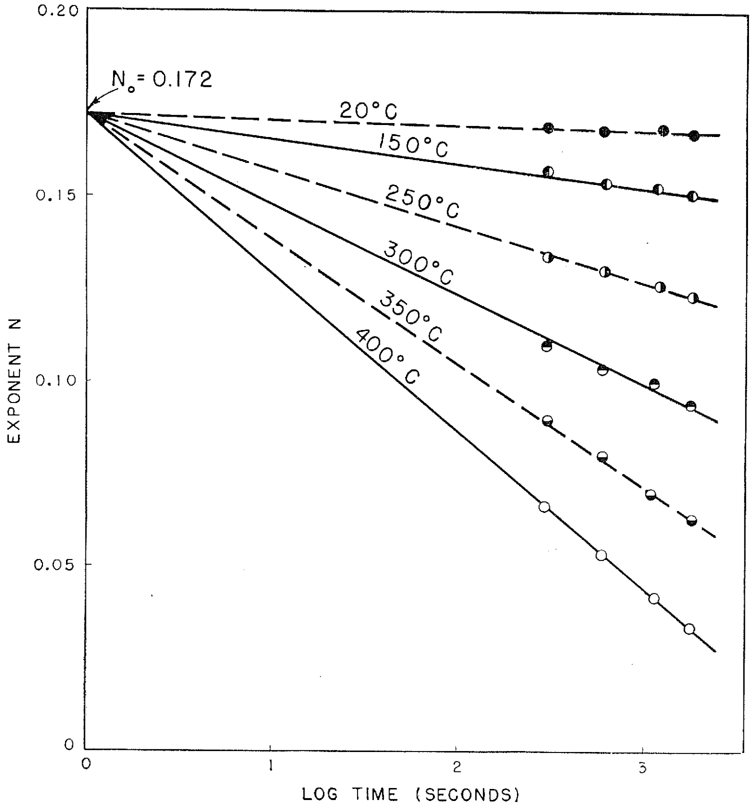

FIG. 70.—Influence of processing time on St. Clair County briquets. (Data from table 67)

critical density, respectively, and where P and P_c are any pressure and the critical pressure, respectively, and N is the slope of the line. Transposed to non-logarithmic form, equation 4 becomes

$$D = D_c\,(P/P_c)^N \qquad (5)$$

and it is now seen that the slope of the line N may be considered as the pressure exponent N.

TABLE 67.—DATA FOR EXPONENT N IN BRIQUETTING EQUATION FOR VARIOUS TEMPERATURES AND VARIOUS BRIQUETTING PERIODS OF TIME FOR ST. CLAIR COUNTY BRIQUETS
(Data for Fig. 70)

Temperature (°C.)	Logarithm briquetting time (seconds)			
	2.4771	2.7781	3.0792	3.2553
20	0.169	0.168	0.168	0.167
150	0.157	0.154	0.152	0.150
250	0.134	0.130	0.126	0.123
300	0.110	0.104	0.100	0.094
350	0.090	0.080	0.070	0.063
400	0.076	0.053	0.043	0.034

INFLUENCE OF TIME ON BRIQUET DENSITY

EXPERIMENTAL RESULTS WITH ST. CLAIR COUNTY COALS

Inspection of the data assembled for the St. Clair County coals (figs. 66, 67, 68 and 69, and also fig. 70) shows a straight-line relationship between the exponent N and the logarithm of the time for various temperatures, and that these lines also meet at a common point (N_o) which for St. Clair County coals is 0.172 and log t equals zero (time equals 1 second).

MATHEMATICAL ANALYSIS

This relationship may be expressed algebraically

$$N = N_o - M \log t \qquad (6)$$

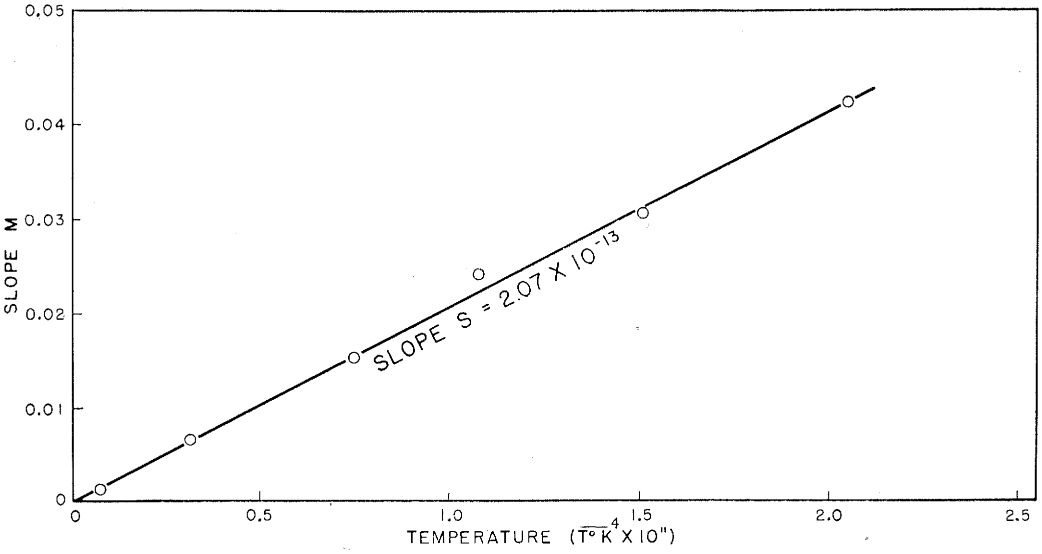

FIG. 71.—Influence of temperature on slope S for St. Clair County briquets ($N_o = 0.172$). (Data from table 68)

where M is the slope of a line in the family of curves, the value of M being different for each temperature.

The slope M may be obtained by use of equation 6; to illustrate find slope M for St. Clair County coal at 400° C. and 30 minutes (log 1800 seconds equals 3.2553). From figure 70, N_0 equals 0.172; and from table 8, N equals 0.034; therefore from equation 6

$$M = \frac{0.172 - 0.034}{3.2553} = 0.0424 \qquad (7)$$

TABLE 68.—DATA FOR SLOPE S IN BRIQUETTING EQUATION FOR VARIOUS TEMPERATURES AND VARIOUS BRIQUETTING PERIODS OF TIME FOR ST. CLAIR COUNTY BRIQUETS

(Data for Fig. 71)

Temperature			Slope M
°C	°K	(°K)×10''	
20	293	0.08	0.0012
150	423	0.32	0.0065
250	523	0.75	0.0152
300	573	1.08	0.0239
350	623	1.51	0.0305
400	673	2.05	0.0424

Figure 71 (data from table 68), which presents the data on the relationship of slope M and the temperature, reveals a straight-line relationship between the slope M and the fourth power of the absolute temperature (degrees Kelvin, written °K).

The equation for this curve (fig. 71) may be expressed algebraically

$$M = S \times \overline{T°K}^{4} \qquad (8)$$

where S is the slope of the line, with a numerical value of 2.07 x 10^{-13} for St. Clair County coal.

GENERAL BRIQUETTING EQUATION

The slope S may be obtained by the use of equation 8. To illustrate: Find slope S for St. Clair County coal. The temperature of 400° C. is 673° Kelvin and from table 64 the slope M at 400° C. is 0.0424; therefore from equation 8

$$S = \frac{0.0424}{[673]^4} = 2.07 \times 10^{-13} \qquad (9)$$

From equation 6 and 8

$$N = N_o - S \times \overline{T°K}^{4} \log t \qquad (10)$$

And from equations 5 and 10

$$D = D_c \left[P/P_c\right]^{N_o - S \times \overline{T°K}^{4} \log t} \qquad (11)$$

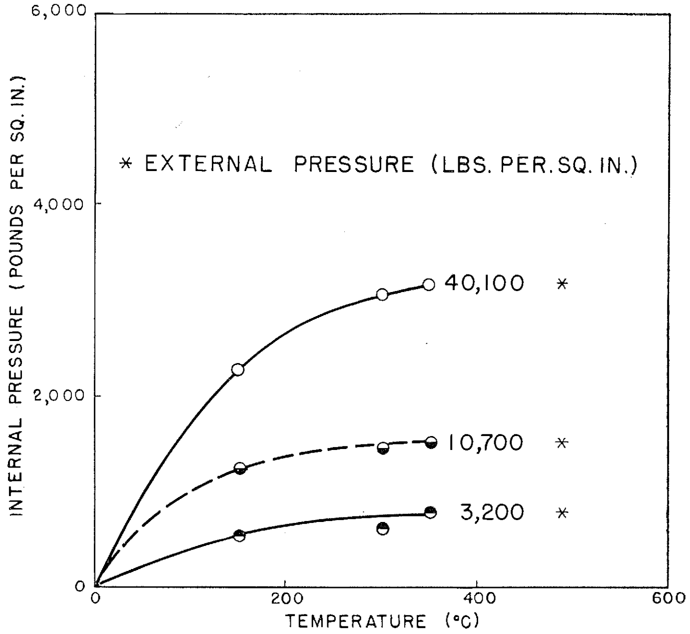

FIG. 72.—Relationship between internal pressure and temperatures for various external pressures on Will County briquets.

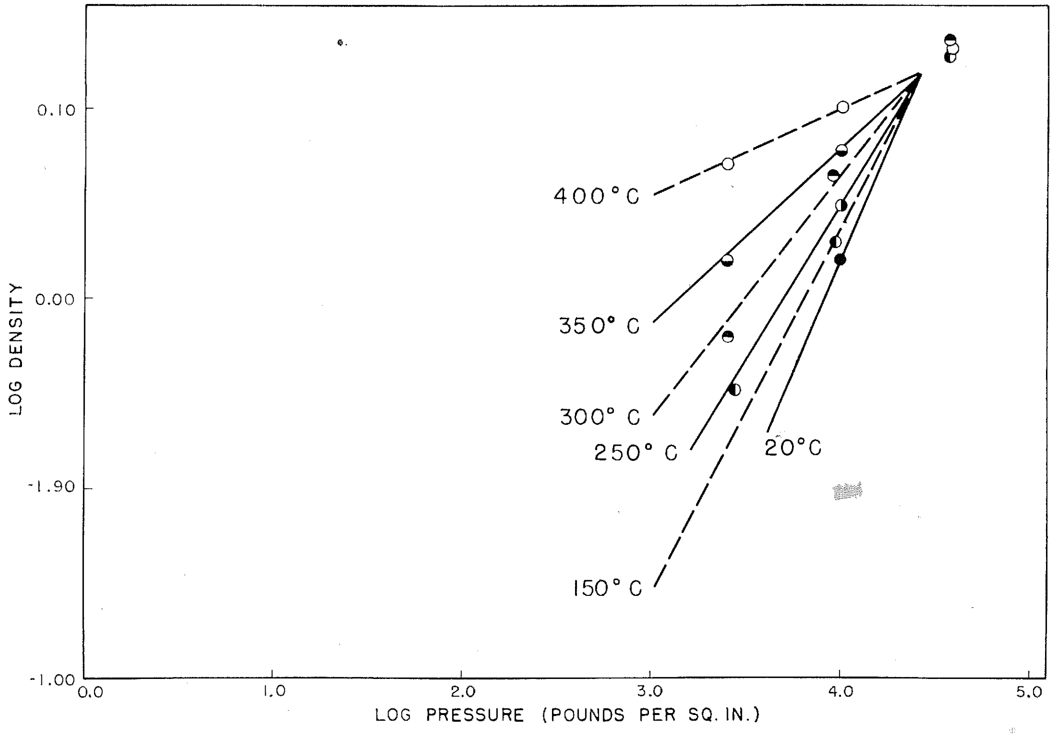

FIG. 73.—Relationship between logarithm of the density and logarithm of the pressure for Will County briquets processed at various temperatures.

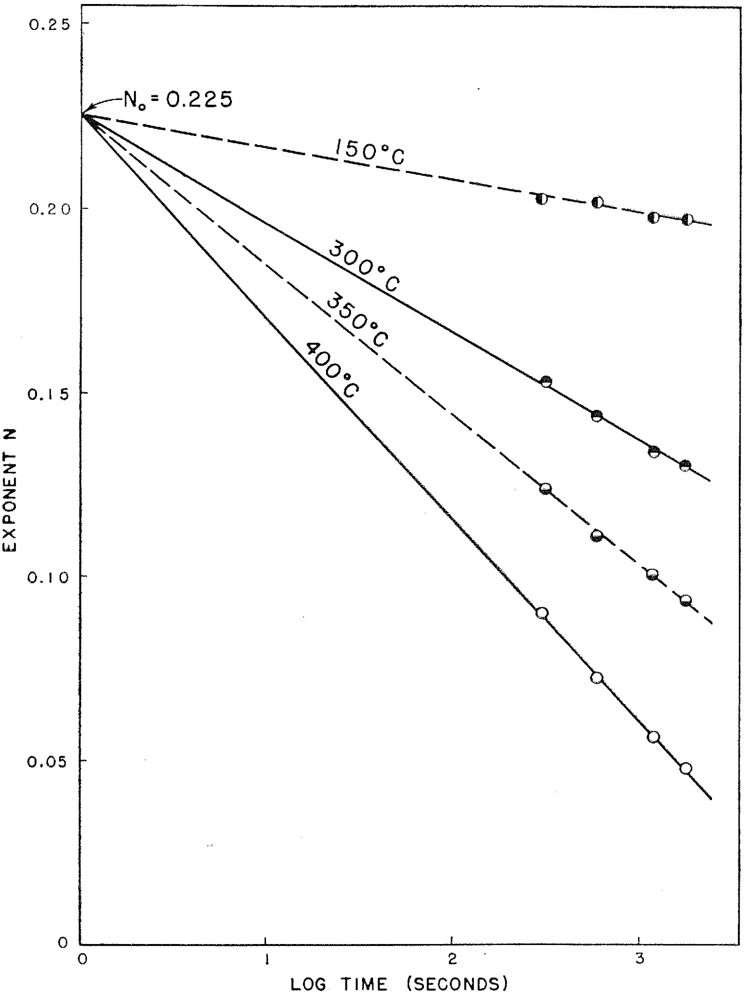

FIG. 74.—Influence of time on exponent N for Will County briquets.

which is the general briquetting equation for bituminous coals; this equation provides the relationship between density, pressure, temperature, and time for obtaining a pore-free briquet from coal (crushed or lump) with D_c, P_c, N_0 and S characteristic of any coal (and necessary to be determined experimentally).

NUMERICAL CONSTANTS FOR RELATIONSHIPS OF PRESSURE, TEMPERATURE, AND TIME

Using the same procedure that has been presented for St. Clair County briquets, a study was made of the briquetting properties of Will County coal, Franklin County coal, Pocahontas coal, Franklin County deduster dust, a blend of fusain and coal, and hand-picked vitrain and hand-picked durain. For sake of brevity, the data are presented only in graphic form. The information for each coal includes (a) internal-pressure graph, (b) density-pressure graph for various temperatures, (c) the time graph, and (d) the temperature graph. This presentation will be followed by a tabulation of briquetting constants for the 8 coals, the values of which are obtained from the graphs.

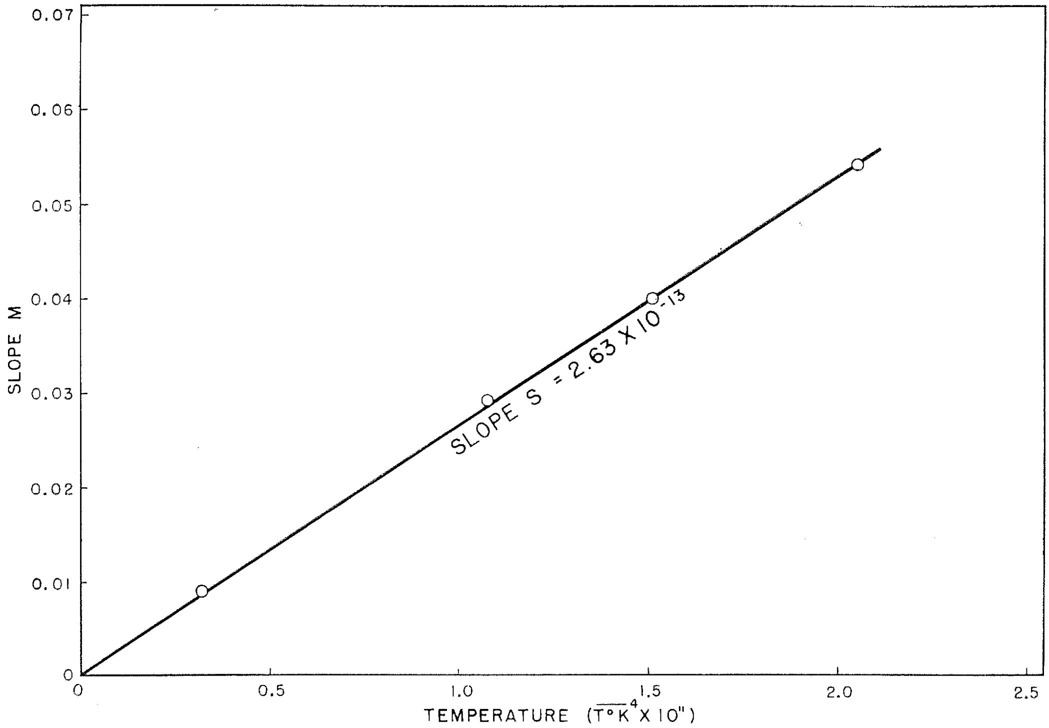

FIG. 75.—Influence of temperature on slope S for Will County briquets. ($N_o = 0.225$)

WILL COUNTY BRIQUETS

Figures 72, 73, 74 and 75 which are graphs for Will County briquets, reveal their numerical constants as follows: D_c, 1.320; P_c, 25,100; N_o, 0.225; and S, 2.63 $\times 10^{-13}$.

FRANKLIN COUNTY BRIQUETS

The corresponding graphs for Franklin County briquets (figs. 76, 77, 78, and 79) provide constants as follows: D_c, 1.380; P_c, 44,700; N_o, 0.165; and S, 1.32 $\times$ 10^{-13}.

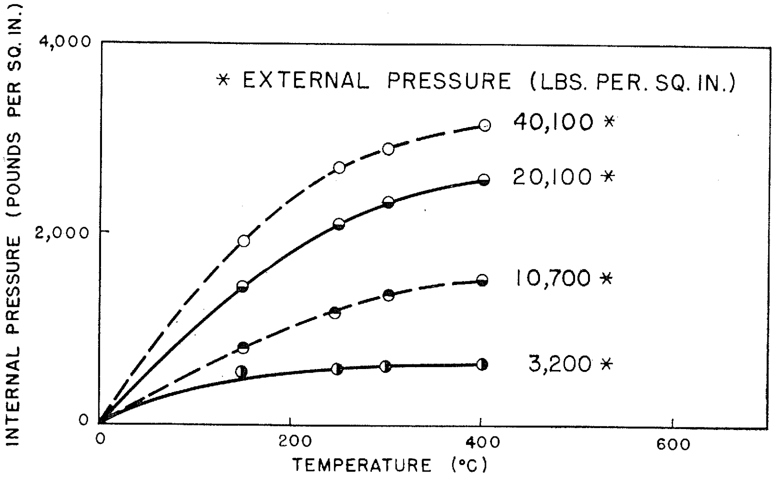

FIG. 76.—Relationship between internal pressure and temperature for various external pressures for Franklin County briquets.

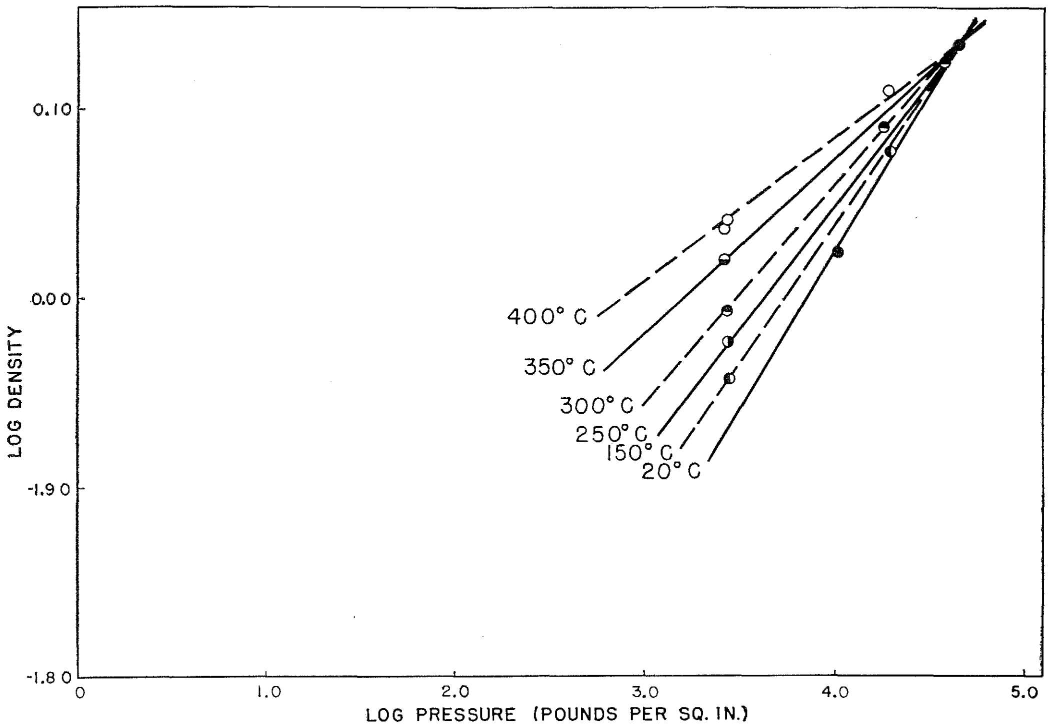

FIG. 77.—Relationship between logarithm of the density and logarithm of the pressure at various temperatures for Franklin County briquets.

POCAHONTAS BRIQUETS

Figures 80, 81, 82 and 83 provide constants as follows: D_c, 1.380; P_c, 56,200; N_o, 0.150; and S, 1.01 $\times$ 10^{-13}.

FRANKLIN COUNTY DEDUSTER DUST BRIQUETS

The graphs for Franklin County deduster dust briquets (figs. 84, 85, 86, 87) provide constants as follows: D_c, 1.400; P_c, 50,100; N_o, 0.142; and S, 1.06 $\times$ 10^{-13}.

ST. CLAIR COUNTY FUSAIN BLEND BRIQUETS

The graphs for briquets made from a blend of 25 percent fusain and 75 percent St. Clair County coal (figs. 88, 89, 90 and 91) provide constants as follows: D_c, 1.380; P_c, 39,800; N_o, 0.168; and S, 2.13 $\times$ 10^{-13}.

FRANKLIN COUNTY VITRAIN BRIQUETS

The graphs for Franklin County vitrain briquets (figs. 92, 93, 94 and 95) provide constants as follows: D_c, 1.270; P_c, 35,500; N_o, 0.200; and S, 2.05 $\times$ 10^{-13}.

FRANKLIN COUNTY DURAIN BRIQUETS

The graphs for Franklin County durain briquets (figs. 96, 97, 98 and 99) provide constants as follows: D_c, 1.290; P_c, 31,600; N_o, 200; and S, 2.68 $\times$ 10^{-13}.

SUMMARY OF EXPERIMENTAL CONSTANTS

The experimental values of the pressure exponent N at various temperatures, and the intercept N_o for the eight coals have been tabulated (table 69) and graphs have been prepared showing slopes and intercepts of the curves (figs. 70, 74, 78, 82, 86, 90, 94, and 98). For the same coals the experimental values of the slope M at various temperatures and the temperature slope S have been tabulated (table 70) and graphs have been prepared showing the slope M and the slope S (figs. 71, 75, 79, 83, 87, 91, 95, and 99). Finally tabulation

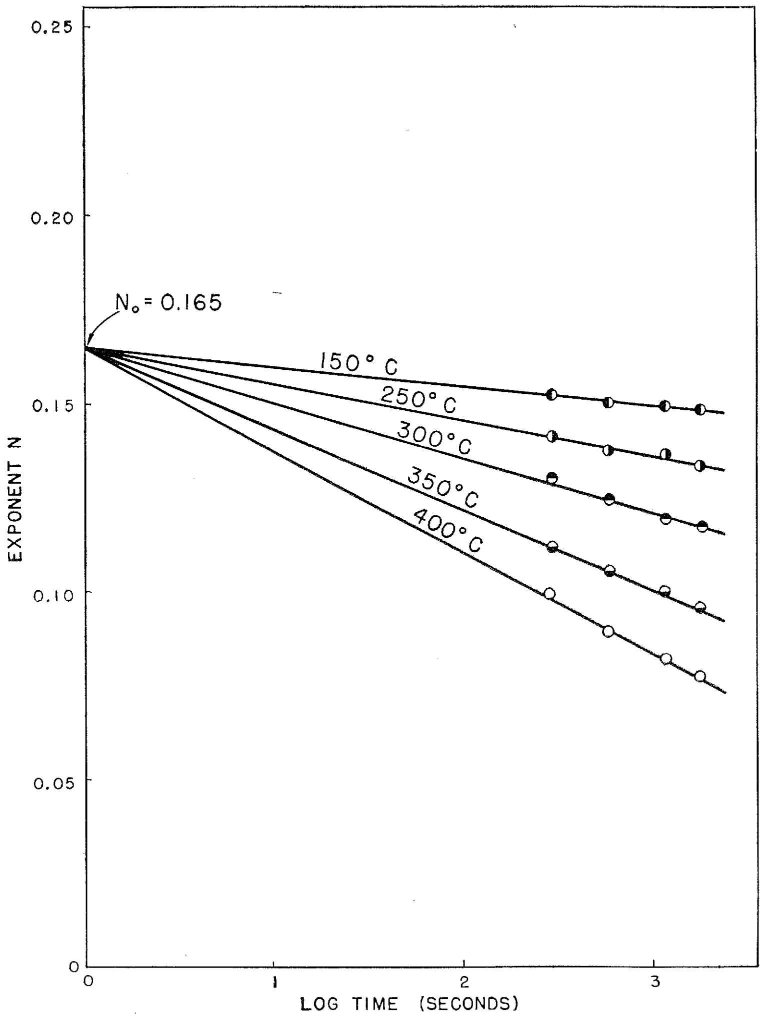

FIG. 78.—Influence of time on exponent N for Franklin County briquets at various temperatures.

TABLE 69.—DATA FOR EXPONENT N IN BRIQUETTING EQUATION FOR VARIOUS TEMPERATURES AND 30-MINUTE PERIODS FOR VARIOUS BRIQUETS
(Data from Figs. 66, 73, 77, 81, 85, 89, and 93)

Temp. °C	Coals[a]							
	A	B	C	D	E	F	G	H
20	0.167	—	—	0.148	—	—	—	—
150	0.150	0.197	0.148	0.137	0.132	0.146	0.177	0.169
250	0.123	—	0.133	0.123	—	—	—	—
300	0.094	0.130	0.117	0.113	0.100	0.094	0.129	0.103
350	0.063	0.094	0.095	0.103	—	—	—	0.067
400	0.034	0.048	0.077	0.082	0.071	0.026	0.063	0.021
N_o	0.172	0.225	0.165	0.150	0.142	0.168	0.200	0.200

[a] A St. Clair County briquets.
B Will County briquets.
C Franklin County briquets.
D Pocahontas briquets.
E Deduster dust briquets.
F 25 percent fusain briquets.
G Vitrain briquets.
H Durain briquets.

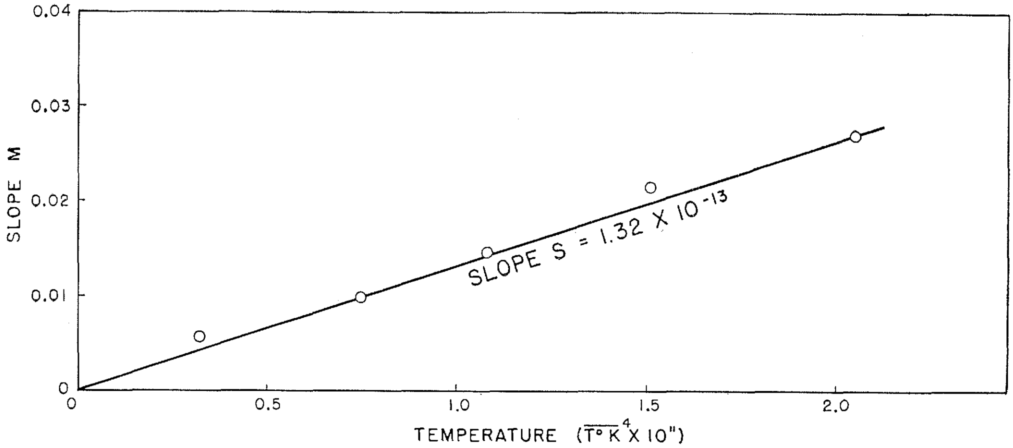

FIG. 79.—Influence of temperature on slope S for Franklin County briquets. ($N_0 = 0.165$)

has been made (table 71) of the experimental values for all constants (D_c, P_c, N_0 and S) for these coals. The values of the critical density D_c and the critical pressure P_c are taken from figs. 66, 73, 77, 81, 85, 89, 93 and 97 and the values for N_0 and S from tables 69 and 70 respectively.

GENERAL SUMMARY OF THE EXPERIMENTAL RESULTS

In order to provide a basis for the mathematical analysis of the briquetting process that follows it may be helpful to summarize briefly the main considerations upon which this analysis is based.

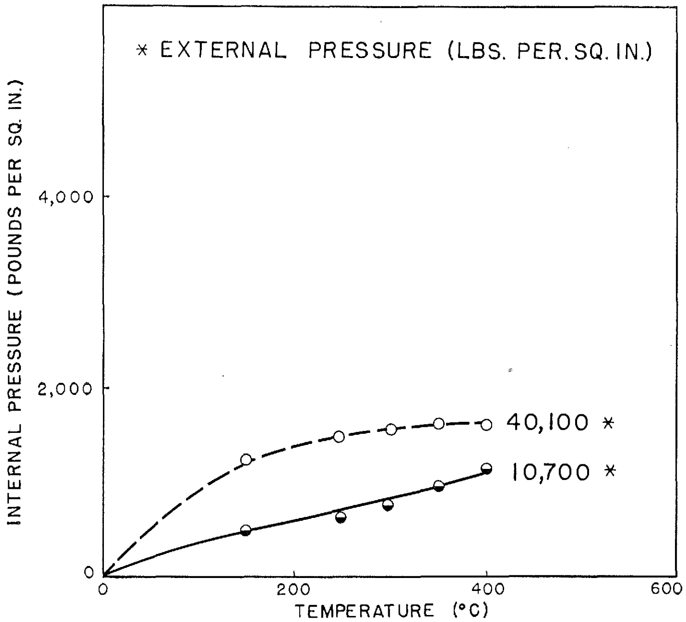

FIG. 80.—Relationship between internal pressure and temperature for various external pressures for Pocahontas briquets.

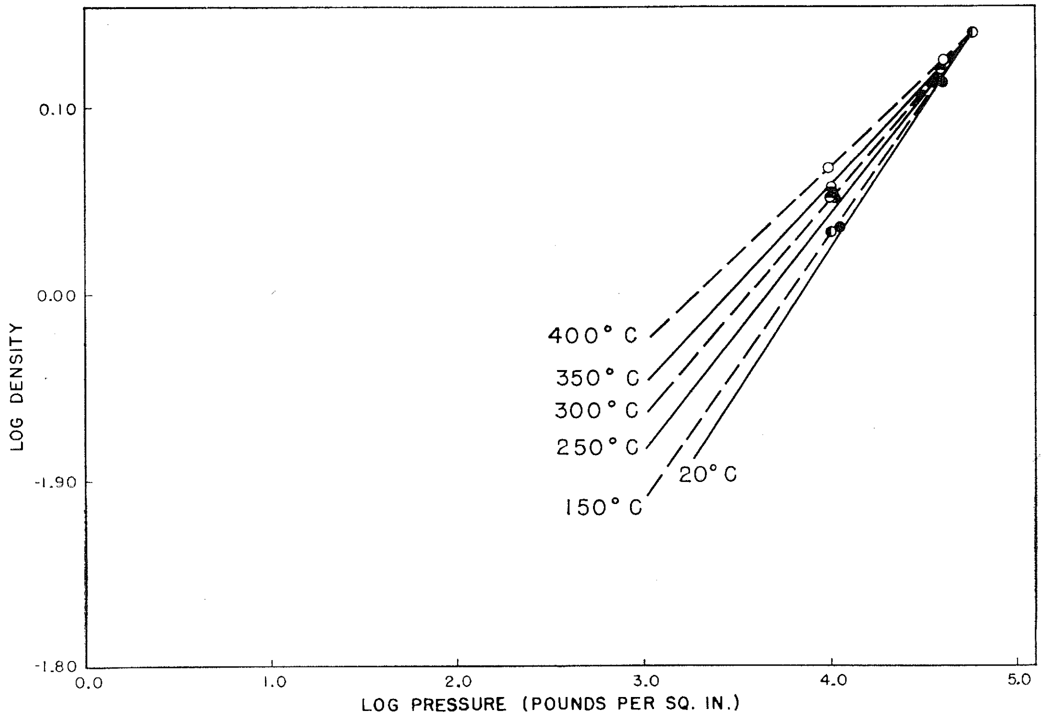

FIG. 81.—Relationship between logarithm of the density and logarithm of the pressure at various temperatures for Pocahontas briquets.

1. It has been shown that briquetting involves four stages of compression: settling, crushing, elimination of pore space (plastic compression) and elastic compression.
2. Compression at relatively low pressures increases linearly with the increase in pressure, but at very high pressures there is slight decrease in rate of compression.
3. The type of compression changes at a critical pressure above which point the character of compression is not affected by temperature.
4. Actual or effective pressure is the difference between actual pressure and internal pressure developed in the coal for any cause.

TABLE 70.—DATA FOR SLOPE M IN BRIQUETTING EQUATION FOR VARIOUS TEMPERATURES AND VARIOUS BRIQUETTING PERIODS OF TIME FOR VARIOUS BRIQUETS

(Data from Figs. 71, 75, 79, 83, 91, 95, and 99)

Temperature		Coals[a]							
°C	(°K)^4×10''	A	B	C	D	E	F	G	H
20	0.08	0.0012	—	—	—	—	—	—	—
150	0.32	0.0065	0.0089	0.0052	0.0040	0.0031	0.0068	0.0071	0.0095
250	0.75	0.0152	—	0.0098	0.0083	—	—	—	—
300	1.08	0.0239	0.292	0.0144	0.0113	0.0129	0.0227	0.0218	0.0297
350	1.51	0.0305	0.0399	0.0215	0.0144	—	—	—	0.0409
400	2.05	0.0424	0.0541	0.0270	0.0208	0.0218	0.0436	0.0421	0.0550
Sx10^{-33}	—	2.07	2.63	1.32	1.01	1.06	2.13	2.05	2.68

[a] A St. Clair County briquets.
B Will County briquets.
C Franklin County briquets.
D Pocahontas briquets.
E Deduster dust briquets.
F 25 percent fusain briquets.
G Vitrain briquets.
H Durain briquets.

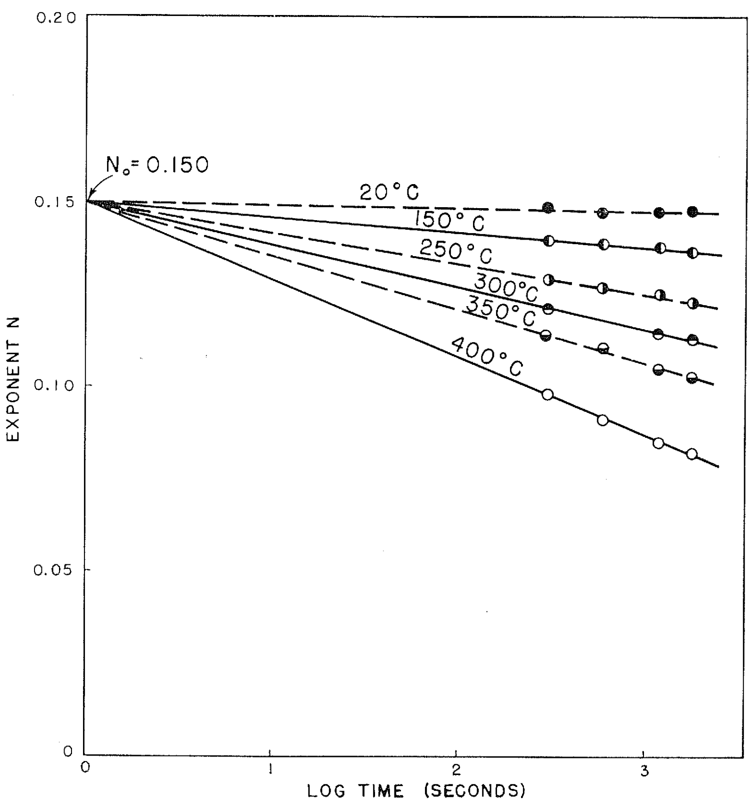

FIG. 82.—Influence of time on exponent N for Pocahontas briquets.

5. A critical density and a critical (effective) pressure is characteristic of the production of pore-free briquets from any coal.

6. A straight-line relationship exists between the logarithm of the pressure and the logarithm of density.

7. The slope of the family of straight lines is a function of the fourth power of the absolute temperature.

8. The interrelationships between density D and pressure P, the absolute temperature °K and the time t, the general briquetting curve may be expressed algebraically as follows:

$$D = D_c \left[P/P_c\right]^{N_o - S \times \overline{T^\circ K}^{4} \log t}$$

TABLE 71.—BRIQUETTING CONSTANTS FOR VARIOUS COALS
(Data from tables 70 and 71 and Figs. 66, 73, 77, 81, 85, and 89)

Coal	D_c	P_c	N_0	$S \times 10^{-13}$
St. Clair	1.320	25100	0.172	2.07
Will	1.320	25100	0.225	2.63
Franklin	1.380	44700	0.165	1.32
Pocahontas	1.380	56200	0.150	1.01
Deduster dust	1.400	50100	0.142	1.06
25 percent fusain	1.380	39800	0.168	2.13
Vitrain	1.270	35500	0.200	2.05
Durain	1.290	31600	0.200	2.68

$$D = D_c\ (P/P_c)\ \underline{N_0 - S(^\circ K)^4 \log t}$$

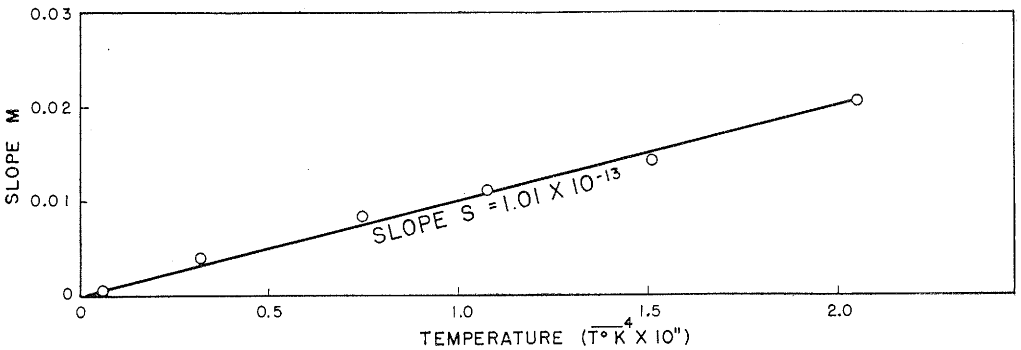

Fig. 83.—Influence of temperature on slope S for Pocahontas briquets. ($N_0 = 0.150$)

where D_c is the pore-free density of the coal, P_c is the pressure required to remove the pore space, N_0 is the pressure exponent for the time of one second, and S is the temperature-time coefficient.

9. The briquetting constants D_c, P_c, N_0, and S are characteristic of each coal, and their values may be found experimentally.

The following discussion of the calculus of coal briquetting is based upon the foregoing nine principles.

CALCULUS OF BRIQUETTING

Introduction

In the mathematical treatment of briquetting, the calculus is applied to plastic and elastic compression stages, and to the phenomena of elastic rebound that takes place when pressure is released in the elastic compression stage. Phenomena of the plastic stage are considered when developed by slow and by rapid pressure (by compression and by impact). The mechanical energy required for briquetting and the density to which any coal may be briquetted under conditions of slow briquetting (compression) are determined. In considering impact, pressure relations are developed for the energy required, the density of an impact briquet resulting from specific energy, and the time of formation of the briquet.

Phenomena in the elastic compression stage include the energy required for elastic compression, the velocity of elastic compression, and the time required. Finally analysis is made of the time of the elastic rebound.

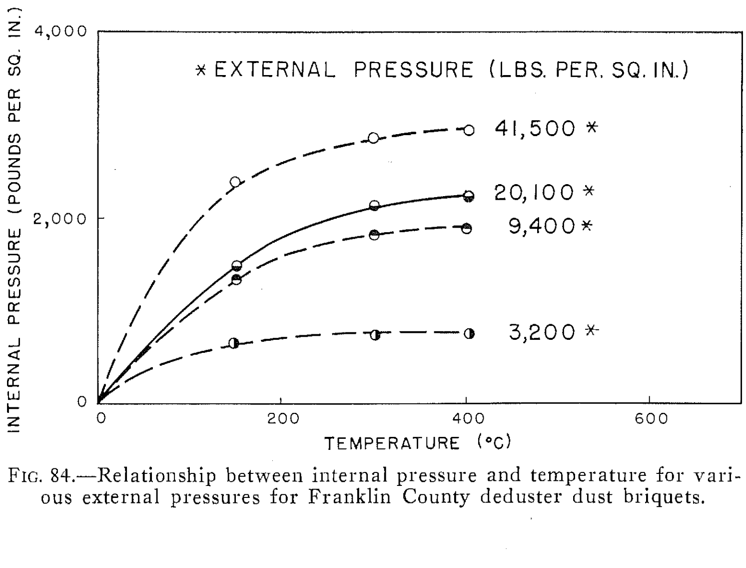

Fig. 84.—Relationship between internal pressure and temperature for various external pressures for Franklin County deduster dust briquets.

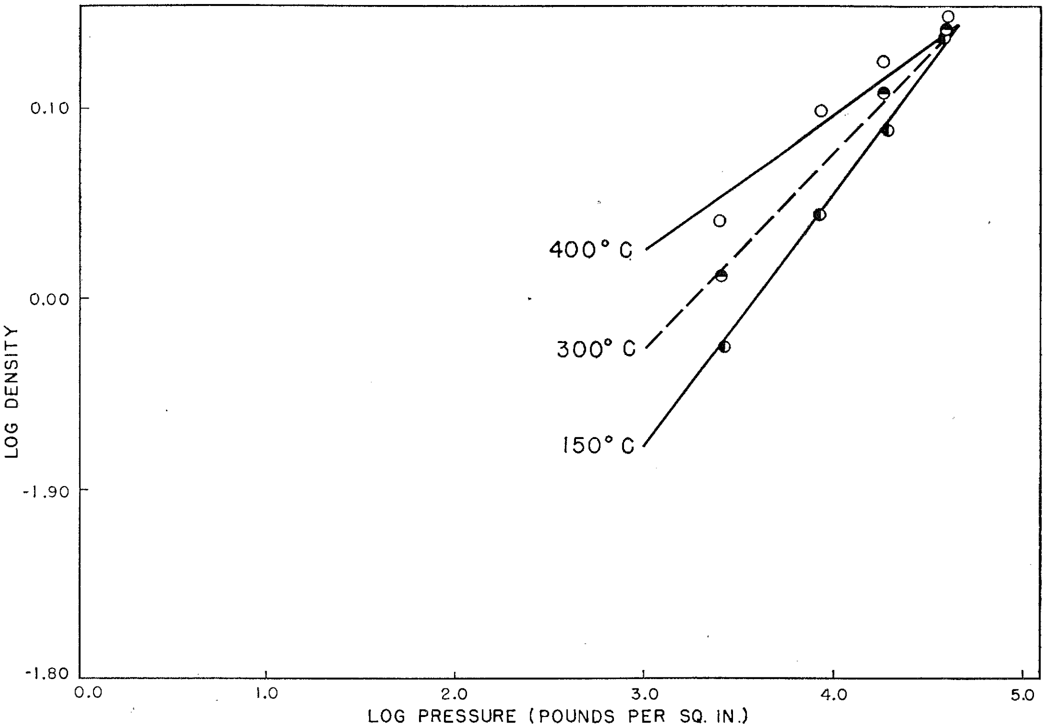

FIG. 85.—Relationship between logarithm of the density and logarithm of the pressure at various temperatures for Franklin County deduster dust briquets.

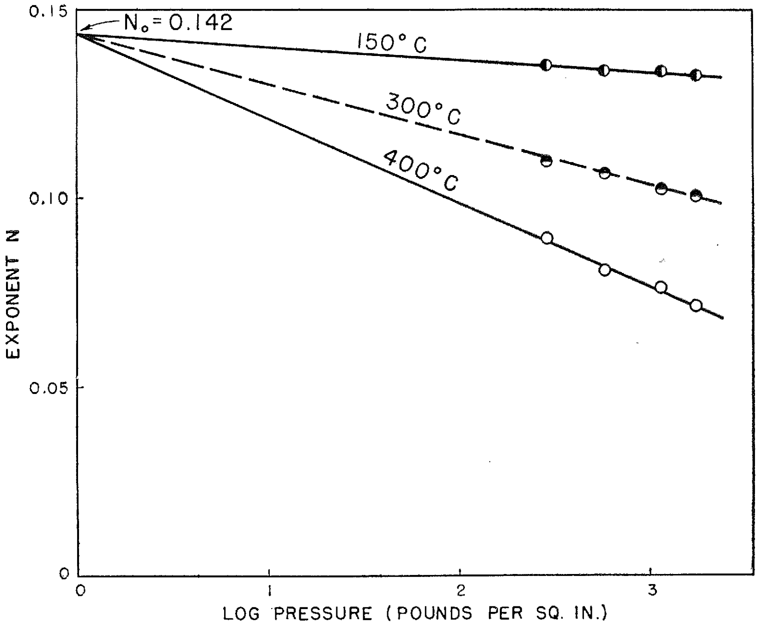

FIG. 86.—Influence of time on exponent N for Franklin County deduster dust briquets.

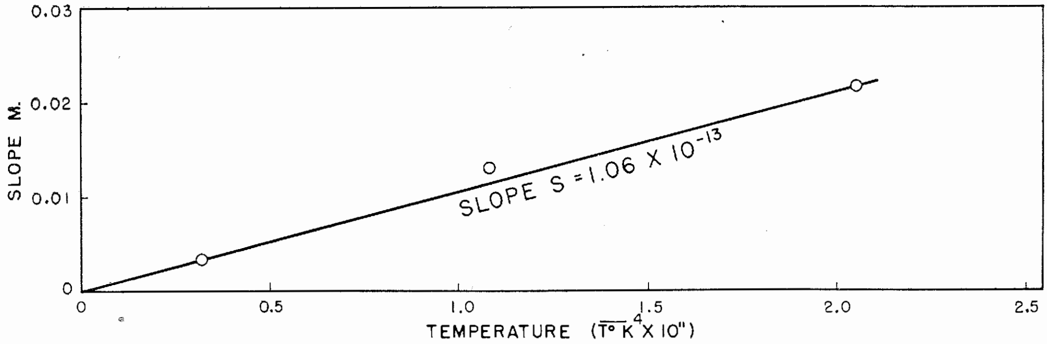

FIG. 87.—Influence of temperature on slope S for Franklin County deduster dust briquets. ($N_o = 0.142$)

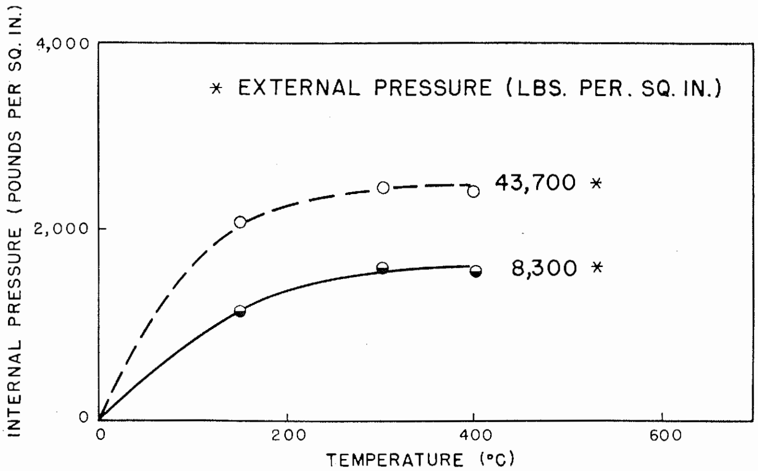

FIG. 88.—Relationship between internal pressures and temperatures for various external pressures for St. Clair County briquets—25 percent fusain and 75 percent crushed lump.

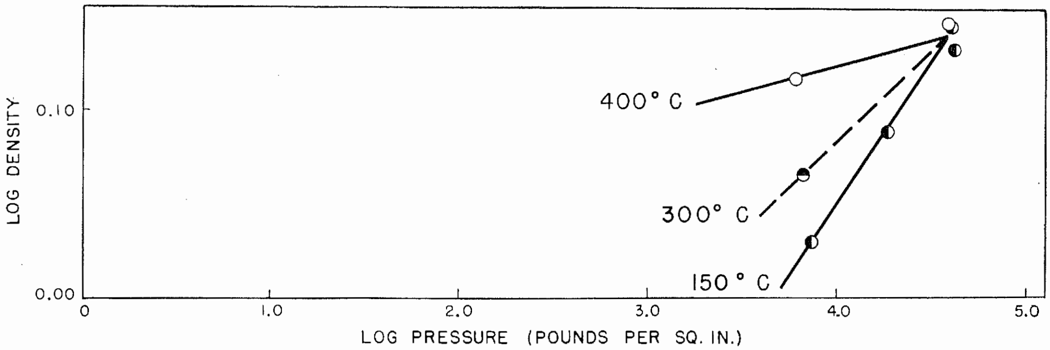

FIG. 89.—Relationship between logarithm of the density and logarithm of the pressure at various temperatures for St. Clair County briquets—25 percent fusain and 75 percent crushed lump.

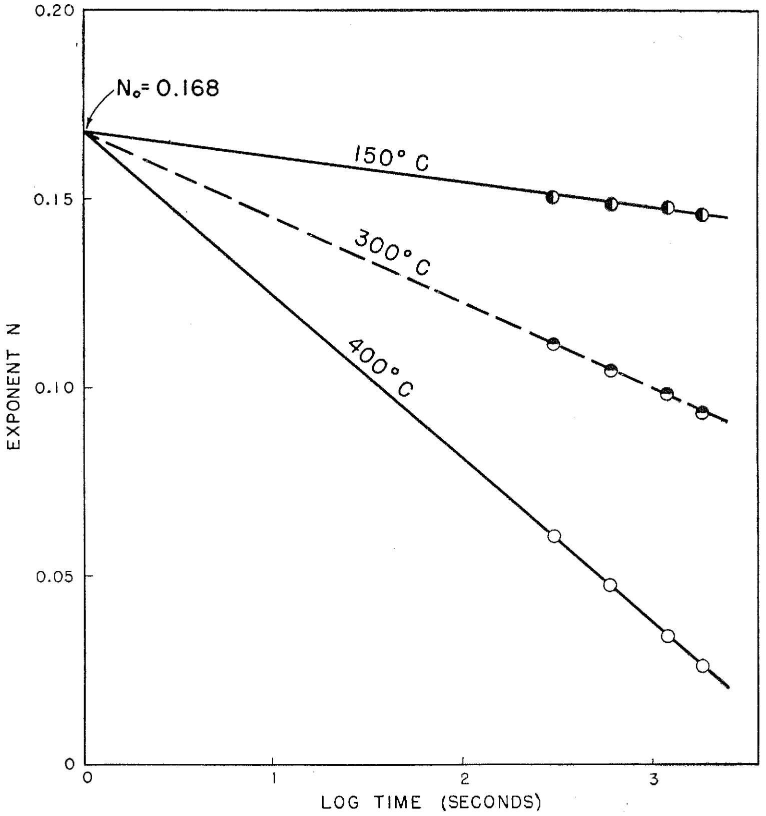

FIG. 90.—Influence of time on exponent N for St. Clair County briquets—25 percent fusain, 75 percent crushed lump.

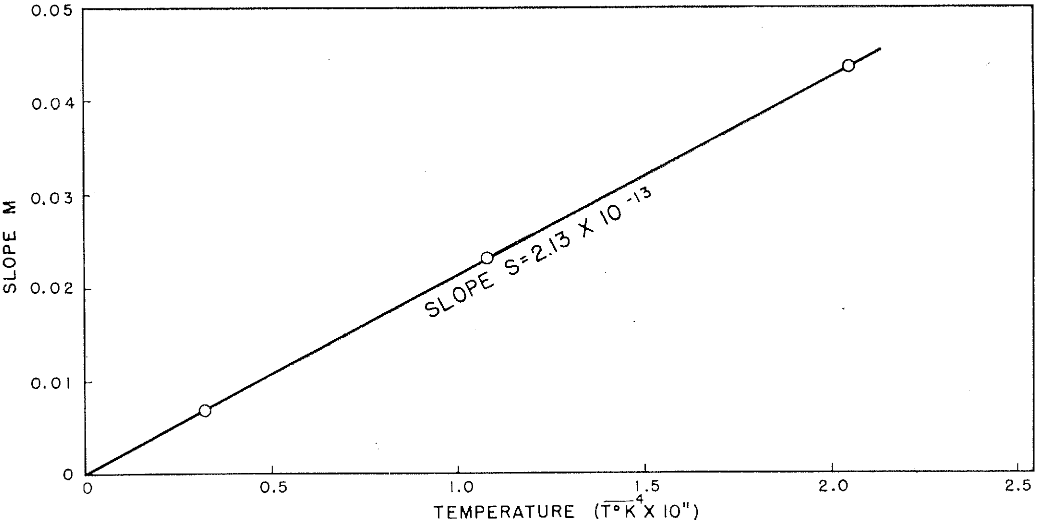

FIG. 91.—Influence of temperature on slope S for St. Clair County briquets—25 percent fusain, 75 percent crushed lump. ($N_o = 0.168$)

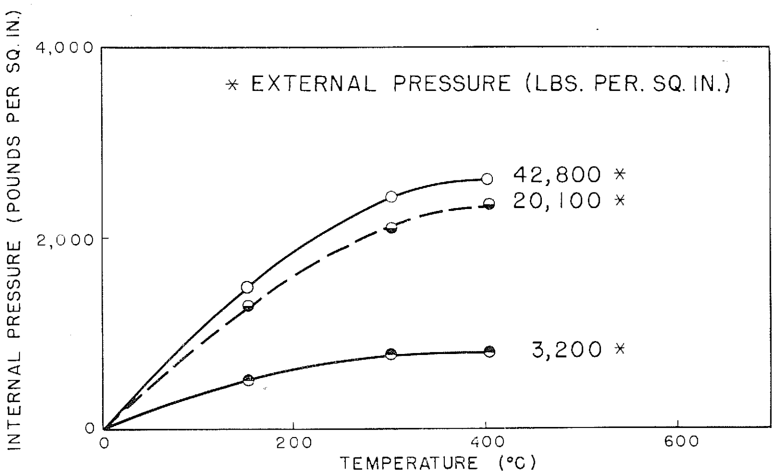

FIG. 92.—Relationship between internal pressure and temperature for various external pressures for Franklin County vitrain briquets.

ANALYSIS OF THE PHENOMENA IN THE STAGE OF PLASTIC COMPRESSION

CONDITIONS OF SLOW COMPRESSION

Equations to be evolved include those (a) for the mechanical energy requirement and (b) for the density to which the coal may be briquetted by any given amount of energy under conditions of application of slowly applied pressure or compression.

MECHANICAL ENERGY REQUIREMENT

Mechanical energy as has been shown in equation 5, involving the interrelationships

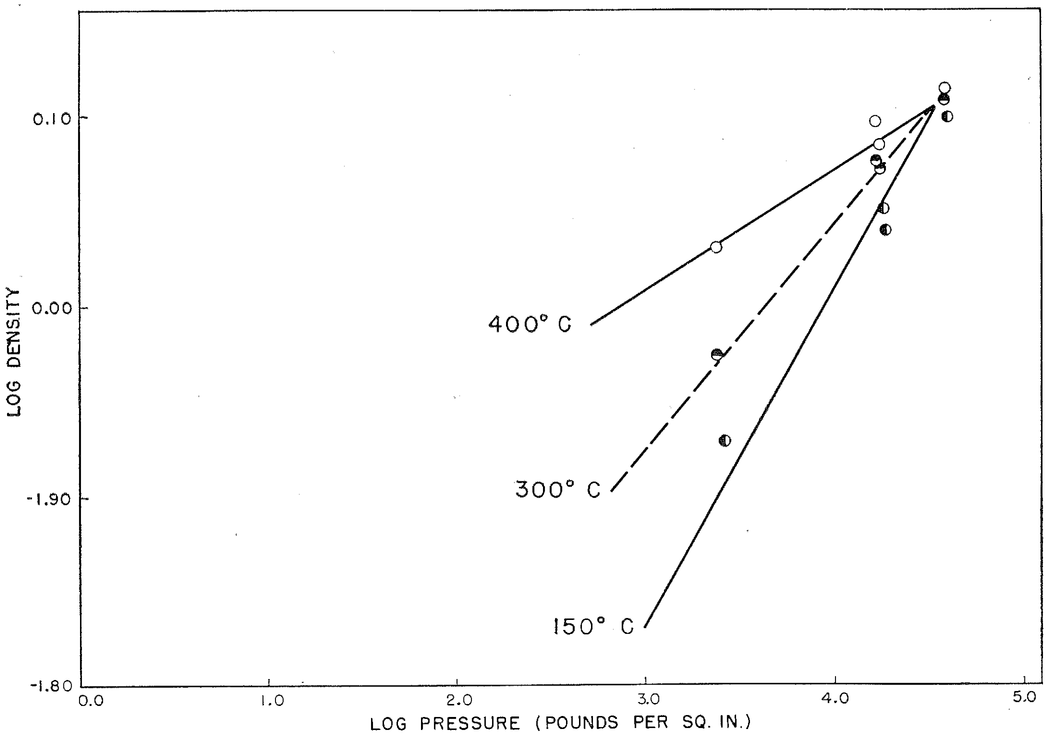

FIG. 93.—Relationship between logarithm of the density and logarithm of the pressure at various temperatures for Franklin County vitrain briquets.

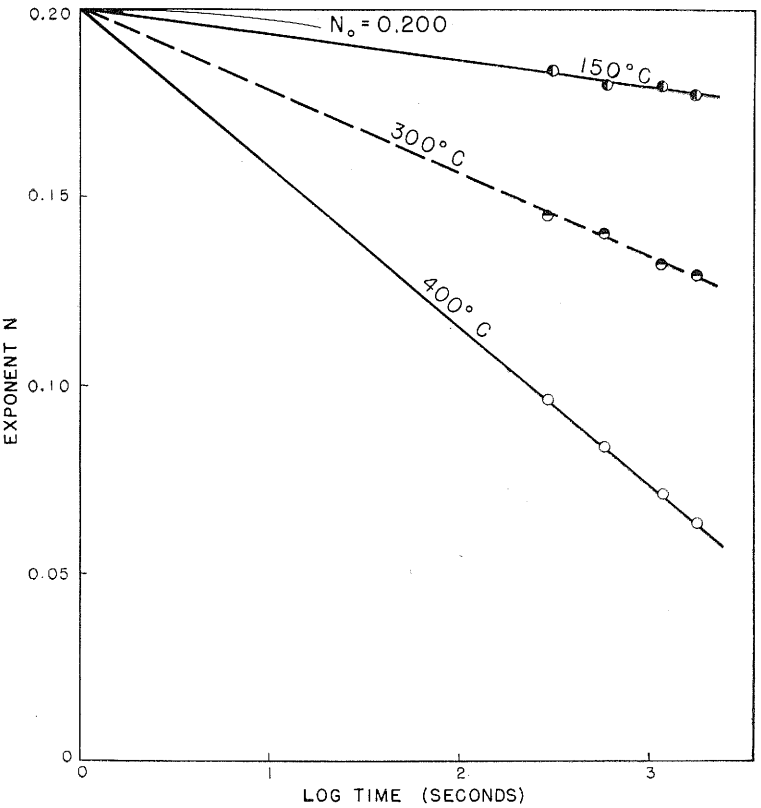

FIG. 94.—Influence of time on exponent N for Franklin County briquets (hand-picked vitrain).

between density, pressure, temperature, and time of briquetting may be expressed as

$$D = D_c\,[P/P_c]^N \qquad (12)$$

where

$$N = N_o - S \times \overline{T^\circ K}^{4} \log t \qquad (13)$$

Equation 12 may be transformed to

$$D = \frac{D_c \times P^N}{P_c^N} \qquad (14)$$

which may be written

$$D = P \frac{N}{K} \qquad (15)$$

where

$$1/K = D_c/P_c^N \qquad (16)$$

Also equation 15 may be transformed to

$$P = K^{1/N}\,D^{1/N} \qquad (17)$$

also since density D is the reciprocal of the height S of a unit briquet, equation 17 may be written

$$P = K^{1/N}\,S^{-1/N} \qquad (18)$$

The energy E necessary to form a unit briquet is the product of the force (pressure in pounds per sq. in.) and the distance S of compression (change of length from coal to briquet in units of inches); this gives the energy in units of inch-pounds per unit briquet (1 cu. in. of coal at unit density); this relation is expressed by formula

$$E = f \times S \qquad (19)$$

and from equation 18 this may be put into integral calculus form as follows:

$$\int_{E}^{E_o} d\,E = -K^{1/N} \int_{S}^{S_o} S^{-1/N}\,d\,S \qquad (20)$$

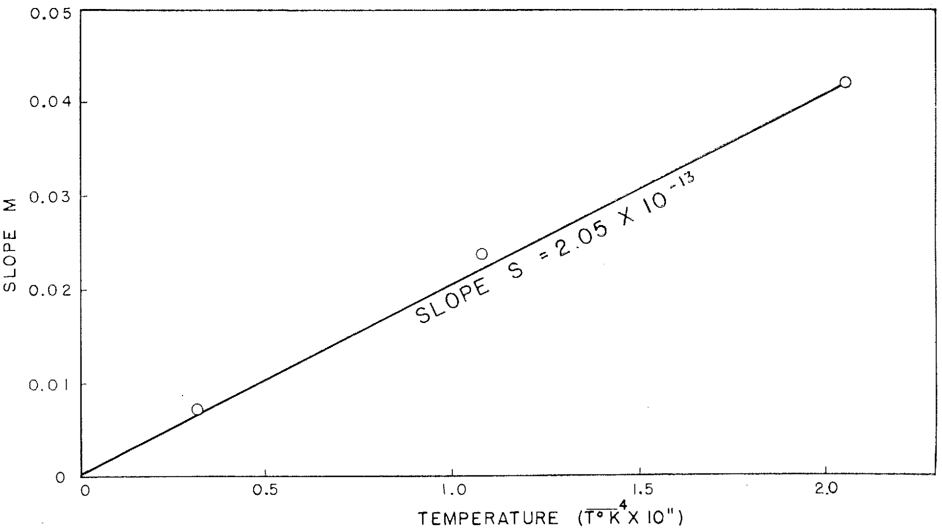

FIG. 95.—Influence of temperature on slope S for Franklin County briquets (hand-picked vitrain). ($N_0 = 0.200$)

Integrating this between the limits of the original height S_0 of the coal and of the height S of the briquet

$$E_0 - E = \frac{NK^{1/N}}{1-N}\left[S_0^{\frac{N-1}{N}} - S^{\frac{N-1}{N}}\right] \qquad (21)$$

And since the density D is the reciprocal of the height S, this may be written

$$E_0 - E = \frac{NK^{\frac{1}{N}}}{1-N}\left[D_0^{\frac{1-N}{N}} - D^{\frac{1-N}{N}}\right] \qquad (22)$$

However the initial energy E_0 of the coal does not enter into the energy of briquetting, and therefore equation 22 becomes

$$E = \frac{NK^{\frac{1}{N}}\,D^{\frac{1-N}{N}}}{1-N} \qquad (23)$$

DENSITY TO WHICH COAL MAY BE BRIQUETTED BY A GIVEN ENERGY

By algebraic transformation of equation 23, the density D may be found which

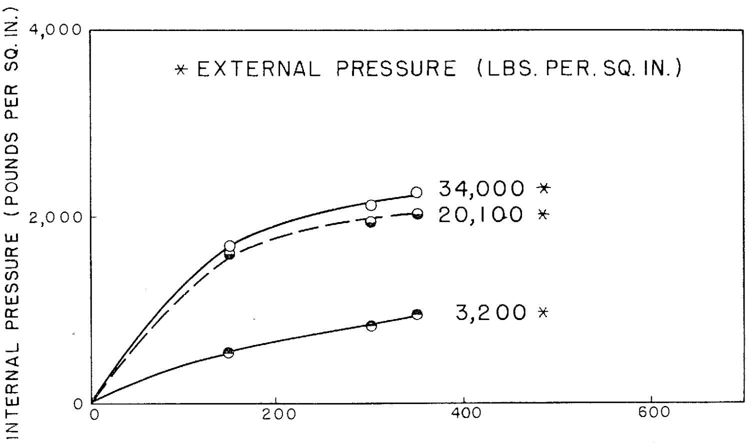

FIG. 96.—Relationship between internal pressure and temperature for various external pressures for Franklin County durain briquets.

results from the application of a briquetting energy E, as follows:

$$D = \left[\frac{E\,(1 - N)}{N K^{\frac{1}{N}}} \right]^{\frac{N}{N-1}} \qquad (24)$$

CONDITIONS OF RAPID BRIQUETTING (IMPACT)

Equations will be evolved for (a) the mechanical (kinetic) energy required, (b) the velocity of impact necessary, and (c) the time required for briquetting by impact.

KINETIC ENERGY

The energy required for impact briquetting may be developed in terms of the gravitational acceleration of the impact hammer.

Since pressure per unit cross is force (mass times acceleration)

$$P = m\,a \qquad (25)$$

where m is the mass of the impact hammer (expressed as its weight in pounds divided by the acceleration of gravity a in inches per sec. per sec.) per unit cross-sectional area of the briquet (expressed in sq. in.) per unit weight of the coal (weight of a briquet of unit density and 1 inch high); and the acceleration a is that due gravity (385 inches per sec. per sec.).

Since the acceleration a is the second derivative of the distance S (height of briquet in reference to unit height) with respect to time, equation 25 may be written

$$P = m \frac{d^2 S}{d t^2} \qquad (26)$$

From equation 17, this may be written

$$\frac{d^2 (1/D)}{d t^2} = \frac{K^{\frac{1}{N}}}{m} \left(\frac{1}{D} \right)^{-\frac{1}{N}} \qquad (27)$$

since by definition of unit briquet the height S is equal to the reciprocal of its density.

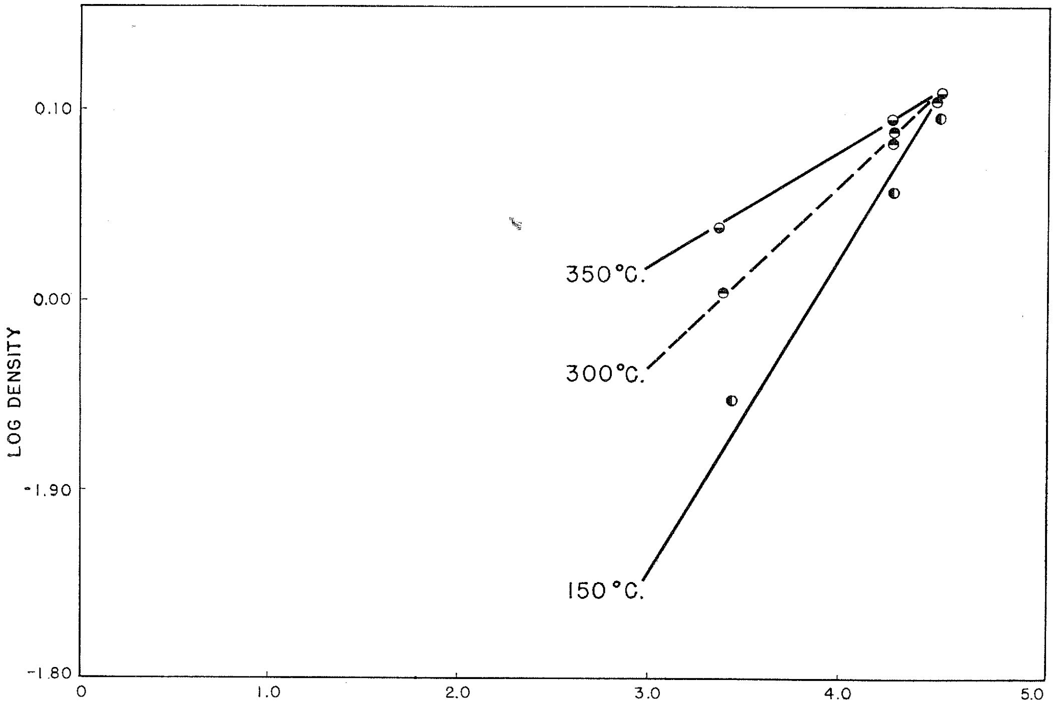

FIG. 97.—Relationship between logarithm of the density and logarithm of the pressure at various temperatures for Franklin County durain briquets.

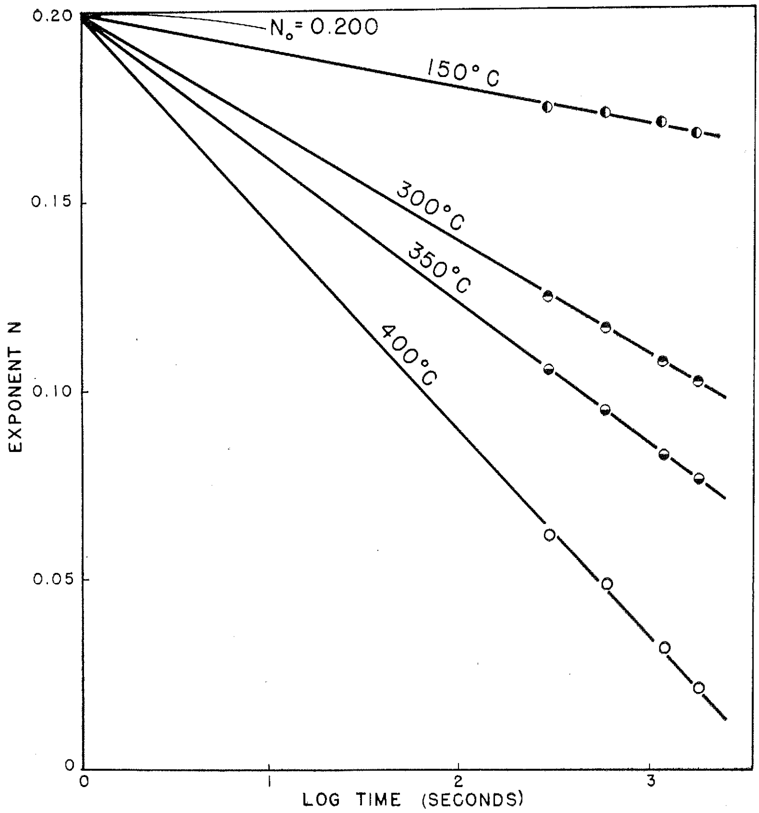

FIG. 98.—Influence of time on exponent N for Franklin County briquets (hand-picked durain).

Equation 20 becomes an energy integral when solved as follows:

$$\frac{d^2\,(1/D)}{d\,t^2} = \frac{d}{d\,t}\left[\frac{d\,(1/D)}{d\,t}\right] = \frac{d\,V}{d\,t} \qquad (28)$$

because the velocity V is the derivative of the distance (reciprocal of density D) with respect to time.

Since equation 27 does not contain an explicit time variable, equation 28 may be written

$$\frac{d\,V}{d\,t} = \frac{d\,V}{d\,(1/D)} \times \frac{d\,(1/D)}{d\,t} = \frac{d\,V}{d\,(1/D)} \times V \qquad (29)$$

and equation 27 becomes

$$\frac{dV}{dt} \times V = \frac{K^{\frac{1}{N}}}{m}\left(\frac{1}{D}\right)^{-\frac{1}{N}} \qquad (30)$$

With integration limits of hammer velocity V_0 at instant of impact and hammer velocity V at any stage of impaction; and of the height $(1/D_0)$ of the loose coal and the height $(1/D)$ of the coal at any stage of impaction, equation 28 may be written

$$\int_{V_0}^{V} V\,d\,V = \int_{\frac{1}{D_0}}^{\frac{1}{D}} \left(\frac{1}{D}\right)^{-\frac{1}{N}} d\left(\frac{1}{D}\right) \qquad (31)$$

By integration, equation 31 becomes

$$\frac{V^2}{2} - \frac{V_0^2}{2} = \frac{NK^{\frac{1}{N}}}{(N-1)\,m}\left[\left(\frac{1}{D}\right)^{\frac{N-1}{N}} - \left(\frac{1}{D_0}\right)^{\frac{N-1}{N}}\right] \qquad (32)$$

The kinetic energy E of the hammer may be written

$$E = \frac{m\,V^2}{2} \qquad (33)$$

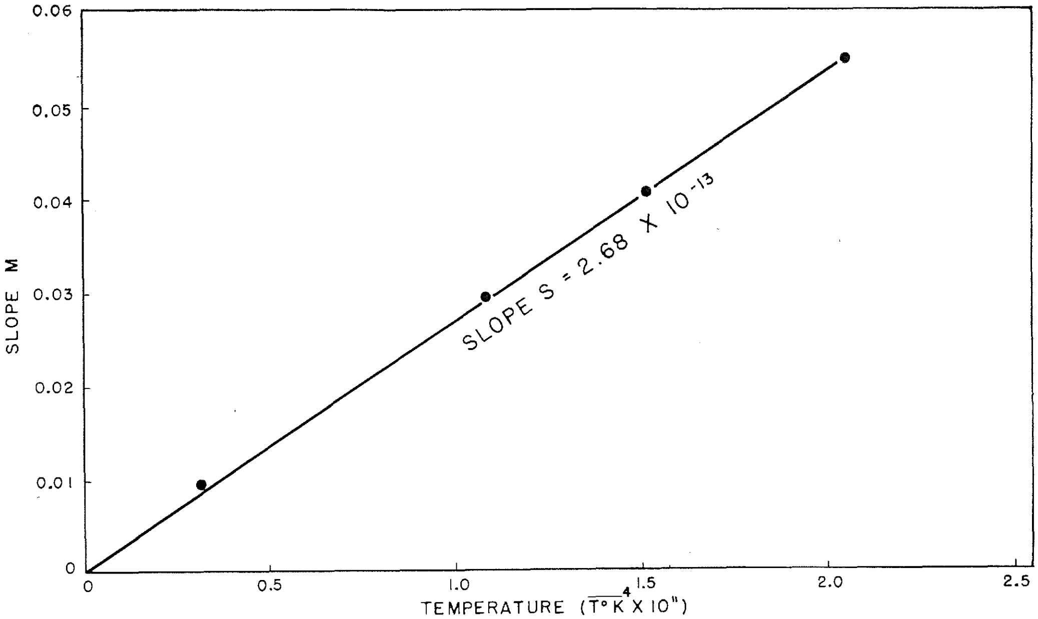

FIG. 99.—Influence of temperature on slope S for Franklin County briquets (hand-picked durain) ($N_o = 0.200$).

Therefore, with algebraic rearrangement, equation 32 becomes

$$E_o - E = \frac{NK^{\frac{1}{N}}}{(1-N)}\left[D^{\frac{1-N}{N}} - D_o^{\frac{1-N}{N}}\right] \tag{34}$$

At the point of the maximum density D_m of the briquet, the energy of the hammer E_m is zero, and therefore the energy E_b required to impact the briquet becomes

$$E_b = \frac{NK^{\frac{1}{N}} D^{\frac{1-N}{N}}}{(1-N)} \tag{35}$$

VELOCITY OF IMPACT BRIQUETTING

In impact briquetting the velocity of the formation of the briquet is that of the velocity of the impact hammer during the interval between which the hammer strikes the coal and the hammer arrives at the point of maximum compression. From the rearrangement of equation 32 the velocity at various densities is shown in equation 36.

Algebraically the sign of the velocity may be either plus or minus; but, when applied to impact briquetting, the negative sign is chosen to represent velocity in the direction of decreasing distance.

TIME REQUIRED FOR IMPACT BRIQUETTING

The time t required to briquet the coal to any density D may be developed from equation 36 as shown in equation 37.

$$V = -\left(V_o^2 - \frac{2NK^{\frac{1}{N}}}{(1-N)\,m}\left[\left(\frac{1}{D}\right)^{\frac{N-1}{N}} - \left(\frac{1}{D_o}\right)^{\frac{N-1}{N}}\right]\right)^{1/2} \tag{36}$$

$$\frac{d\left(\frac{1}{D}\right)}{d\,t} = -\left[V_o^2 - \frac{2NK^{\frac{1}{N}}}{(1-N)\,m}\left(\frac{1}{D}\right)^{\frac{N-1}{N}} + \frac{2NK^{\frac{1}{N}}}{(1-N)\,m}\left(\frac{1}{D}\right)^{\frac{N-1}{N}}\right]^{1/2} \tag{37}$$

For convenience let

$$B = \frac{2\,NK^{\frac{1}{N}}}{(1 - N)\,m} \qquad (38)$$

Then equation 37 may be written

$$d\,t = -\left[V_o^2 + B\left(\frac{1}{D_o}\right)^{\frac{N-1}{N}} - B\left(\frac{1}{D}\right)^{\frac{N-1}{N}}\right]^{-1/2} d\left(\frac{1}{D}\right) \qquad (39)$$

Also for convenience let

$$C = V_o^2 + B \qquad (40)$$

Then equation 39 may be written

$$d\,t = -\,C^{1/2}\left[1 - \frac{B}{C}\left(\frac{1}{D}\right)^{\frac{N-1}{N}}\right]^{-1/2} d\left(\frac{1}{D}\right) \qquad (41)$$

Expanding by the binomial theorem and inserting time limits between D and t and height limits between $1/D_o$ and $1/D$ equation 41 becomes

$$\int_o^t d\,t = \int_{\frac{1}{D_c}}^{\frac{1}{D}} -C\left[1 + \frac{B}{2C}\left(\frac{1}{D}\right)^{\frac{N-1}{N}} + \frac{3\,B^2}{8C^2}\left(\frac{1}{D}\right)^{\frac{2N-2}{N}} + \dots\right] d\left(\frac{1}{D}\right) \qquad (42)$$

Since this is a rapidly converging series, the fourth term and subsequent terms may be omitted. Integrating, equation 30 becomes

$$t = C^{-1/2}\left[\left(\frac{1}{D} - \frac{1}{D_o}\right) + \frac{NB}{2\,(2\,N - 1)\,C}\left\{\left(\frac{1}{D}\right)^{\frac{2N-1}{N}} - \left(\frac{1}{D_o}\right)^{\frac{2N-1}{N}}\right\} + \frac{3\,NB^2}{8\,(3\,N - 2)\,C^2}\left\{\left(\frac{1}{D}\right)^{\frac{3N-2}{N}} - \left(\frac{1}{D_o}\right)^{\frac{3N-2}{N}}\right\} + \dots\right] \qquad (43)$$

and by substituting in the values of B and C (equations 38 and 40) equation 43 becomes

$$t = V_o^{-1}\left[\left(D_o^{-1} - D^{-1}\right) + \frac{N^2\,K^{\frac{1}{N}}\,D^{\frac{1-2N}{N}}}{V_o^2 m\,(1 - N)\,(1 - 2\,N)} + \frac{3N^2\,K^{\frac{2}{N}}\,D^{\frac{2-3N}{N}}}{2\,V_o^4 m^2\,(1 - N)^2\,(2 - 3\,N)} + \dots\right] \qquad (44)$$

Analyses of Phenomena in Stage of Elastic Compression

In order to form a firm briquet by impact briquetting, more impact energy is used than that necessary to eliminate pore space. This excess energy is consumed in an elastic compression of the briquet beyond its critical density. The subsequent elastic expansion of the briquet back to its critical density results in the rebound of the impact hammer. There follows the mathematical development of (a) the energy required for elastic compression, (b) the velocity of elastic compression, (c) the time required for elastic compression, and (d) the time consumed in elastic rebound.

ENERGY REQUIRED FOR ELASTIC COMPRESSION

The energy E_e of the impact hammer consumed during the elastic compression of coal is the total energy E_0 at instant of impact less the energy E_p consumed during the elastic compression of coal. Therefore from equations 33 and 35.

$$E_e = \frac{m V_o^2}{2} - \frac{NK^{\frac{1}{N}}}{(1 - N)} D_c^{\frac{1-N}{N}} \tag{45}$$

for velocity V_o of hammer at time of impact and the critical density D_c.

Also for a coal with bulk modulus N during elastic compression the energy E becomes

$$E = \frac{(N - P)}{2D_c^{-1}}\left[D_c^{-1} - D^{-1}\right]^2 + \left[D_c^{-1} - D^{-1}\right] P_c \tag{46}$$

for critical pressure P_c and critical density D_c.

Also the maximum density D_m for the total elastic energy E_e becomes

$$D_m = D_c\left[\frac{N - P_c}{N - (P_c^2 + 2[N - P_c] E_e D_c)}\right] \tag{47}$$

and the maximum pressure P_m becomes

$$P_m = N\left[1 - \frac{D_c}{D_m}\right] + P_c\left[\frac{P_c}{D_m}\right] \tag{48}$$

VELOCITY OF ELASTIC COMPRESSION

The velocity V of the impact hammer during the elastic compression of coal is

$$V = V_c\left[\frac{mVc^2 - 2E}{mV_c^2}\right]^{1/2} \tag{49}$$

where the energy E for any density D within the elastic zone may be calculated from equation 46; and the critical velocity V_c, from equation 36.

Equation 49 may be written in the form shown in equation 50.

TIME CONSUMED DURING ELASTIC COMPRESSION

From equation 50, the time t may be written in integral form for limit of t and zero and density limits of the reciprocals of D and D_c, respectively, as shown in equation 51.

Equation 51 may be integrated as shown in equation 52.

TIME OF ELASTIC REBOUND

Due to its internal friction, no substance is perfectly elastic. The coefficient of impact I is herein defined as the ratio of the velocity of the hammer after impact to that before impact of an elastic material.

Equation 52, the time t during the elastic rebound of the briquet is shown in equation

$$V = V_c\left[1 + \frac{P_c^2 D_c^{-1}}{mV_c^2 (N - P)} - \frac{(N - P_c)}{mV_c^2 D_c^{-1}}\left(\frac{ND_c^{-1}}{N - P_c} - D^{-1}\right)^2\right]^{1/2} \tag{50}$$

$$-\int_0^t dt = V_c^{-1}\int_{D_o^{-1}}^{D^{-1}}\left[\left(1 + \frac{P_c^2 D_c^{-1}}{mV_c^2 (N - P_o)}\right) - \left(\frac{N - P_c}{mV_c^2 D_c^{-1}}\right)\left(\frac{ND_c^{-1}}{N - P_o} - D^{-1}\right)^2\right]^{-1/2} d\,D^{-1} \tag{51}$$

$$t = V_c^{-1}\left[\left(\frac{D_c^{-1}\, mV_o^2}{N - P_c}\right)^{1/2}\left\{\sin^{-1}\left[\frac{\left(\frac{N - R}{mV_c^2 D_c^{-1}}\right)^{1/2}\left(\frac{ND_c^{-1}}{N - P_c} - D^{-1}\right)}{\left(1 + \frac{P_c^2 D_c^{-1}}{mV_c^2 (N - P_c)}\right)^{1/2}} - \sin^{-1}\frac{\left(\frac{N - P_c}{mV_c^2 D_c^{-1}}\right)^{1/2}\left(\frac{ND_o^{-1}}{N - P_c} - D^{-1}\right)}{\left(1 + \frac{P_c^2 D_c^{-1}}{mV_c^2 (N - P_c)}\right)^{1/2}}\right]\right\}\right] \tag{52}$$

$$t = I^{-1}\left(\frac{D_c^{-1}\,m}{N - P_c}\right)^{1/2}\cos^{-1}\left[\frac{\left(\dfrac{N - P_c}{mV_c^2\,D_c^{-1}}\right)^{1/2}\left(\dfrac{ND_c^{-1}}{N - P_c} - D^{-1}\right)}{\left(1 + \dfrac{P_c^2\,D_c^{-1}}{mV_c^2\,(N - P_c)}\right)^{1/2}}\right] \tag{53}$$

53 where the time t is taken in the opposite direction and therefore the angle whose sine is the bracketed quantity becomes the complementary angle whose cosine is the same bracketed quantity.

SUMMARY

Before considering the section on the application of mathematical theory to certain phases of experimental operation, it is desirable to assemble the additional critical items thus far developed in this article beyond the nine listed (pages 171, 172, and 173). These are:

1. For a particular coal briquetted at a specified temperature, pressure, and time, the briquetting equation may be written

$$D = P\frac{N}{K} \tag{54}$$

2. The energy E necessary to briquet under these conditions is then

$$E = \frac{NK^{\frac{1}{N}}D^{\frac{1-N}{N}}}{1 - N} \tag{55}$$

3. The density to which the briquet is compressed by the energy E is

$$D = \left[\frac{E\,(1 - N)}{NK^{\frac{1}{N}}}\right]^{\frac{N}{N-1}} \tag{56}$$

4. Results of experimental tests indicate that the energy relationship developed mathematically from data based on slow (compression) briquetting is valid for rapid (impact) briquetting.

MATHEMATICAL SOLUTION OF CERTAIN EXPERIMENTAL PROBLEMS

Mathematical processes are applied to the solution of three phases of briquet production as follows: (1) the determination of

TABLE 72.—RELATIONSHIP BETWEEN DENSITY AND PRESSURE FOR ST. CLAIR COUNTY COAL; TEMPERATURE, 400°C.; TIME, 1 SECOND
(Data for Fig. 100)

Height (inches)	Density	Pressure (pounds per sq. in.)
1.667	0.60	260
1.538	0.65	410
1.429	0.70	630
1.333	0.75	940
1.250	0.80	1360
1.176	0.85	1940
1.111	0.90	2710
1.053	0.95	3710
1.000	1.00	4990
0.952	1.05	6630
0.909	1.10	8690
0.870	1.15	11300
0.833	1.20	14400
0.800	1.25	18300
0.769	1.30	22900
0.757	1.32	25100

N = 0.172.

TABLE 73.—INFLUENCE OF TEMPERATURE ON COMPACTION CURVE OF ST. CLAIR COUNTY BRIQUETS; TIME 30 MINUTES
(Data for Fig. 101)

Height (inches)	Pressure (pounds per sq. in.)		
	150°C[a]	300°C[b]	400°C[c]
1.667	140	—	—
1.538	230	10	—
1.429	380	30	—
1.333	590	60	—
1.250	910	120	—
1.176	1400	310	—
1.111	2000	420	—
1.053	2800	760	—
1.000	4000	1300	10
0.952	5500	2200	30
0.909	7500	3600	100
0.870	10100	5900	430
0.833	13400	9100	1600
0.800	17500	14100	5100
0.769	22700	21500	16000
0.757	25100	25100	25100

[a] N = 0.151.
[b] N = 0.094.
[c] N = 0.034.

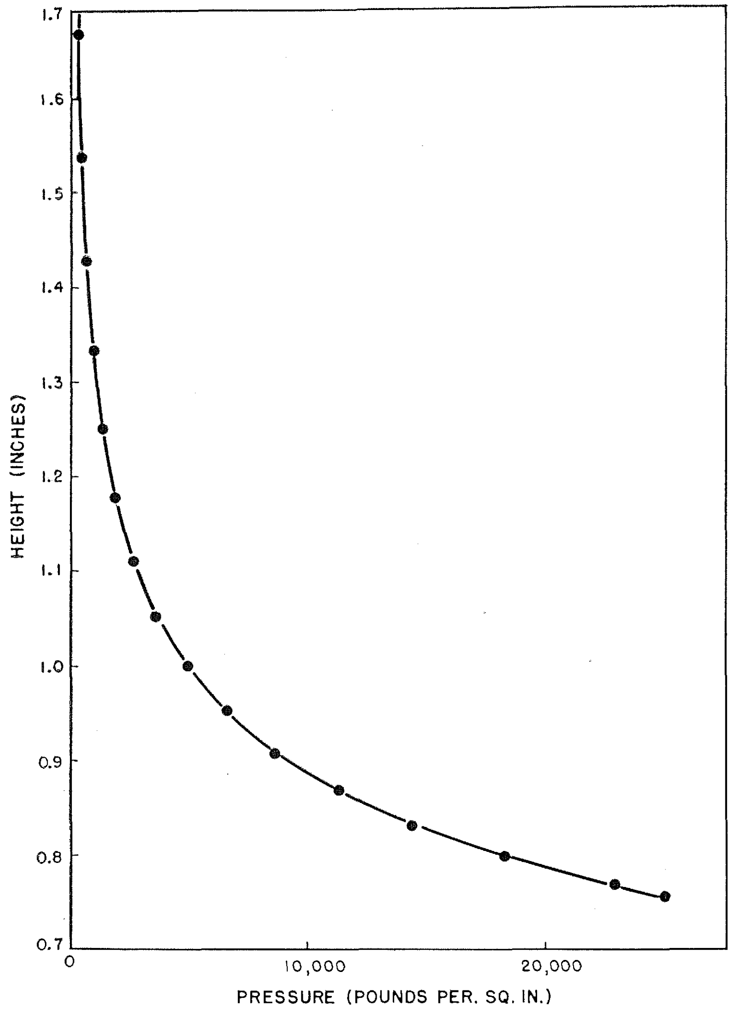

FIG. 100.—Compaction curve for St. Clair County briquets at temperature of 400° C. for one second. $D_c = 1.320$; $P_c = 25{,}100$; $N = 0.172$. (Data from table 72)

the relation of the height of the briquet to the pressure required for impact briquetting as shown by graphs, with analysis of the influence of temperature and time; (2) determination of the relation of the height of the briquet to the time required for impact briquetting with comparison of the experimental and theoretical values, and (3) determination of the energy in horsepower required to produce one ton of briquets also as affected by temperature and time.

ENERGY GRAPH ANALYSIS

An energy graph (fig. 100, table 72) or compaction curve of St. Clair County briquets made at a temperature of 400° C. and a time of 1 second, in which the height of the briquet in inches is plotted against the pressure in pounds per sq. in., is the basis of the following analysis, the energy in units of inch-pounds, being the area beneath the curve.

Influence of temperature.—The influence of temperature on the energy graph of St.

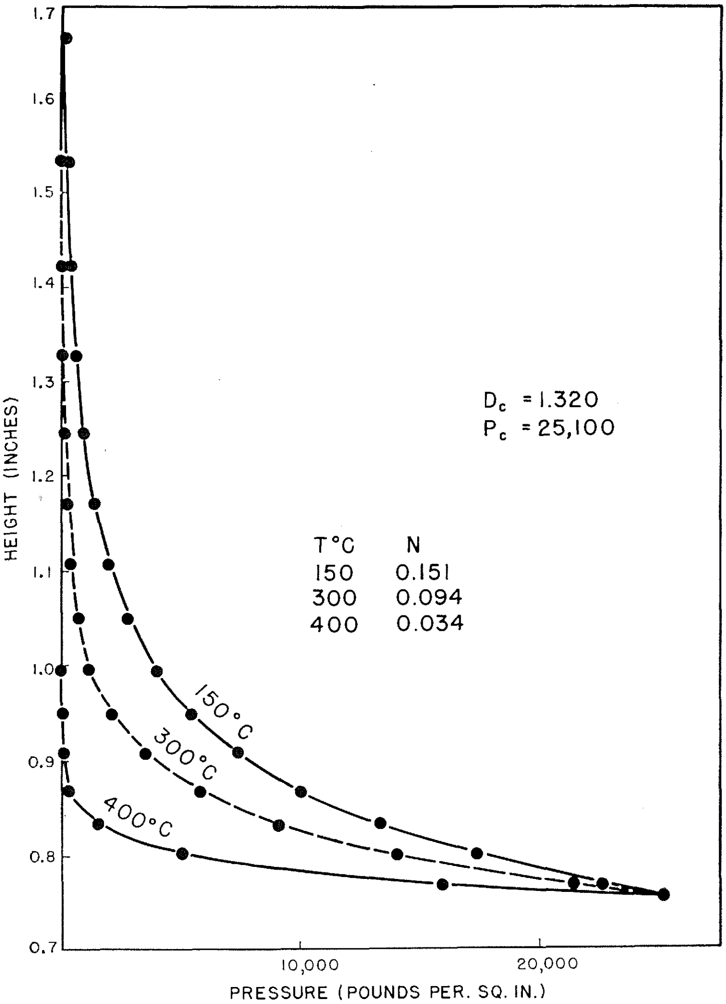

FIG. 101.—Influence of temperature on the compaction curve for St. Clair County briquets processed for 30 minutes. (Data from table 73)

Clair County coal briquetted for a period of 30 minutes at 150°, 300°, and 400° C. (fig. 101, table 73) is indicated by the decrease in energy (area beneath the curve) with the increase in temperature.

Influence of time.—The fact that energy decreases with the increase in time (fig. 101, table 74) is indicated by the effect of differences in briquetting time on the energy graph of St. Clair County coal briquetted at a temperature of 400° C. at periods of 1 second, 60 seconds, and 1800 seconds (30 minutes).

TIME-HEIGHT GRAPH FOR IMPACT BRIQUETTING AS A BASIS FOR ECCENTRIC PRESS DESIGN

In view of the mechanical characteristics of the eccentric type of press, which was regarded as the most suitable type of briquetting apparatus and one in which the operating speed of about 60 r.p.m. resulted in a compression speed of approximately 0.1 second, it was desirable to obtain information on the effect of very rapid briquetting, that is in the order of one second or

Table 74.—Influence of Time on Compaction Curve of St. Clair County Briquets; Temperature, 400°C
(Data for Fig. 102)

Height (inches)	Pressure (pounds per sq. in.)		
	1 second[a]	60 seconds[b]	1800 seconds[c]
1.667	260	10	—
1.538	410	20	—
1.429	630	40	—
1.333	940	70	—
1.250	1400	140	—
1.176	1900	270	—
1.111	2700	490	—
1.053	3700	840	—
1.000	5000	1400	10
0.952	6600	2400	30
0.909	8700	3800	100
0.870	11300	6000	430
0.833	14400	9400	1600
0.800	18300	14300	5100
0.769	22900	21400	16000
0.757	25100	25100	25100

[a] $N = 0.172$.
[b] $N = 0.097$.
[c] $N = 0.034$.

less, by use of the impact type of press. Such information would make it possible to determine the size of briquet that could be made in such a press, assuming a certain size of press and speed of operation. Previously in this investigation, an idea of the nature of these effects could be obtained only by means of extrapolation, this being the method used in the mathematical analysis of the briquetting data obtained by the hydraulic press. Experimental determinations were desirable to validate or disprove the conclusions reached by such extrapolation. The following procedure was employed. A graph was first set up showing theoretical time-height relationships determined by extrapolation; a graph was then prepared on the basis of experimental data in which the theoretical conditions of rapid compression were employed; and finally the two graphs were compared and conclusions were drawn.

THEORETICAL DATA FOR TIME-HEIGHT GRAPH

The theoretical time-height graph (fig. 103) shows the various heights of the briquet during impact versus the various time intervals of impact. The graph is prepared on the basis of actual results with an impact press and the use of briquetting equations.

Briquetting conditions.—The briquetting conditions used in preparing the graph (fig. 103) were those observed in briquetting a 39.4-gram sample of dry St. Clair County coal at 377° C. in a 1.5-inch die in a Turner impact press in which a 500-pound hammer was dropped a distance of 54 inches with a period of impact of about 0.008 second.

Briquetting constants.—The time was plotted from equation 44 which contains the following constants: V_0, the velocity of the hammer at the instant of impact; D_0, the density of the coal prior to impact; N, the pressure exponent; K, the proportionality constant; and m, the mass of hammer per unit briquet.

The value of V_0 is as follows:

$$V_0 = \sqrt{2gh} = 204.0 \qquad (57)$$

where the gravitational constant g is 385 inches per sec. per sec., the height h is 54 inches, and the velocity is in units of inches per second.

The value of D_0 is 0.610. This corresponds to a briquet height of 1.639 in. for a unit briquet and to an actual height of 2.230 in. because the ratio of the actual weight of the coal used to that required for a unit briquet was 1.36.[1]

The value of N is 0.249, being calculated from equation 13 for condition N_0 equals 0.172, S equals 2.07×10^{-13}, T°K equals 650, and t equals 0.008.

The value of K is 9.938, being calculated from equation 16 for conditions of D_c equals 1.320, and P_c equals 25,100.

The value of m is as follows

$$m = W/g\,Ah = 0.538 \qquad (58)$$

where the weight of the hammer m is 500 pounds; the value of the gravitational constant g is 385; the cross-sectional area A of the briquet is 1.767; and the height of actual briquet at unit density is 1.36.

In order to calculate the time of impact during the interval between the contact of the hammer with the coal and the point of

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[1] The concept unit briquet refers to a briquet having a density of unity when compressed to a briquet 1 inch high.

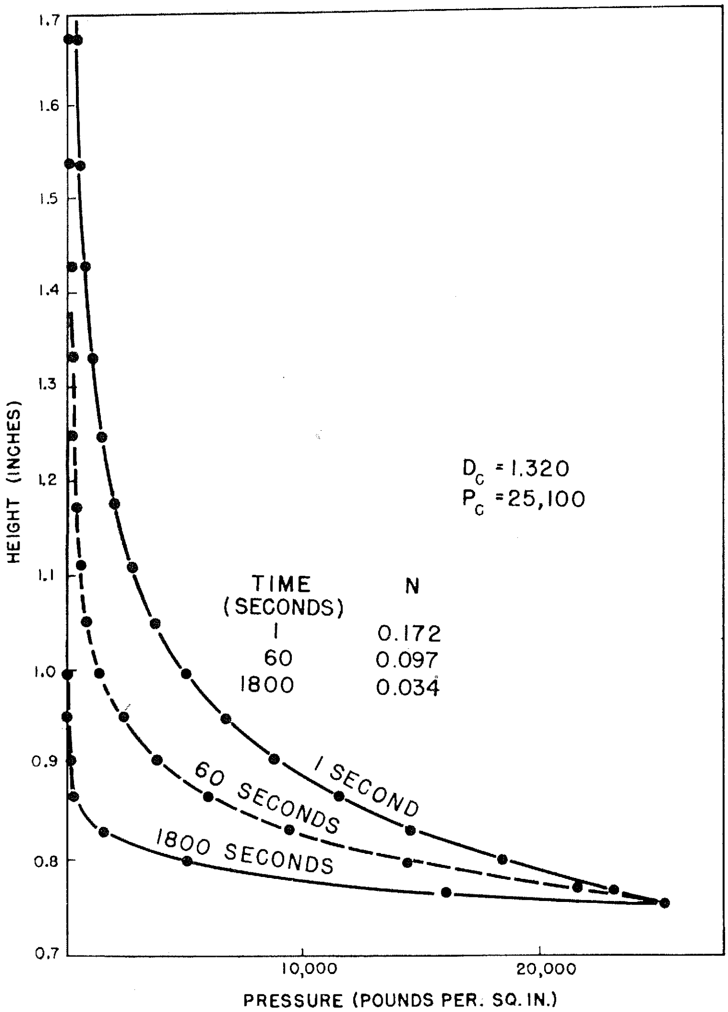

FIG. 102.—Influence of time on the compaction curve for St. Clair County briquets processed at 400° C. (Data from table 74)

maximum compression, it is necessary to find the maximum density D_m to which the briquet is impacted. The energy E of the hammer at time of impact is calculated as follows:

$$E = mgh = 11,200 \tag{59}$$

TABLE 75.—INFLUENCE OF TEMPERATURE ON THE HORSEPOWER HOUR ENERGY REQUIRED TO BRIQUET ST. CLAIR COUNTY COAL; TIME, 30 MINUTES

(Energy E calculated from equation 23)

Temperature (°C.)	N	K	E H.P.-Hours
150	0.151	3.498	8.0
300	0.094	1.963	4.6
400	0.034	1.069	1.6

TABLE 76.—INFLUENCE OF TIME ON THE HORSEPOWER-HOUR ENERGY REQUIRED TO BRIQUET ST. CLAIR COUNTY COAL; TEMPERATURE, 400°C.

(Energy E calculated from equation 23)

Time (seconds)	N	K	E H.P.-hours
1	0.172	4.328	9.2
60	0.097	2.024	4.8
1800	0.034	1.069	1.6

where m is 0.538; g is 385; and h is 54 (distance of hammer drop). Substituting this value of the energy E in equation 24, the value of the maximum density D_n is found to be 1.597.

CONSTRUCTION OF THE THEORETICAL TIME-HEIGHT GRAPH

The graph (fig. 103) represents the three parts of the hammer motion: (1) the part from the top of the uncompacted coal to the top of the compacted briquet, (2) the part traveled by the hammer to the top of the compacted briquet, and (3) the part represented by the rebound of the hammer from the top of the compacted briquet.

Part 1 of the graph (fig. 103) deals with the period of contact of the hammer with the coal and was constructed by use of equation 44 which gives the relation between time and distance, the distance being the height of the hammer from the bottom of the briquet. Parts 2 and 3 of the graph (fig. 103) deal with the periods before the hammer contacted the coal and after it rebounded from the briquet respectively, and were constructed by use of equation

$$t = \left(\frac{2\,S}{g}\right)^{1/2} \qquad (60)$$

which gives the relation between time and distance of a freely falling hammer, the

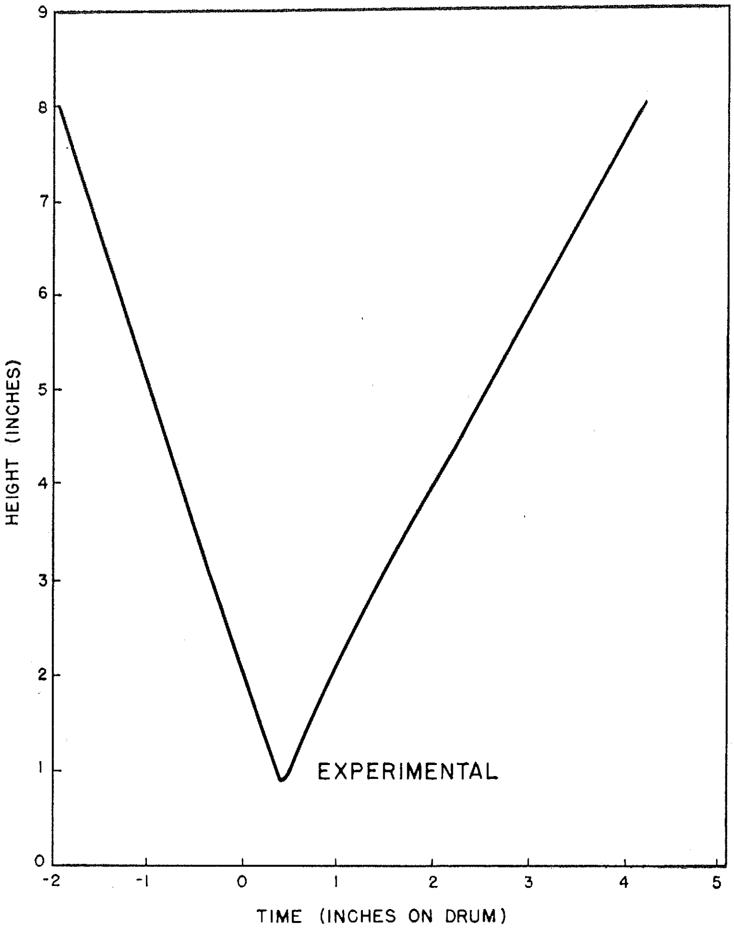

FIG. 103.—Time-distance graph of impact of hammer during briquetting —experimental. (Data from tables 77, 78, 79)

TABLE 77.—THEORETICAL TIME-DISTANCE DATA FOR IMPACT HAMMER FROM POSITION OF CONTACT WITH COAL TO POSITION OF MAXIMUM COMPRESSION OF BRIQUET

(Time t is calculated from equation 44)

(Data for Fig. 103)

Density	Height (inches)		Time (seconds)		Time[a] (inches)
	Unit	Actual	Unit	Actual	
0.610	1.639	2.230	0.0000	0.0000	0.000
0.647	1.543	2.100	0.0006	0.0008	0.052
0.679	1.471	2.000	0.0009	0.0012	0.077
0.716	1.397	1.900	0.0013	0.0018	0.118
0.755	1.324	1.800	0.0017	0.0023	0.150
0.800	1.250	1.700	0.0021	0.0030	0.196
0.851	1.176	1.600	0.0025	0.0034	0.222
0.905	1.103	1.500	0.0028	0.0038	0.248
0.975	1.029	1.400	0.0032	0.0044	0.287
1.047	0.955	1.300	0.0036	0.0049	0.320
1.134	0.882	1.200	0.0040	0.0054	0.353
1.238	0.809	1.100	0.0045	0.0061	0.398
1.320	0.758	1.030	0.0048	0.0065	0.425
1.360	0.735	1.000	0.0049	0.0067	0.437
1.511	0.662	0.900	0.0054	0.0073	0.477
1.597	0.625	0.851	0.0056	0.0076	0.496

[a] 1 inch on chronometer drum equals 0.0153 second.

distance in Part 2 being that of the hammer measured from its original position and in Part 3 being that of the hammer measured from the position of the top of its rebound.

Part 1 of graph.—For convenience the mathematical theory of the height-time relationship was developed for a unit briquet which by definition has a density of unity when compressed to a briquet an inch high. The pore-free density of the briquets made in these tests is 1.320. In order to make a pore-free briquet about 1 inch high it was necessary to use 1.36 times as much coal as was required to make a briquet of unit height $(\frac{1 \text{ inch}}{1.32})$.

By using equation 44, a series of heights (table 77, col. 3) in steps of 0.1 inch were assumed ranging from that of the uncompacted coal to that of the briquet at its maximum density. The corresponding unit heights (table 77, col. 2) were calculated by dividing the actual heights by the factor 1.36. The corresponding densities (table 77, col. 1) were calculated as the reciprocals of the unit heights. The unit time (table 77, col. 4) was calculated by equation 44, and the actual time (table 77, col. 5) was determined by multiplying the unit time (col. 4) by the factor 1.36. Column 6 gives values of actual time in inches (1 inch equals 0.0153 second).

Part 2 of graph.—Distances d in steps of 2 inches each were measured from the bottom of the briquet to the position of the hammer (table 78, col. 1).[2] The distances were measured from the original heights of the hammer, that is from 54 inches above the top of the loose coal (table 78, col. 2) to arbitrarily selected distances d.[3] The values for time, t, (table 78, col. 3) are

TABLE 78.—THEORETICAL TIME-DISTANCE DATA FOR DROP OF HAMMER PRIOR TO IMPACT OF COAL

(Time t calculated from equation 60)

(Data for Fig. 103)

d (inches)	s (inches)	Time (seconds)		$-t_3$[a] (inches)
		t_1	t_2	
8.00	48.23	0.5005	0.0290	1.900
6.00	50.23	0.5108	0.0187	1.228
4.00	52.23	0.5208	0.0087	0.571
2.23	54.00	0.5295	0.0000	0.000

[a] 1 inch on chronometer drum equals 0.0153 second.

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[2] The distance 2.23 in. is the thickness of the loose coal and represents the distance of the hammer above the bottom of the briquet when the hammer first contacts the coal.

[3] The values of S in column 2 equal 56.23 in. minus the values of d in column 1.

TABLE 79.—THEORETICAL TIME-DISTANCE DATA FOR IMPACT HAMMER FROM POSITION OF LEAVING CONTACT WITH BRIQUET
(Time t calculated from equation 60)
(Data for Fig. 103)

d (inches)	s (inches)	Time (seconds)			Time[a] (inches)
		t_1	t_2	t_3	
1.03	23.69	0.3507	0.0000	0.0087	0.562
2.03	22.69	0.3434	0.0073	0.0160	1.046
4.03	20.69	0.3279	0.0228	0.0315	2.059
6.03	18.69	0.3116	0.0391	0.0478	3.124
8.03	16.69	0.2944	0.0563	0.0650	4.248

[a] 1 inch on chronometer drum equals 0.0153 second.

TABLE 80.—INFLUENCE OF DISTANCE FROM POSITION OF MAXIMUM COMPRESSION IN SURVEY BRIQUETTING PRESS ON THICKNESS OF BRIQUET
(Data for Fig. 105)

Distance (inches)	Angle B (degrees)	Thickness (inches)
0	0.00	1.000
1	2.55	1.004
2	5.09	1.014
3	7.64	1.032
4	10.18	1.056
5	12.73	1.086
6	15.28	1.126
7	17.82	1.167
8	20.37	1.218
9	22.91	1.274
10	25.46	1.337
11	28.01	1.405
12	30.55	1.479
13	33.10	1.560
14	35.64	1.644
15	38.19	1.735
16	40.74	1.831
17	43.28	1.931
18	45.83	2.038
19	48.37	2.143
20	50.92	2.256

those for falling bodies using equation 60 in which the values used for the heights S are those given in column 2 and the value of the gravitational constant g is 385 in. per sec. per sec. The values of time (table 78, col. 4) are measured backward from the point of contact between hammer and coal considered as zero time (time equals 0.5295 second minus time t), the equivalent values of time were finally expressed in inches (table 78, col. 5).

Part 3 of graph.—The heights d of the hammer after it left the briquet were measured in steps of 2 inches each from the bottom of the briquet[4] (table 79, col. 1). Heights S were measured from the height of the rebound (table 79, col. 2) to positions S which are 24.72 inches minus d.[5] The values of time (table 79, col. 3) are calculated by use of equation 60 for various heights in column 2. The values of time (table 79, col. 4) are based on the assumption that the point at which the hammer leaves the briquet is zero time (t_2 equals 0.3507 sec. minus t). The equivalent values of time (table 79, col. 5) are based on the assumption that the point at which the hammer leaves the briquet is zero time (t_2 equals 0.3507 sec. minus t). The equivalent values of time (table 79, col. 5) are based on the assumption that the point at which the hammer contacts the loose coal is zero time.[6] The equivalent values of time (table 79, col. 6) are given in inches.

The resulting theoretical height-time graph (fig. 103) prepared from the data (tables 77, 78 and 79) shows the relationship between the height of the briquet and the necessary time of pressure application. The circles on the upper part of the left arm are from columns 1 and 5, table 77; those on the lower part of the left arm are from columns 3 and 6, table 77; and those on the right arm are from columns 1 and 6, table 79.

EXPERIMENTAL TIME-HEIGHT GRAPH

An experimental time-height graph was prepared (fig. 104) for a St. Clair County coal impacted under the identical conditions used in the calculation of the theoretical time-height graph (fig. 103).

This agreement between theory and experiment for an impact time of less than

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[4] The height 1.03 in. is equivalent to the final density (1.32) of the briquet and represents the point at which the rebounding hammer leaves the briquet.

[5] The height of rebound of the hammer is calculated from its velocity as it leaves the briquet at a density 1.32; by equation 57 this velocity is found to be 135 in. per sec.; and the height of the rebound corresponding to this velocity is 23.69 in.

[6] t_3 equals t_2 plus 0.0087 sec. The value of 0.087 sec. is the sum of the time of compaction 0.0076 sec. plus the time of expansion from maximum density to 1.320, that is 0.0011 sec.

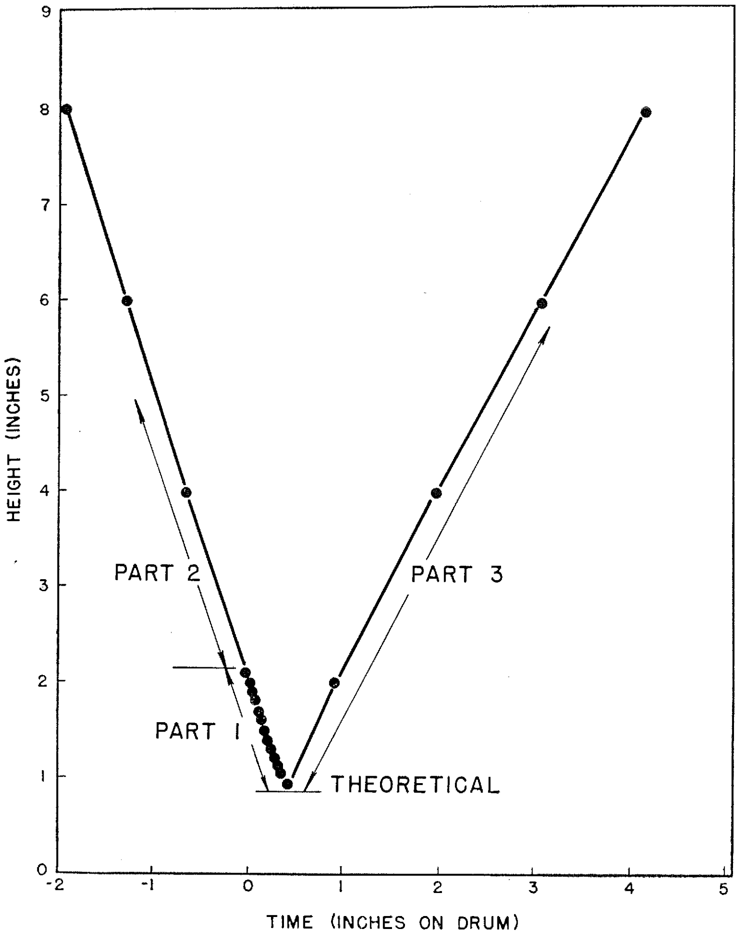

FIG. 104.—Time-distance graph of impact of hammer during briquetting—theoretical.

0.01 second (actually 0.0076 second) validates the equations (theory) for rapid briquetting developed by using equations based on the experimental results of relatively slow briquetting. Such validation of the theory provided a substantial basis for the design of the large scale eccentric rotary press. The experimental results obtained from this press provided further substantiation of the correctness of the theory.

MECHANICAL ENERGY REQUIRED FOR BRIQUETTING

That the graphic representation of mechanical energy as equal to the area beneath the energy graph is supported mathematically from the previously developed calculus equation can be shown as follows:

Consider the energy in horsepower-hours necessary to produce one ton of St. Clair County briquets at a temperature of 400° C. and at a time of 60 seconds (experimental data from table 74).

For this coal the critical density D_c equals 1.320 and the critical pressure P_c equals 25,100 pounds per sq. in. From equation 6 (p. 163) the pressure exponent N

$$N = N_o - S \times \overline{T^\circ K}^{\,4} \log t \tag{61}$$

where, from table 71, N_0 equals 0.172 and S equals 2.07×10^{-13} for St. Clair County coal. Substituting these values equation 13 becomes

$$N = 0.172 - 2.07 \times 10^{-13} \times \overline{673}^{\,4} \times \log 60 = 0.097 \tag{62}$$

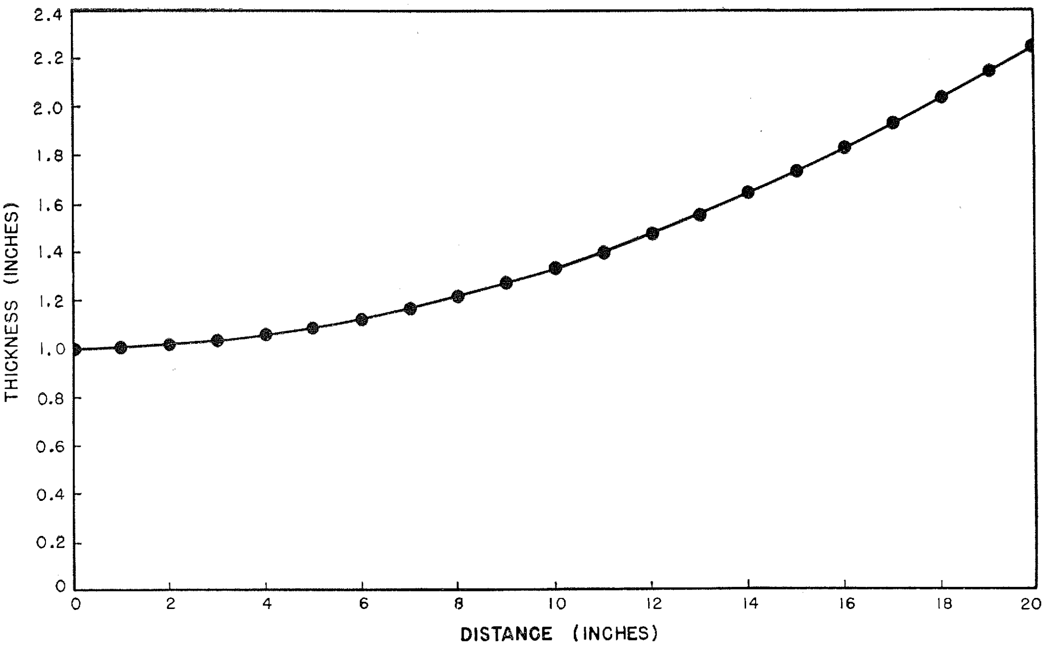

FIG. 105.—Influence of distance of briquet from its position at maximum compression in Piersol briquetting press on thickness of briquet. (Data from table 80)

TABLE 81.—INFLUENCE OF DISTANCE FROM POSITION OF MAXIMUM COMPRESSION IN SURVEY BRIQUETTING PRESS ON DENSITY OF VARIOUS COALS
(Data for Fig. 106)

Distance (inches)	Thickness (inches)	Densities				
		$D_c = 1.27$	$D_c = 1.29$	$D_c = 1.32$	$D_c = 1.38$	$D_c = 1.40$
0	1.000	1.270	1.290	1.320	1.380	1.400
1	1.004	1.265	1.285	1.315	1.375	1.394
2	1.014	1.252	1.272	1.302	1.361	1.380
3	1.032	1.230	1.250	1.279	1.337	1.356
4	1.056	1.202	1.222	1.250	1.307	1.326
5	1.086	1.169	1.188	1.215	1.271	1.289
6	1.126	1.128	1.146	1.172	1.226	1.243
7	1.167	1.088	1.107	1.131	1.183	1.199
8	1.218	1.043	1.059	1.084	1.133	1.149
9	1.274	0.997	1.013	1.036	1.083	1.099
10	1.337	0.950	0.966	0.987	1.033	1.047
11	1.405	0.904	0.918	0.939	0.982	0.996
12	1.479	0.859	0.872	0.892	0.933	0.946
13	1.560	0.814	0.827	0.846	0.885	0.898
14	1.644	0.772	0.785	0.803	0.840	0.852
15	1.735	0.732	0.744	0.761	0.796	0.807
16	1.831	0.694	0.705	0.721	0.754	0.765
17	1.931	0.658	0.668	0.684	0.715	0.725
18	2.038	0.623	0.633	0.648	0.677	0.687
19	2.143	0.593	0.602	0.616	0.644	0.653
20	2.256	0.563	0.572	0.585	0.612	0.621

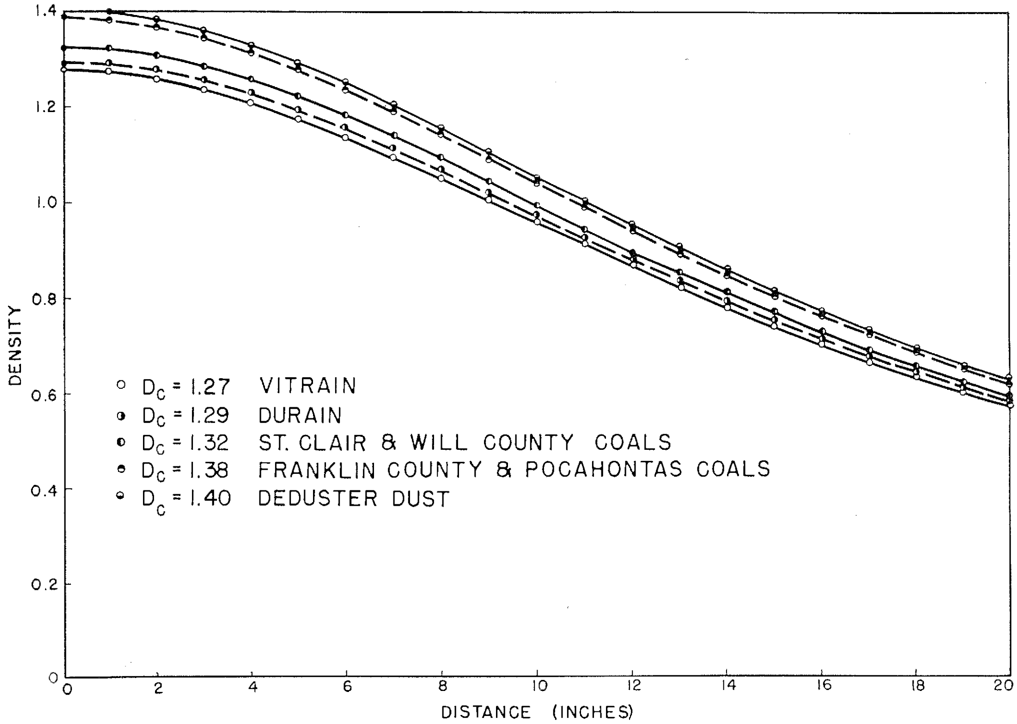

FIG. 106.—Influence of distance of briquet from its position at maximum compression in Piersol briquetting press on density of briquets made from various coals. (Data from table 81)

From equation 16 the briquetting constant K

$$K = P_c \frac{N}{DC} \qquad (63)$$

Substituting the above values equation 13 becomes

$$K = 25{,}100 \frac{0.097}{1.320} = 2.025 \qquad (64)$$

From equation 23 the mechanical energy E required for making a unit briquet (one cubic inch at unit density with weight of 16.387 grams) is

$$E = \frac{NK^{\frac{1}{N}} \; D^{\frac{1-N}{N}}}{1-N} \qquad (65)$$

Substituting in the above values

$$E = \frac{0.097 \times 2.025^{\frac{1}{0.097}} \times 1.32}{1\text{-}0.097} \; \frac{1\text{-}0.097}{0.097} = 2044 \qquad (66)$$

One ton (2000 pounds) is equivalent to 9.07×10^5 grams. Thus it takes 5.56×10^4 unit briquets (16.387 gr.) to weigh one ton. Thus the energy required to make one ton of these briquets under above conditions is the product of the number of briquets per ton and the energy necessary to make each briquet; this product is 1.136×10^8 inch pounds which is 9.47×10^6 foot-pounds. One horsepower-hour equals 1.98×10^6 foot-pounds. Therefore it requires 4.8 horsepower-hours to briquet one ton of St. Clair County coal at 400° C. and 60-second periods of application of pressure.

INFLUENCE OF TEMPERATURE

By the same method of calculation, the influence of temperature on energy used to briquet St. Clair County coal for 30 minutes was determined (table 75 and fig. 101) and the results indicate that the energy decreases with increase in temperature, thus agreeing with data shown in figure 101.

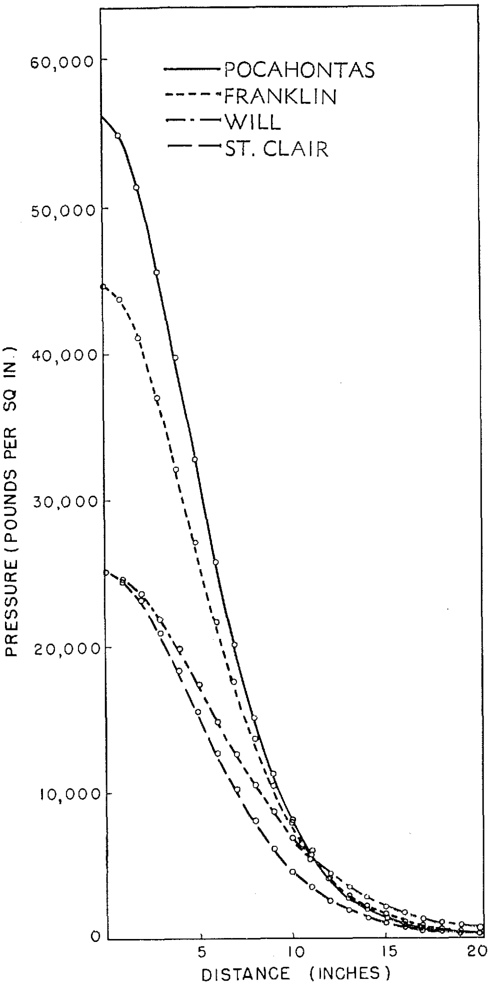

FIG. 107.—Influence of distance of briquet from its position at maximum compression in Piersol briquetting press on pressure of briquets made from various coals. (Data from table 83)

INFLUENCE OF TIME

The influence of time on the energy used to briquet St. Clair County coal at 400° C. was likewise determined (table 76, fig. 69) with results indicating that energy decreases with increase of time, the same trends being indicated as are shown graphically in figure 102.

PRESSURE DISTRIBUTION IN PIERSOL PRESS

From the eccentricity and the diameters of the dies in the Piersol press, the width of opening between the dies may be determined from various distances from the position of maximum compression. Referring again to fig. 6, article 1, the width S of the spacing between the dies may be calculated from

$$S = D - A \cos B - [A^2 \cos^2 B - A^2 + C^2]^{1/2} \qquad (67)$$

Where diameter D of the outer die is 22.5 in., the diameter C of the inner die is 18.5 in., the distance A between centers is 3 in., and the angle B measures the circumference distance from position of maximum compression.

TABLE 82.—INFLUENCE OF TEMPERATURE ON DISTANCE-PRESSURE DISTRIBUTION FROM BRIQUETS FROM FRANKLIN COUNTY COAL
(Data for Fig. 109)

Distance (inches)	Pressure (Pounds per sq. in.)		
	150°C $N=0.148$	250°C $N=0.133$	350° C $N=0.095$
0	44,700	44,700	44,700
1	43,700	43,500	43,200
2	40,900	40,600	39,000
3	36,300	35,600	32,400
4	31,500	30,600	26,100
5	25,400	24,000	18,600
6	20,300	19,100	13,100
7	15,800	14,300	8,800
8	11,900	10,500	5,700
9	8,700	7,400	3,500
10	6,300	5,200	2,100
11	4,500	3,600	1,300
12	3,200	2,500	730
13	2,200	1,700	420
14	1,600	1,100	240
15	1,100	760	120
16	770	510	80
17	510	340	40
18	370	230	30
19	260	160	20
20	180	110	10
Total pressure	300,190	286,510	243,970

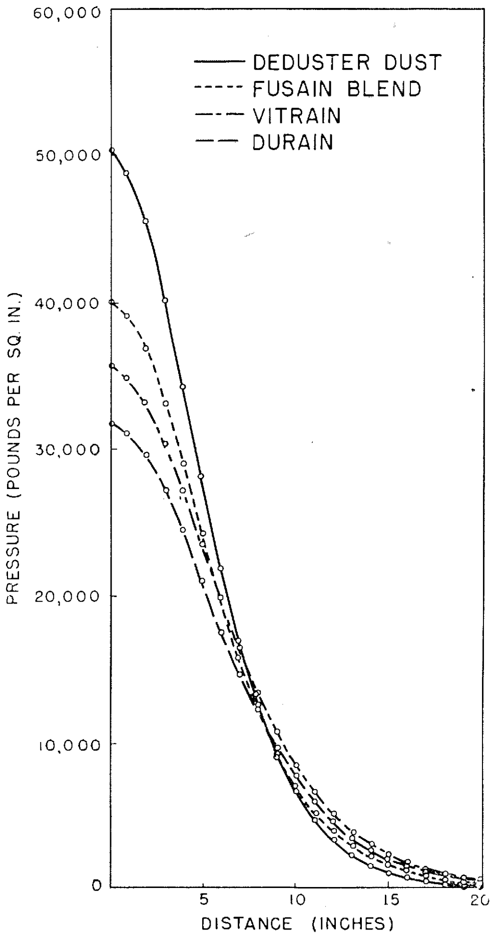

FIG. 108.—Influence of distance of briquet from its position at maximum compression in Piersol briquetting press on pressure of briquets made from various coals. (Data from table 83)

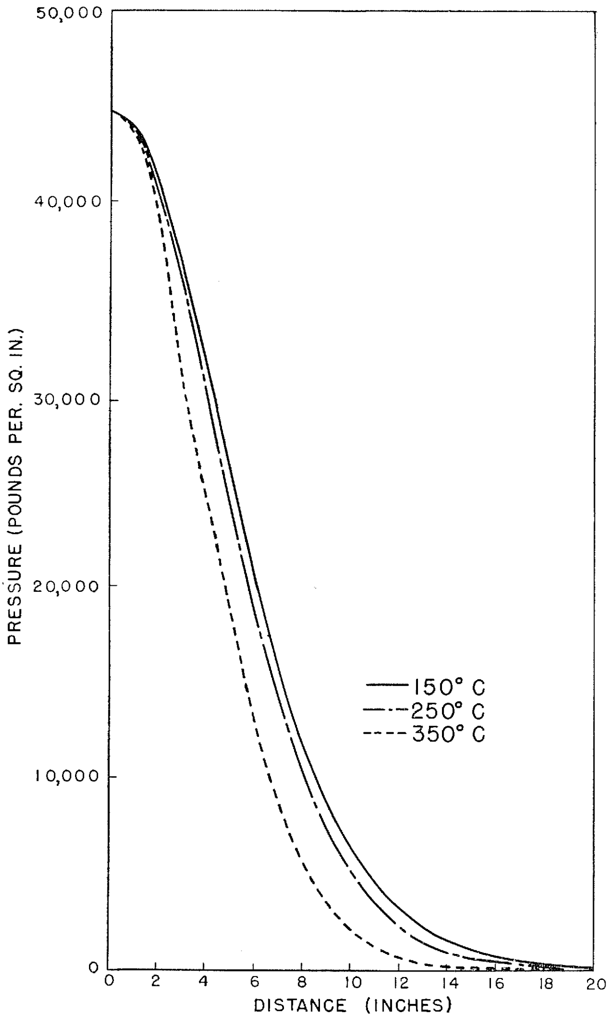

FIG. 109.—Influence of distance of briquet from its position at maximum compression in Piersol briquetting press on pressure of briquets made from Franklin County coal. (Data from table 82)

TABLE 83.—INFLUENCE OF DISTANCE FROM POSITION OF MAXIMUM COMPRESSION IN SURVEY BRIQUETTING PRESS ON PRESSURE OF VARIOUS COALS
(Data for Figs. 107-108)

Distance (in.)	Pressure (Pounds per sq. in.)							
	St. Clair Co.	Will Co.	Franklin Co.	Pocahontas W. Va.	Deduster dust	Fusain blend	Vitrain	Durain
0	25,100	25,100	44,700	56,200	50,100	39,800	35,500	31,600
1	24,500	24,600	43,700	54,800	48,700	39,000	34,800	31,000
2	23,100	23,600	41,100	51,300	45,400	36,700	33,100	29,400
3	20,900	21,800	37,000	45,600	40,000	33,000	30,300	27,000
4	18,300	19,700	32,100	39,700	34,100	28,800	27,000	24,300
5	15,500	17,400	27,200	32,700	28,000	24,400	23,400	20,900
6	12,600	14,800	21,800	25,500	21,700	19,700	19,600	17,400
7	10,200	12,600	17,500	20,100	16,900	15,900	16,400	14,600
8	8,000	10,500	13,600	15,100	12,500	12,300	13,200	11,800
9	6,100	8,600	10,300	11,200	9,100	9,400	10,600	9,400
10	4,600	6,900	7,700	8,100	6,500	6,900	8,300	7,600
11	3,500	5,400	5,800	6,100	4,600	5,300	6,500	5,800
12	2,500	4,400	4,200	4,100	3,200	3,900	5,000	4,500
13	1,900	3,500	3,000	2,900	2,200	2,800	3,800	3,400
14	1,400	2,800	2,200	2,000	1,500	2,100	2,900	2,600
15	1,000	2,100	1,600	1,400	1,000	1,500	2,300	2,000
16	740	1,700	1,100	1,000	710	1,100	1,700	1,500
17	550	1,300	830	700	490	770	1,300	1,200
18	400	1,100	600	490	330	580	1,000	890
19	300	850	440	350	230	420	780	700
20	220	670	320	250	160	320	610	540
Total pressure	181,390	209,420	317,690	381,290	327,420	285,290	278,090	248,130

From the value of the density of the briquet at maximum compression and from the above width of opening distribution the pressure distribution may be calculated from the briquetting equation (Article 8) for any coal for which the briquetting constants have been determined experimentally. This permits the calculation of effect of temperature on pressure distribution for the press. Thus for a given set of dies of known dimensions and eccentricity, information necessary for the required mechanical strength of the press may be calculated from the pressure distribution.

THICKNESS OF BRIQUET

As the thickness of a briquet during its compression is equal to the width of the opening between the dies, this distribution of briquet height at various distances from position of maximum compression is shown in figure 68 (data from table 61).

DENSITY DISTRIBUTION FOR VARIOUS COALS

The optimum pressure for forming a briquet is that which is required to compress it to its critical density. With this consideration in mind, figure 70 (data from table 61) shows the density distribution in the Piersol press for St. Clair, Will, and Franklin County coal, for Pocahontas coal, for deduster dust, for fusain blend, for vitrain and for durain.

PRESSURE DISTRIBUTION OF VARIOUS COALS

Figures 70 and 71 (data from table 63), which show pressure distribution and total pressure for these coals, reveal that the total pressure required by this press ranges up to 380,000 pounds (Pocahontas coal). A comparison of these 8 curves (figs. 70 and 71) further reveals that the critical pressure is the important factor which influences the total amount of pressure required to briquet a particular coal.

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