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THE INFLUENCE OF STORAGE CONDITIONS UPON THE PHYSICAL PROPERTIES OF LIGNITE

By

Carl J. Eckhardt, Jr.

and

Chapin Winston Yates

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The benefits of education and of useful knowledge, generally diffused through a community, are essential to the preservation of a free government.

Sam Houston

Cultivated mind is the guardian genius of Democracy, and while guided and controlled by virtue, the noblest attribute of man. It is the only dictator that freemen acknowledge, and the only security which freemen desire.

Mirabeau B. Lamar

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The helpfulness of these individuals has constituted a sub-substantial contribution to the conduct of this investigation. The purpose of this acknowledgment is to assure the fact that the appropriate credit is given to these individuals for their timely assistance.

PART 1

INTRODUCTION

The fact that the American people are being called upon at this time to alter radically their mode of living in many respects has established at once the need for careful thinking and the creation of a new yet appropriate sense of values. One important reason for America's greatness in the past has been the tremendous natural resources with which it has been endowed. Much depends now upon the fashion in which the United States continues to utilize these resources both for its own more abundant life and for that of other peoples of the world.

In 1939, Texas produced minerals, which aggregated 16½ per cent of the nation's total, valued at $701,939,862.00.[1] The pattern of this State's mineral productivity is at once of great interest to the student of matters related to fuels because of the paradoxical circumstances under which this productiveness has been developed. This interest may be attributed to the prolific production of liquid and gaseous fuels on one hand and the almost negligible production of solid fuels on the other. Thus in the year under consideration the value of the petroleum, natural gas, and natural gasoline produced represented more than 91 per cent of the State's total, but the value of the solid fuel produced approximated only 0.1 per cent of this total value.

The liquid, gaseous and solid fuels deposited within the confines of the State of Texas have made the productivity of this commonwealth assume a position of very great importance to the nation as a whole. Inasmuch as it produces more than twice as much petroleum and natural gas as any other state of the nation, its position as a source of potential energy is almost universally recognized. These fuels lend themselves very readily to transportation. As a result of this circumstance Texas' contribution to the American way of life has been very great in this respect. Unfortunately, however, even the State of Texas itself has not yet become conscious of the extent to which it may need in the ultimate to resort to the use of its lignitic solid fuels in order to preserve the present pattern of its existence or to improve upon that pattern in the future.

The position of eminence occupied by Texas in the production of petroleum is very clearly revealed by the statistical data which follow.

TABLE I

U. S. PRODUCTION OF CRUDE PETROLEUM FOR 1940[2]
BY STATE AND RANK

(Thousands of Barrels)

State	1940 Production	1940 Rank	Cumulated Production	Cumulated Rank
Texas	493,126	1	6,579,724	1
California	223,881	2	5,570,078	2
Oklahoma	155,952	3	4,805,911	3
Illinois	146,788	4	698,813	7
Louisiana	103,961	5	1,060,366	5
Kansas	66,270	6	1,121,064	4
New Mexico	39,001	7	274,631	12
Wyoming	25,683	8	500,950	10
Arkansas	25,583	9	506,225	9
Michigan	19,764	10	145,117	14
Pennsylvania	17,353	11	997,068	6
Montana	6,768	12	83,532	17
Kentucky	5,193	13	167,166	13
New York	4,999	14	118,777	16
Indiana	4,843	15	130,975	15
Mississippi	4,380	16	4,487	19
West Virginia	3,444	17	410,770	11
Ohio	3,169	18	588,387	8
Colorado	1,350	19	39,620	18
Other States	339	....	1,390	....
U. S. Total	1,351,847		23,805,051	

Thus it is apparent that Texas produced 36.5 per cent of the nation's total petroleum in 1940 and that it has produced 27.6 per cent of the nation's cumulated total production. The true significance of this production of petroleum cannot, however, be observed by inspecting data relating to the United States alone. For that reason additional data are presented here.

TABLE II

PRODUCTION OF CRUDE PETROLEUM FOR 1940[3]

Geographical Subdivision	Production in Barrels	Texas' Per Cent of Total
Texas	493,126,000	100.0
United States	1,351,847,000	36.5
North and South America	1,668,571,000	29.6
World Total	2,146,105,000	23.0

These data give abundant evidence of the fact that this productivity on the part of Texas has begun and will continue to be of tremendous importance to the economic welfare of the people of the world in time of peace and to the survival of this nation in time of global war.

The statistical data which relate to the position which Texas has taken with regard to the production of gaseous fuel are no less interesting. Even though Texas produced more than three times as much natural gas as any other state in the nation in 1939, its production increased more than 18 per cent in 1940.

TABLE III

U. S. PRODUCTION OF NATURAL GAS FOR 1940 BY STATE AND RANK[4]

(Millions of Cubic Feet)

State	1940 Production	Rank
Texas	1,575,000	1
Louisiana	435,000	2
California	430,000	3
Oklahoma	310,000	4
West Virginia	205,000	5
Illinois	131,000	6
New Mexico	126,000	7
Kansas	115,000	8
Pennsylvania	102,000	9
Kentucky	59,000	10
Ohio	50,000	11
Arkansas	41,000	12
Wyoming	40,000	13
Montana	27,200	14
New York	15,200	15
Michigan	14,000	16
Mississippi	6,800	17
Indiana	3,200	18
Colorado	2,900	19
Missouri	400	20
Other States	5,400	....
U. S. Total	3,694,100	....

Thus is becomes apparent that Texas is producing more than 40 per cent of the nation's supply of natural gas.

No claim for distinction as a solid fuel producing State may be made for Texas. The justification for this statement may be seen in the data which follow:

TABLE IV

PRODUCTION OF SOLID FUEL IN 1940[5]

(In Tons)

State	Total Production	Rank
Pennsylvania	168,087,639	1
West Virginia	126,437,621	2
Illinois	50,610,430	3
Kentucky	49,140,904	4
Ohio	22,771,552	5
Indiana	18,868,572	6
Virginia	15,348,075	7
Alabama	15,324,163	8
Colorado	6,588,742	9
Tennessee	6,008,456	10
Wyoming	5,808,042	11
Kansas	3,578,952	12
Utah	3,575,586	13
Iowa	3,231,177	14
Missouri	3,096,741	15
Montana	2,867,200	16
North Dakota	2,218,434	17
Washington	1,650,352	18
Oklahoma	1,645,981	19
Maryland	1,503,433	20
Arkansas	1,453,611	21
New Mexico	1,110,615	22
Texas	620,555	23
Other States	709,307	....
U. S. Total	512,256,140	....

Thus it becomes apparent that in the field of solid fuel production Texas accounts for only 0.2 per cent of the nation's total.

The present productiveness or lack of productiveness under these circumstances is naturally important to practically every phase of the nation's activity. The crux of the situation cannot, however, be found by considering production alone. The factors of prime importance with which the nation as a whole and each of its subdivisions should be concerned are (1) the period of time during which the nation may expect to continue to receive these important supplies at their present rate of utilization, (2) the extent to which it may accelerate present rates of production for its own improvement and that of other nations, and (3) the fashion in which it may project the use of these resources as far into the future as possible with propriety. In order to consider these factors some conception must be gotten of the magnitude of the estimated reserves of these fuels to which the nation has access. Despite the fact that there is no method by which the precise magnitude of these reserves can be established, the consideration of the most reliable information of this character available is not without purpose.

TABLE V

ESTIMATED PROVED U. S. CRUDE OIL RESERVES

(Thousands of Barrels)

	1940 Production[2]	Estimated Proved[6] Reserve Jan. 1, 1941	Period of Adequacy In Years
Arkansas	25,583	306,218	11.97
California	223,881	3,291,382	14.70
Colorado	1,350	23,223	17.20
Illinois	146,788	315,305	2.14
Indiana	4,843	13,703	2.83
Kansas	66,270	692,088	10.44
Kentucky	5,193	40,999	7.89
Louisiana	103,961	1,215,459	11.69
Michigan	19,764	34,579	1.75
Mississippi	4,380	40,242	9.19
Montana	6,768	89,443	13.22
Nebraska	251	3,749	14.94
New Mexico	39,001	692,141	17.75
New York	4,999	65,001	13.00
Ohio	3,169	30,284	9.56
Oklahoma	155,952	1,001,909	6.42
Pennsylvania	17,353	187,647	10.81
Texas	493,126	10,623,516	21.54
West Virginia	3,444	52,444	15.23
Wyoming	25,683	304,821	11.87
Other States	88	362	4.11
U. S. Total	1,351,847	19,024,515	14.07

Texas' petroleum reserve of 10,623,516,000 barrels of oil represents more than 55 per cent of the nation's total reserve. Approximately 34 per cent of proved petroleum reserve of the world is deposited in this State. Callous thinking on the part of many individuals has caused them to conclude that the vastness of this reserve justifies the lack of concern over the conservation of this most critical material. The vastness and importance of this supply of petroleum impose a very solemn obligation upon the commonwealth so endowed to produce and utilize it with sound judgment.

A study of the foregoing information need not cause any dour and doleful misgivings in this matter. An examination of the table which follows will reveal the fact that with the passage of the years the known petroleum reserve has increased despite the increase in the rate of production. Yet it should be observed that present known reserves are adequate in all cases for a comparatively short period of years. If the reserves are subsequently extended materially, the period of their adequacy in the case of petroleum is still a very short period of time. Particular significance attaches itself, therefore, to the nation's dedicating itself to the very careful conservation of a source of energy which is now being produced under optimum circumstances but will subsequently no doubt have to be produced under less favorable circumstances.

TABLE VI

ESTIMATES OF U. S. CRUDE OIL RESERVES AND COMPARATIVE PRODUCTION[7]

(Thousands of Barrels)

Year	Estimates Reserves Beginning of Year	Cumulated Production Prior to Estimate	Actual Production Subsequent to Estimate
1939	17,348,146	21,187,141	.....
1938	15,507,000	19,973,887	1,213,254
1937	13,063,000	18,694,727	2,492,414
1935	12,177,000	16,598,444	4,588,697
1934	13,300,000	15,690,379	5,496,762
1925	5,000,000	7,905,929	13,281,212
1921	9,000,000	5,429,868	15,757,273
1915	7,500,000	3,335,457	17,851,684
1914	6,000,000	3,069,694	18,117,447

The extent to which present reserves may be extended is naturally problematical. Some general idea of the magnitude of the adequacy in years may nevertheless be gotten from the foregoing tabulation. Information of value may, moreover, be gotten when the supposed periods of adequacy of the different fuels are compared.

TABLE VII

U. S. KNOWN NATURAL GAS RESERVES OF 1935[8]

Region	Reserve Trillions of Cubic Feet	Per Cent
Appalachian Field	7.0	11.3
North Central State	0.1	0.2
Midcontinent and Gulf Coast Fields	47.0	75.8
Rocky Mountain States	2.0	3.2
California	5.9	9.5
	62.0	100.0

By virtue of the fact that the present annual production of this fuel exceeds three trillion cubic feet per annum it appears that the present known reserve constitutes a twenty-year supply. If more liberal values of the magnitude

of the reserves are selected a one hundred trillion cubic feet reserve may be regarded as a thirty-year supply of this gaseous fuel.

Only a casual inspection of information relating to the nation's solid fuel reserve is required to reveal the fact that its magnitude is of a very much greater order than that of the known petroleum and known natural gas reserves.

TABLE VIII

U. S. SOLID FUEL RESERVES OF 1936[9]

State	1939 Production Millions of Tons	Estimates Reserve Millions of Tons	Period of Adequacy Years
Pennsylvania	143.7	117,890	820
West Virginia	107.9	147,748	1,369
Illinois	46.5	197,795	4,258
Kentucky	42.8	121,546	2,840
Ohio	19.6	91,960	4,692
Indiana	16.7	51,974	3,112
Virginia	13.2	21,136	1,601
Alabama	12.0	66,627	5,552
Colorado	5.9	316,758	53,688
Wyoming	5.4	620,310	114,872
Tennessee	5.3	25,290	4,772
Utah	3.3	93,128	27,882
Missouri	3.3	83,681	25,512
Iowa	3.1	28,693	9,407
Kansas	2.9	29,654	10,155
Montana	2.8	380,932	135,562
North Dakota	2.1	599,946	287,055
Washington	1.7	63,666	37,672
Maryland	1.5	7,678	5,222
New Mexico	1.2	20,673	17,085
Oklahoma	1.2	54,756	46,403
Arkansas	1.1	1,516	1,352
Texas	0.8	30,913	38,640
Other States	0.7	6,381	9,668
U. S. Total	444.55	3,180,765	7,155

The pattern of the fuel conservation problem with which Texas is confronted is much like that of the parent nation. Inasmuch, however, as Texas' responsibility to the rest of the nation with regard to the provision of liquid and gaseous fuels is exceptionally great, more than a usual amount of responsibility must be assumed by it. Only a casual inspection of the actual facts relating to Texas' sources of potential energy is required to reach a very pertinent conclusion.

TABLE IX

TEXAS' PRODUCTION, RESERVES, AND PERIOD OF ADEQUACY OF POTENTIAL ENERGY

Fuel	Annual Production Trillions of Btu.	Reserve Trillions of Btu.	Period of Adequacy Years
Solid Fuel	9	450,000	50,000
Liquid Fuel	3000	60,000	20
Natural Gas	1500	30,000	20

The foregoing data reveal three very significant facts which deserve the careful consideration of all individuals who are interested in the welfare of this commonwealth and hence the welfare of the nation. They are as follows:

1. The potential energy which reposes in Texas' solid fuel reserve is five times as great as that of petroleum and natural gas combined.
2. The rate of utilization of potential energy in the form of liquid and gaseous fuels combined is 500 times as great as that of solid fuel.
3. The period of adequacy of the solid fuel reserve at its present rate of utilization is 2,500 times as great as that of either petroleum or natural gas.

Unconcern over the facts presented hereinbefore must lead to the ultimate retrogression in the progress and stability of the nation's pattern of human existence.

Many people rest sublimely upon the hypothesis that long before natural resources have been depleted human ingeniousness will have made due provision for the depletion of such materials. A short sighted policy of this nature can lead only to destruction. Improvements of tremendous importance have been made with the passage of the years in the economy with which such natural resources may be utilized. No single improvement nor all improvements combined justify for even a moment the belief that the conservation of the natural resources is either less important or less necessary than before. The ingeniousness of all scientists and engineers, who have devoted the best attributes of their nature to this important and critical problem, has had as its inspiration the inherent desire to project the blessings endowed by Providence as far into the future as possible.

Texas' supply of lignite approximates 23 billion tons. It is composed among other constituents by 35 per cent of moisture as mined. It may not be transported or utilized with the ease which is characteristic of liquid and gaseous fuels. It cannot, in fact, be used for many purposes for which liquid and gaseous fuels appear to be indispensable. The existing failure to use this reserve of potential energy to a greater extent must be attributed to sheer ignorance and the unwillingness of the people of the State to concern themselves with a just obligation and responsibility. The very fact that the more admirable fuels are essential in many cases justifies the efforts which are being put forth to find the means by which lignite may be used in a balanced program of purposeful fuel utilization.

The opportunity for purposeful research in this field is very great by virtue of the fact that little investigative work has thus far been done. Within a period of approximately twenty years enough has been learned about lignite as a grate fired fuel to improve the efficiency with which it may be burned approximately 20 per cent. In the same period the technique for burning this fuel in pulverized form has been developed to a considerable extent at two important Texas power-generating stations both of which have since been converted to the use of natural gas. Inasmuch as little of the basic fundamental information with regard to lignite has as yet been made available, an almost unlimited opportunity for research exists in the following fields:

1. The development of processes by means of which lignite may be used economically as a solid fuel for direct heat liberation purposes.

2. The development of processes by means of which gas producing units established directly upon the lignite beds may be used to provide potential energy through existing underground distribution networks.
3. The development of processes by means of which liquid fuels may be manufactured from such lignitic solid fuel.

In all three cases the principal process will, no doubt, be accompanied by by-product processes which are likewise of importance. The field of research in lignite is in fact yet so young that a single research project may cast an important influence upon each of the phases of endeavor mentioned above.

PART 2

PURPOSE OF INVESTIGATION

General information with regard to the tendency of lignite to shatter and disintegrate while in storage and while being handled appears to abound. The following statements relating to this characteristic are typical:

"It does not store successfully in lump form. After being in storage for a short time, the lumps shatter and disintegrate and the coal virtually pulverizes itself, making it difficult to keep it on the ordinary grate surface."[10]

"When exposed to relatively dry air, the raw lump lignite loses much of this moisture and disintegrates into fine particles or loosely coherent lumps; such a mass is practically unburnable because, unlike bituminous coal, it does not fuse together or coke in a fire."[11]

The foregoing statements, if qualified to provide specific information with regard to storage conditions, are true. It should not, however, be inferred that lignite undergoes such an extensive size degradation under all storage conditions. As might very naturally be supposed, the extent of the size degradation depends upon the nature of the storage conditions. The extent of this variation may be observed on an accompanying illustration which shows the slacking tendencies of identical lignite samples stored under like storage conditions with but one exception, namely, the number and frequency of moisture absorption-rejection cycles. The variable factor just mentioned was used in this case because it was believed to be of considerable importance in the case of the size degradation processes of this low rank solid fuel.

Despite the fact that specific and reliable information with reference to this characteristic of lignite based upon painstaking experimental work does not abound, very little has been done to enlarge knowledge in this respect. The fact that the characteristics of this solid fuel are still spoken of in terms of generalities accounts to a considerable extent for the failure to utilize this source of potential energy to a greater extent. It does not, however, seem reasonable to presume that lignite will be used to any greater extent in the immediate future unless considerably more fundamental information is made available.

Programs of this nature are usually conducted for the purpose of making observations of a relative character in the case of different fuels of a standard size or for the purpose of testing different sizes of the same fuel. The test program hereinafter described relates specifically to neither of these usual test procedures. Instead in this case an effort has been made to determine the physical properties of lignite and the extent to which these properties are influenced by the presence, absence, addition, and removal of moisture. An effort has been made in this case to study under various storage conditions the influence of variation in moisture content upon the size degradation, slack index, size stability, friability, dust index, and loss in weight of Texas lignite.

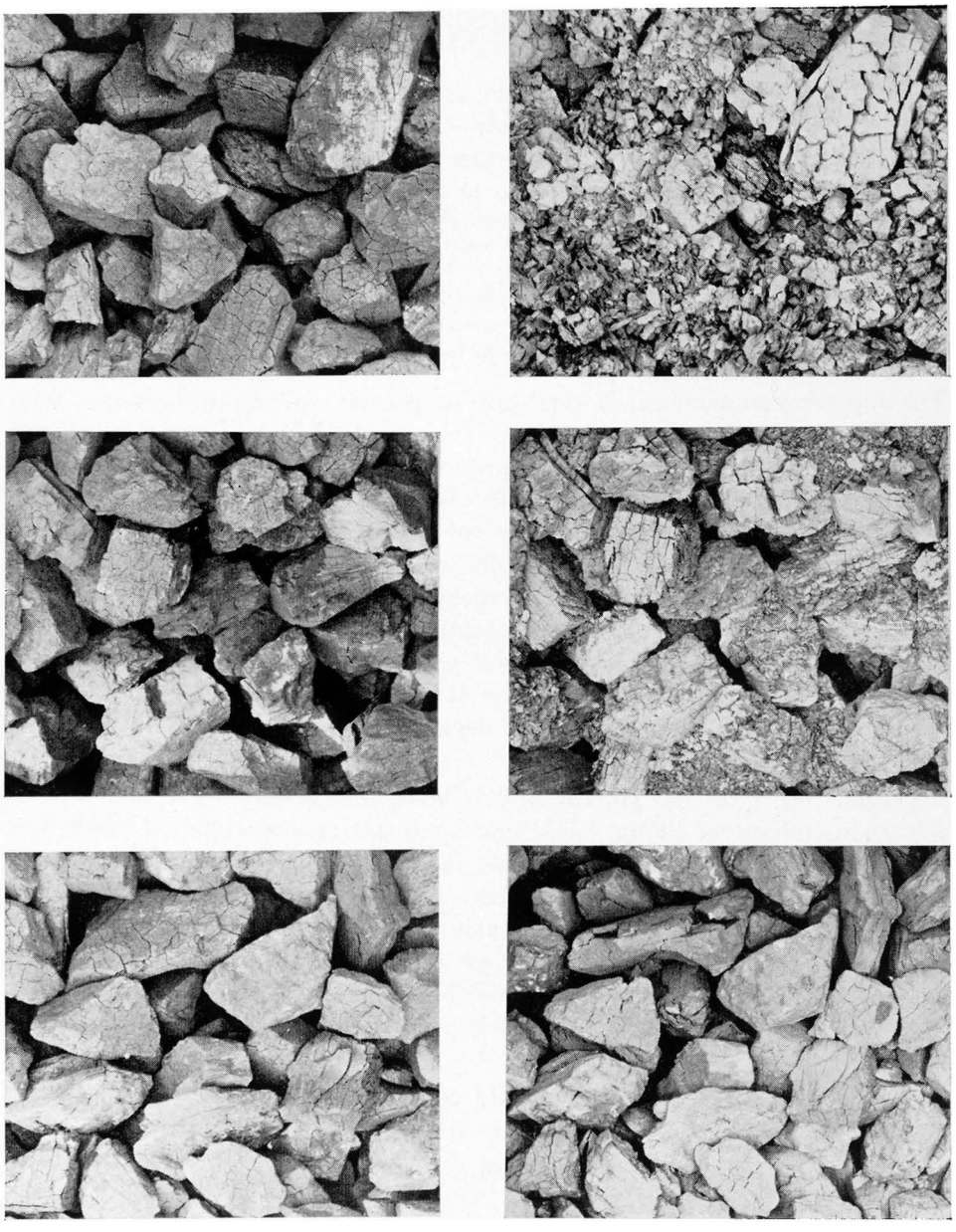

FIG. 1. Photographic record of lignite showing condition of samples at the beginning and end of 21-day storage period with but one variable factor. Lignite in the top views was permitted to undergo one moisture absorption-rejection cycle each 48 hours, that in center views was permitted to undergo six such cycles each 48 hours and that in the bottom views was permitted to undergo one continuous moisture rejection phase.

In this case moisture content was selected as the variable factor because it was believed to be the most critical factor in the slacking process of this solid fuel. Fieldner, Selvig, and Frederic[12] have described the mechanics of the slacking process in the following manner:

"Coals that slack readily contain relatively large amounts of moisture. When exposed to the weather such coals lose moisture rapidly. As the coal loses moisture at the surface there is a gradual drift of moisture from the interior of the piece to the surface. If the loss of moisture at the surface proceeds at a faster rate than it is replaced by moisture from the interior of the coal piece, there undoubtedly is greater shrinkage of the coal at the surface as compared to the interior of the piece and stresses are generated in the surface coal. These stresses in the surface coal cause it to crack and disintegrate. Likewise when air-dried coal is wetted by rain, the exposed surfaces of the coal pieces gain moisture more rapidly than the interior of the piece, causing greater expansion in the surface coal and the coal breaks down further. As this process of air-drying and wetting is continued when the coal is exposed to the weather, the slacking proceeds and the exposed lumps of coal may disintegrate completely."

Inasmuch as the cause of the disintegration of such lignite was known in advance in this case, the program was confined to a series of repetitive tests for the purpose of determining specific values of the properties previously mentioned as the storage period of the lignite under observation was extended over a period of 160 days.

PART 3

PREPARATION OF SAMPLES

In order to study the influence of storage conditions upon these physical properties seven series of samples of lignite were prepared for the following types of storage:

1. Samples exposed directly to the atmosphere.
2. Samples exposed to the atmosphere but protected from sunshine.
3. Samples exposed to the atmosphere but protected from rain.
4. Samples exposed to the atmosphere but protected from both sunshine and rainfall.
5. Samples exposed to the atmosphere in a basement to avoid wide variations in temperature and humidity.
6. Samples sealed in steel containers and subjected to atmospheric temperatures.
7. Samples submerged under water in steel containers and subjcted to atmospheric temperatures.

In order that these tests might be conducted a sufficient amount of lignite was screened to obtain 22,512 pounds of this solid fuel consisting of particles all of which passed through a 3-inch screen and all of which were retained upon a 2-inch screen. The samples so prepared possessed the following characteristics upon an "As Prepared" basis:

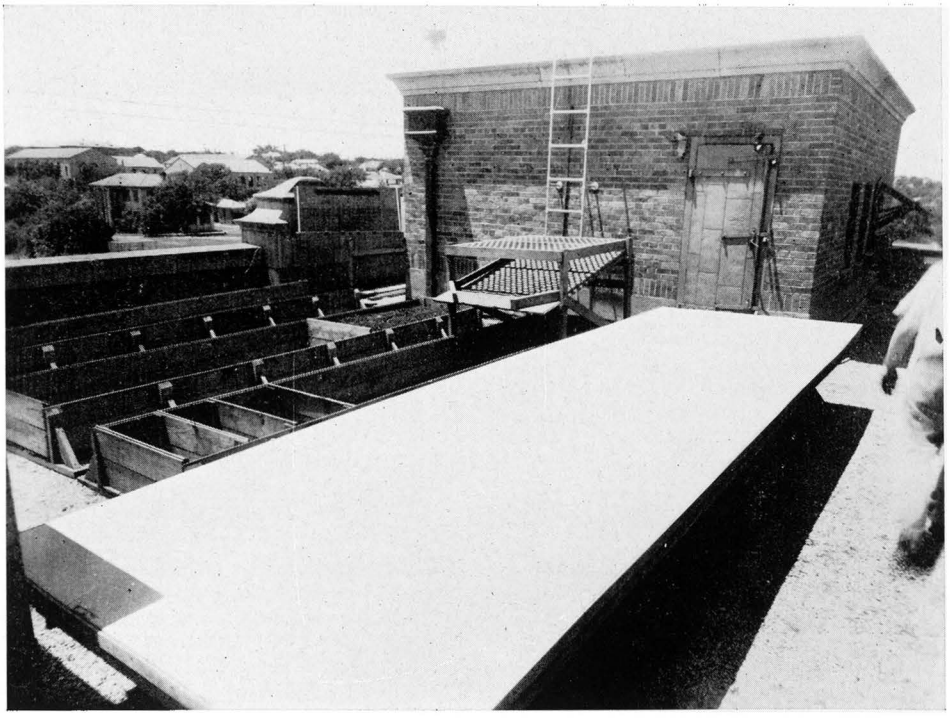

FIG. 2. View showing uncovered bins in background for completely exposed samples and cloth-covered bins in foreground for samples to be protected from sunshine.

Item	Per Cent by Weight and Heating Value
Moisture	34.05%
Ash	8.57%
Sulphur	0.86%
Heating Value	7,206 Btu/Lb.

Six series of samples were placed in bins and containers upon the roof of the Main Heating and Power Plant of The University of Texas in which this fuel is used for steam-generating purposes. The other series of samples was stored in the concrete basement of an adjoining building.

All bins prepared for lignite samples which were to be permitted to remain in contact with the atmosphere were constructed of wood. Because of the size degradation tendencies of the lignite in storage it was necessary to provide bins of different sizes in order that the depth of the fuel beds in storage might be kept constant. For the purpose of subsequent identification a designation number was assigned to each series of samples.

Series of Samples	Aggregate Weight in Lbs.	Designation Number
Samples completely exposed	6,600	1
Samples protected from sun	5,300	2
Samples protected from rain	5,450	3
Samples protected from sun and rain	2,000	4
Samples in basement	1,050	5
Samples sealed in cans	1,114	6
Samples sealed under water	998	7

In addition to the uncovered bins, cloth covered bins and glass covered bins previously mentioned or shown, four additional kinds of storage were

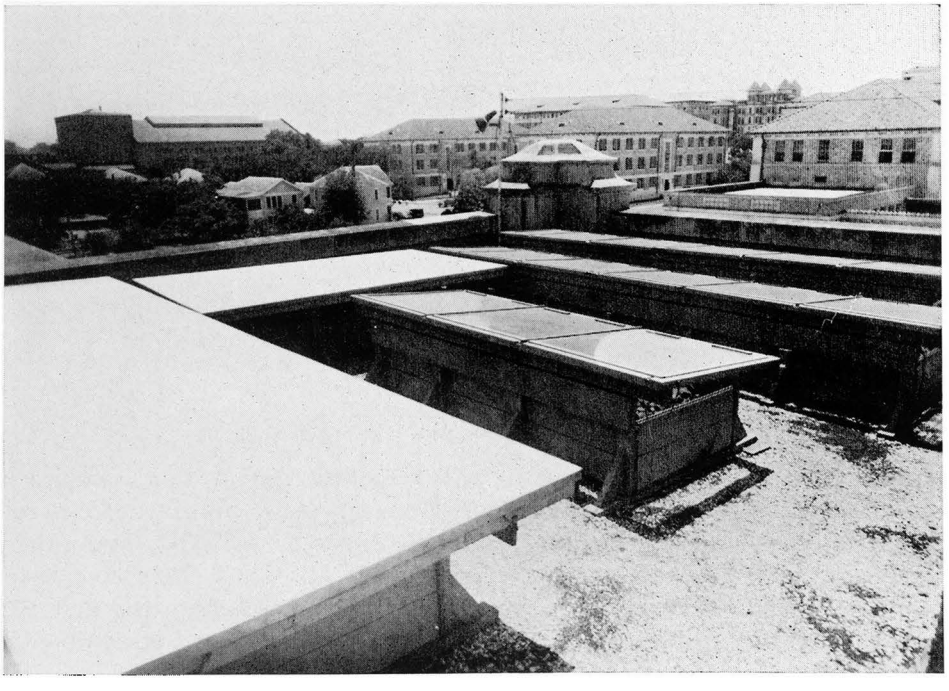

FIG. 3. View of glass-covered bins by means of which lignite was subjected to atmospheric conditions but protected from rain.

provided. The samples of lignite which were to be protected from both sunshine and rain were placed under bins provided with a roof. The character of this construction was such as to permit the atmospheric air to come intimately in contact with the samples so stored. No special treatment of any nature was given to the fifth series of samples which was stored in a basement except to make certain that this material came into contact with the atmosphere in that space. It was protected from water and all other materials by which its characterictics might have been influenced. The sixth series of samples was placed into 26 gallon galvanized steel cans provided with tight-fitting lids. A seal was provided in the case of each such steel container in order to establish the certainty that in the course of the storage period air might not pass into or out of the container. The containers so sealed were placed in the immediate proximity of other samples in order that the material in this case might be subjected to the same temperatures. The seventh series of samples was placed into similar steel containers. Before these containers were covered, however, a sufficient amount of water was added to each can to assure the fact that the sample so confined was completely submerged.

FIG. 4. Samples protected from atmosphere during storage both in an "as prepared" state and in a submerged state.

The lignite placed into storage was so arranged that unit samples of material exposed completely, protected from sunshine, protected from rain and protected from both sunshine and rain might be removed from storage for test purposes at the end of 0, 6, 13, 20, 27, 34, 41, 54, 84, 111, and 160 days in storage. The sample arrangement was, moreover, such that unit samples from basement storage, from sealed cans and from under water in sealed cans might be removed for test purposes at the end of 0, 27, 54, 84, 111, and 160 days in storage.

PART 4

DESCRIPTION OF APPARATUS

The term size degradation is used here to denote the tendency of lumps of lignite to undergo a reduction in size while in storage with no handling other than that by which the size determinations are made at the end of the test period.

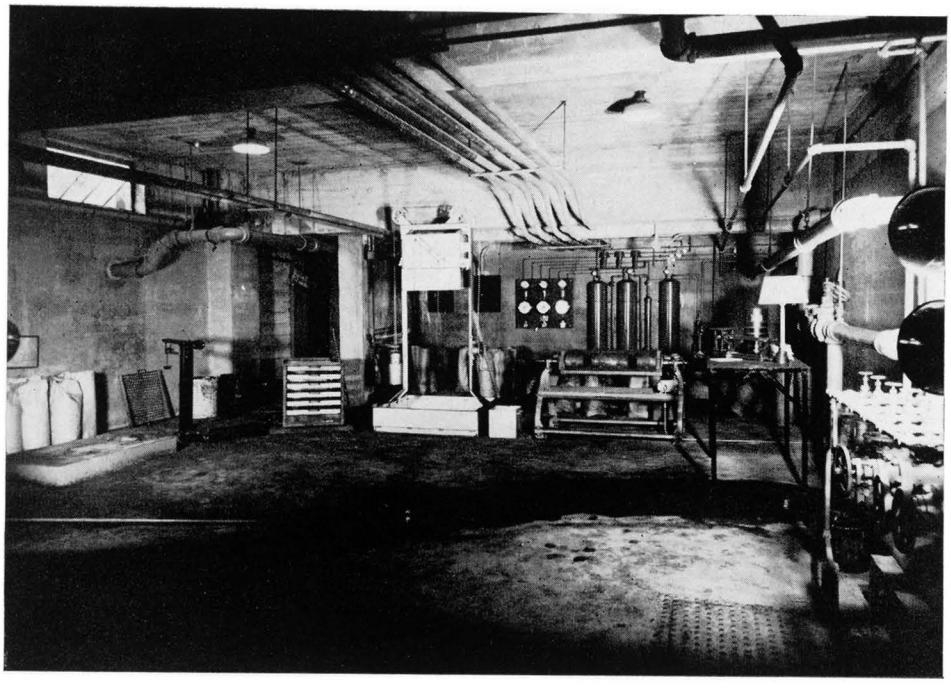

FIG. 5. Solid fuels test laboratory used to determine physical properties of Texas lignite.

The apparatus used for the purpose of determining the size degradation of this fuel consisted of two sets of round hole screens. Those used to prepare the samples involved two sizes of openings only, namely, 3 inch and 2 inch. The set of screens used to make size determinations at the end of the test periods contained screens of 3, 2, 1½, 1, ¾, and ½ inch sizes. The frames of the first set mentioned were comparatively large and those for the tests at the end of the storage periods were made of a 2 foot square shape. The construction of these screens conformed in every detail to the American Society for Testing Materials Standard Specifications *Sieves for Testing Purposes* A.S.T.M. Designation: E 11. The scales used to weigh the fuel in all cases were checked to make certain that they were sensitive to weights less than ¼ pound.

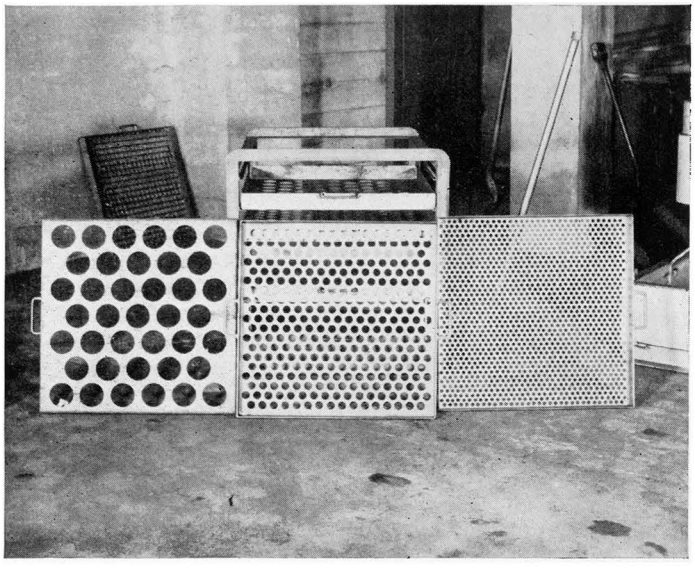

FIG. 6. Round hole screens used for size degradation and size stability tests.

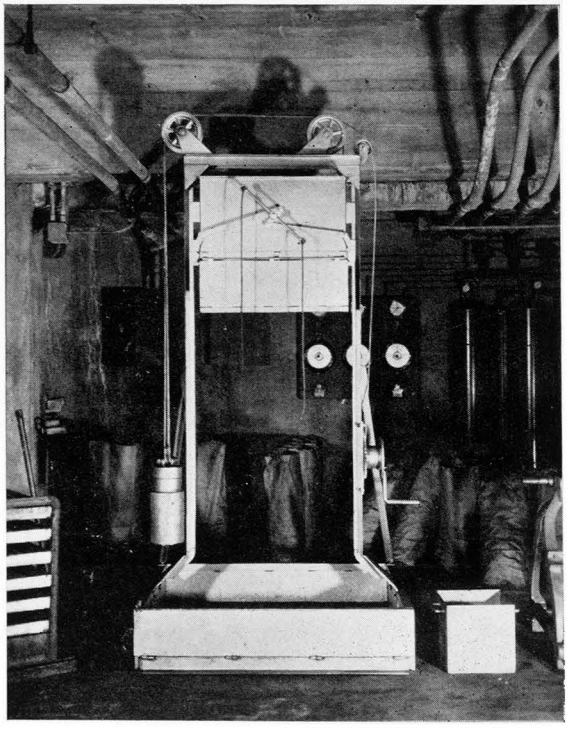

FIG. 7. Drop shatter test apparatus.

The Drop Shatter Test Apparatus consisted essentially of a movable fuel box from which samples of lignite could be dropped through a given height onto a steel plate. With this apparatus and the round hole screens previously mentioned and suitable scales it was possible to determine the size stability of the lignite. The size stability is regarded as a measure of the solid fuel's ability to withstand breakage when subjected to handling. The fuel box of the Drop Shatter Apparatus consisted of a fabricated steel box 18 inches in width, 28 inches in length and 15 inches in depth. Its arrangement was such that when the fuel was released the latter fell exactly 6 feet onto a steel plate 38 inches in width and 48 inches in length having a thickness of ½ inch. The bottom of the fuel box consisted of two doors hinged lengthwise and provided with a latch by means of which they could be permitted to swing open freely without impeding the fall of the lignite. The dimensions of the test apparatus and the important details of construction were made to conform to the provisions of the American Society for Testing Materials Tentative Method of *Drop Shatter Test for Coal* A.S.T.M. Designation: D 440–37T.

In the course of the construction of this apparatus three changes in design were made. These changes could not be expected to alter in any fashion the results obtained. They were made because it was believed that they would expedite the test procedure. An inspection of the two types of Drop Shatter Apparatus shown in Figure 8 will reveal the following differences between the recommended and actual apparatus.

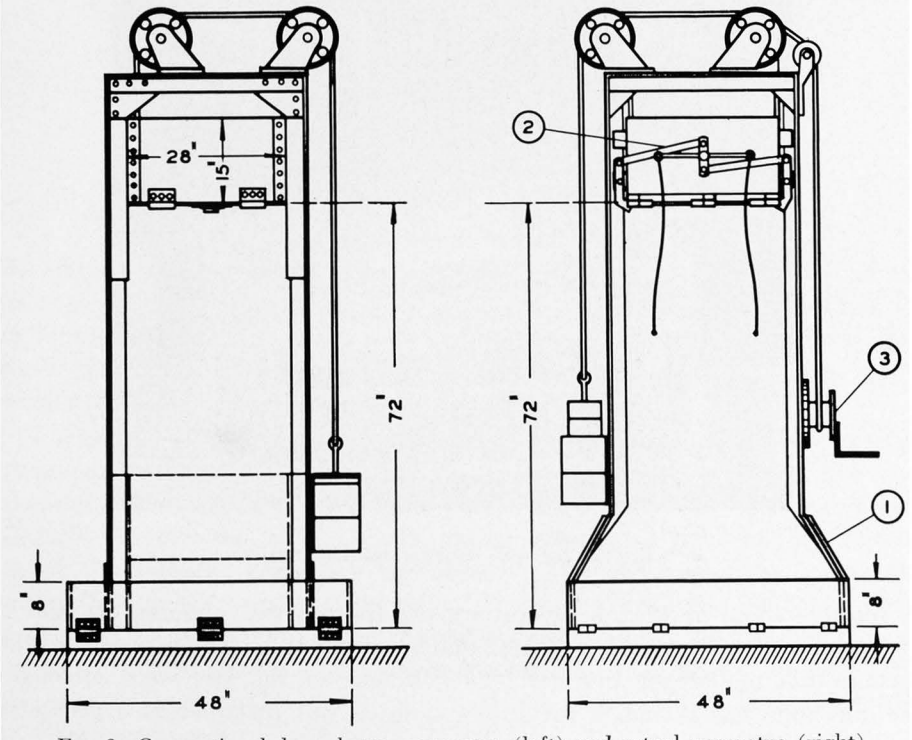

FIG. 8. Conventional drop shatter apparatus (left) and actual apparatus (right).

1. In the case of the modified apparatus the vertical coal box supporting standards were bent outward at the bottom and extended to the sides of the bottom steel plate so that removal and recharging operations might be conducted with greater facility in the absence of the obstruction otherwise offered by these standards.
2. The latching mechanism at the bottom of the coal box of the actual apparatus was fashioned in a somewhat more complicated nature in order that the bottom of the coal box might be opened with less possibility of retarding the movement of the bottom half of the box to which the latch-releasing mechanism was attached.
3. A hand-operated winch was included in the design of the actual apparatus so that after the fuel had been dropped from its box the latter could be returned to its lower or charging position with dispatch.

The scales and screens used in conjunction with size stability tests were the same previously described in the case of size degradation tests.

The friability of the solid fuel samples was determined with the use of Tumbler Test Apparatus. This apparatus was constructed in accordance with the American Society for Testing Materials Tentative Method of *Tumbler Test for Coal* A.S.T.M. Designation: D 441–37T. It consisted essentially of a multiple jar mill. The cast iron jars used were carefully machined in such a fashion that their internal diameter was 7¼ inches and their depth was likewise 7¼ inches. In order that tests might be conducted in multiple, the rack of the mill was constructed of a sufficient length to permit the rotation of four jars simultaneously.

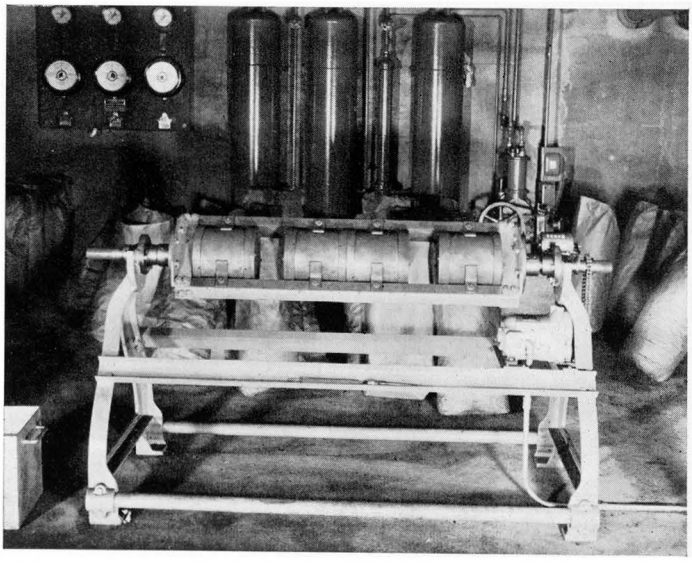

FIG. 9. Jar mill used for tumbler tests.

A rotative speed of 40 ± 1 revolutions per minute was obtained by the use of a gear motor, a set of sprockets and a suitable chain. In order to make certain that the proper number of revolutions of the jars were effected in the one hour test period, a revolution counter was installed as a permanent accessory of the test apparatus.

The interior of each cast iron jar was provided with a steel frame having suitable lifting shelves. The two rings of each frame were made of ¾ inch by ⅛ inch steel in such a manner as to have an external diameter of 7⅛ inches. The three lifting shelves of each frame consisted of ¾ inch by ⅛ inch steel flats 6½ inches in length. These lifting shelves were attached radially to the two rings by means of small brackets in such a fashion that the extremities of the shelves were flush with the outer edges of the two rings. The dimensions of the attachment brackets were, furthermore, such that the clearance between the outer edge of the shelves and the outside of the rings was ⅝ inch.

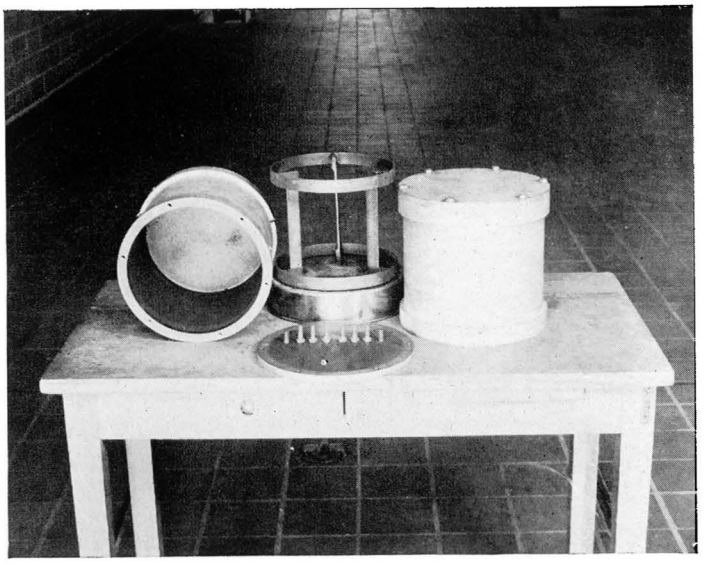

FIG. 10. Cast-iron tumbler jars, jar frames and lids.

The frames were carefully fabricated by a welding process. The lids of the jars were arranged for a suitable gasket and they were held in position on the tops of the jars in each case by the use of six machine screws. The proper position of the frames within the jars was assured by the use of sealed set screws.

Two sets of sieves were used for this test procedure. The sieves used in the preparation of the samples for the jars were sieves having in one case 1.50 inch actual openings between the wires and in the other 1.06 inch actual openings between the wires. These square hole sieves used in the preparation of the samples were two feet square. The sieves used to screen the lignite after it had been tumbled were likewise square hole members. These sieves were provided with round metal frames which measured 8 inches in diameter. For this sizing after tumbling operations had been completed sieve hole sizes of 1.06, 0.750, 0.531, 0.375, 0.0469, and 0.0117 inches between the wires were used.

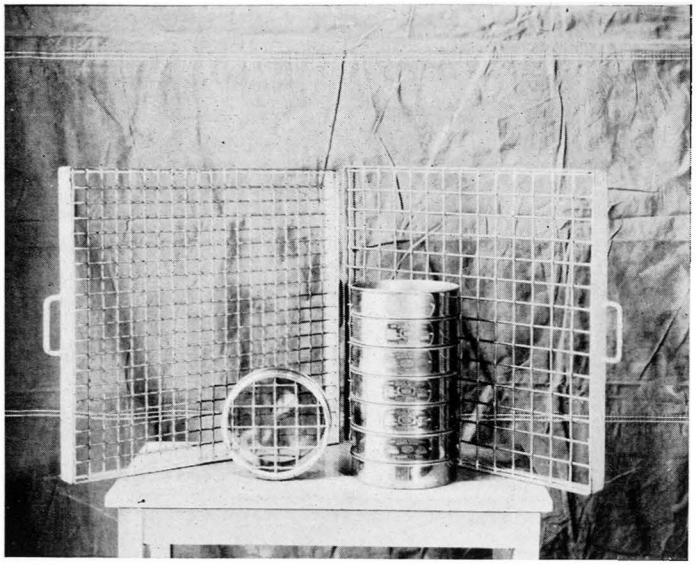

FIG. 11. Initial sample preparation sieves and final sizing sieves for tumbler tests.

The character of the sieves in both cases was such as to conform to the American Society for Testing Materials Standard Specifications for *Sieves for Testing Purposes* A.S.T.M. Designation: E 11. The balance used to weigh the initial 1000 gram sample and to weigh the segregated material after sieving operations had been completed at the conclusion of the test was sensitive to 1 gram.

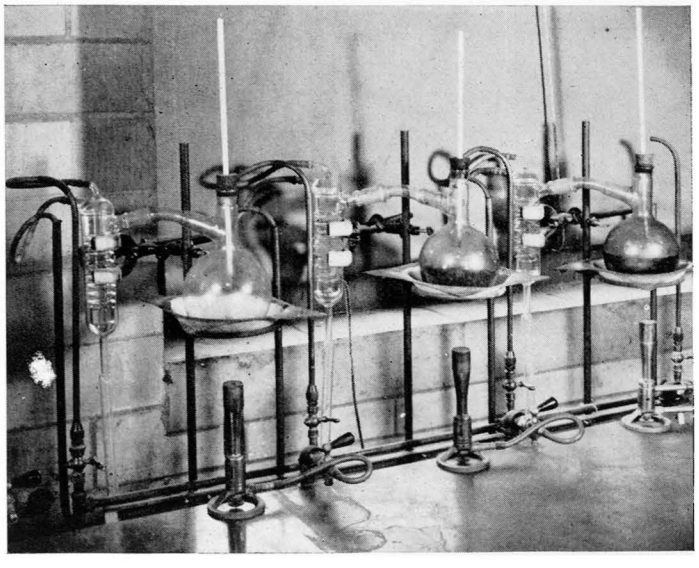

FIG. 12. Moisture determination apparatus.

The sample preparation operations prescribed for the moisture determination of solid fuels other than lignite produce considerable moisture losses in the case of the solid fuel last mentioned. It was not, therefore, possible to follow such a test procedure in the determinotion of the moisture content of the lignite in this investigation. The apparatus used to make such moisture determinations consisted essentially of a distillation flask, a water cooled condenser, a glass funnel, a measuring tube, a thermometer, suitable supporting structures and a source of heat. The glass distillation flasks having a comparatively large neck and a capacity of one liter were used. The condensers were likewise fashioned of glass and proportioned in such a manner as to permit the flow of a comparatively large amount of water for cooling purposes in a counter current direction.

PART 5

TEST PROCEDURE

Size Degradation Test Procedure:

Size degradation was regarded in this investigation as being that property of lignite which caused lumps of this fuel to disintegrate while in storage when subjected to no operations other than those required to place it into storage at the beginning of the test period and to screen it for a size determination at the end of the test period. Inasmuch as the same sample of lignite was to be used for size stability tests, the actual weight of the sample in each case differed to take into consideration the character of the storage involved as well as the duration of the test period. Thus samples ranging from 50 pounds to 700 pounds were used. At the time the samples were placed in storage care had been exercised to make certain that all sample material was of such an order as to pass a 3 inch round hole screen and to be retained upon a 2 inch screen of the same variety.

At the end of the test period in each case the sample was removed from storage with care to avoid all unnecessary handling and screened. In these operations the round hole screens of 2, 1½, 1, ¾, and ½ inch sizes were used. The screening operations were conducted in such a fashion as to use small increments of material. In this manner satisfactory contact between the individual coal pieces and the screen was assured. In the case of the 2, 1½, and 1 inch screens, individual lumps of lignite which did not readily pass through a screen were tried by hand to ascertain as to whether they would pass through the screen if changed in position without exerting any force upon such lumps. Up-ending the lumps was not employed in sizing or screening the smaller fuel particles. Care was, however, exercised to see that all particles came intimately in contact with the screens.

The lignite remaining upon each screen and that passing through the smallest screen, namely, that of ½ inch size, was weighed separately. Great care was exercised to make certain that the aggregate weight of the screened material was within one per cent of the total weight before screening operations were begun. The weights of the screened sizes was then converted to a per cent by weight basis. An Average of Screen Openings in Inches was designated and an Average of Screen Openings Factor was then applied to each size of screened material. The magnitude of this factor for each size of fuel is shown in an accompanying table.

TABLE X

AVERAGE OF SCREEN OPENINGS FACTOR

Retained on	Passing	Average of Screen Openings, Inches	Average of Screen Openings, Factor
2 inch	3 inch	2.500	1
1½ inch	2 inch	1.750	0.07
1 inch	1½ inch	1.250	0.5
¾ inch	1 inch	0.875	0.35
½ inch	¾ inch	0.625	0.25
	½ inch	0.250	0.1

The per cent by weight of each size of screened lignite was then multiplied by its appropriate Average of Screen Openings Factor and the sum of these products was obtained. The sum of these products was subtracted from 100 per cent and the answer in per cent was called size degradation.

The manner in which these results were recorded may be observed on an accompanying table. The term Slack Index was used in this case to denote

TABLE XI

SIZE DEGRADATION TEST FOR SOLID FUELS

Date of Test: June 24, 1942 (160)

Fuel Index No. 11 Fuel Storage No. 1

Screen Analysis of Fuel Using Round-Hole Screens

Retained on	Passing	Weight Recorded lb.	Weight Per Cent (1)	Average of Screen Openings		Product of (1) × (3)
				Inches (2)	Factor (3)	
Sample						
2 in.	3 in.	699¾	100.0	2.500	1.00	100.00 = S
Tested Fuel						
2 in.	3 in.	20½	2.9	2.500	1.00	2.900
1½ in.	2 in.	5½	0.8	1.750	0.70	0.560
1 in.	1½ in.	20½	2.9	1.250	0.50	1.450
¾ in.	1 in.	38½	5.5	0.875	0.35	1.925
½ in.	¾ in.	149¾	21.4	0.625	0.25	5.350
	½ in.	465	66.5	0.250	0.10	6.650
Total (Sum of products (1) × (3) for dropped fuel)						18.835 = s

$$\text{Size Degradation, per cent} = 100 - \frac{100 \times s}{S} = 100 - s = 100 - 18.8 = 81.2$$

Slack Index = 88

the per cent by weight of the original sample of lignite which ultimately passed through the ¾ inch screen. This value in each case was recorded as a separate item.

Size Stability Test Procedure:

Size stability tests were conducted at the end of each storage period in the case of lignite which had been placed in the various kinds of storage. The original sample, which had been screened so as to consist only of material all of which passed a 3 inch screen and all of which was retained upon a 2 inch screen, was now re-screened in such a fashion as to discard all fuel particles which passed through the 2 inch screen. Then 50 pounds of the lignite passing through a 3 inch screen and retained upon a 2 inch screen at the end of the storage period was taken as the Size Stability Test sample. The test procedure employed was that prescribed by the American Society for Testing Materials[13] for this test as follows:

"Procedure

5. (a) A 50-lb. portion of the coal sample prepared in accordance with Section 4 shall be given two drops. The coal shall be placed in the box of the shatter test machine, leveled and then dropped a distance of 6 ft. onto the plate. All the coal on the plate shall be carefully returned to the box and again dropped. After the second drop the material shall be successively run through the screens specified in Section 2 (b). In screening, care shall be taken to prevent further breakage of the coal. The screening shall be carried out in such small increments as to permit satisfactory contact between the individual pieces of coal and the screen. On the three larger screens, 2, 1½, and 1 in., individual pieces of coal not readily passing through the screens shall be tried by hand to determine whether they will pass through the openings in any position without forcing. When using the screens with ¾ in. openings and smaller, the coal shall come into intimate contact with the screen either by shaking or rolling by hand without up-ending the individual lumps.

(b) The coal remaining on each screen, and that which passes through the bottom screen shall be weighed either separately or in cumulative portions, on a scale sensitive to ¼ pound or less. By the cumulative portion method the largest 2 to 3-in. sized lumps shall be weighed into a tared container, which container shall then be reweighed after addition of the successive individual smaller screened sizes of dropped coal. If the final net weight so obtained, or the sum of the separate weights, shows a loss of over 1 per cent, the test shall be rejected and another made, the loss in each case to be included in the percentage passing the ½ in. screen. At least two tests shall be made to obtain size stability results agreeing within 2 per cent. When three or more tests are considered advisable and are made, all the results within a maximum to minimum limit of 3 per cent may be averaged.

Report

6. The percentage weight screen analysis shall be reported to the nearest 0.1 per cent, and the percentage size stability to the nearest 0.5 per cent.

NOTE.—A numerical example of tabulating the results and of calculating size stability, per cent, is shown in Table I (here Table XII) where the average of the screen size openings limiting the different sizes is expressed to the nearest 0.005 in. . . ."

As may be observed the Size Stability reported in this case consists of the sum of the products of the weight of the various sizes of lignite particles expressed on a percentage basis and the appropriate Average of Screen Openings Factor. The term Shatter Index was used in this case to denote the per cent by weight of the original sample of lignite which ultimately passed through the 3/4 inch screen after the test sample had been given two drops from the Drop Shatter Apparatus. In all cases the Shatter Index was expressed as a separate item.

TABLE XII

DROP SHATTER TEST FOR SOLID FUELS

Date of Test: June 24, 1942 (160)

Fuel Index No. 11 Fuel Storage No. 3

Screen Analysis of Fuel Using Round-Hole Screens

Retained on	Passing	Weight Recorded lb.	Weight Per Cent (1)	Average of Screen Openings		Product of (1) × (3)
				Inches (2)	Factor (3)	
Sample						
2 in.	3 in.	50	100.0	2.500	1.00	100.00 = S
Dropped Fuel						
2 in.	3 in.	14¼	28.5	2.500	1.00	28.500
1½ in.	2 in.	10	20.0	1.750	0.70	14.000
1 in.	1½ in.	10½	21.0	1.250	0.50	10.500
¾ in.	1 in.	5½	11.0	0.875	0.35	3.850
½ in.	¾ in.	4½	8.8	0.625	0.25	2.200
	½ in.	5¼	10.5	0.250	0.10	1.050
Total (Sum of products (1) × (3) for dropped fuel)						60.100 = s

$$\text{Size Stability, per cent} = \frac{100 \times s}{S} = \frac{100 \times s}{100} = s = 60.1$$

Shatter Index = 19

Friability Test Procedure:

Tumbler tests were conducted at the end of each storage period in the case of lignite which had been placed in the various kinds of storage. For these tests the sample was prepared and the test was conducted in the manner prescribed by the American Society for Testing Materials under Tentative Method of *Tumbler Test for Coal* A. S. T. M. Designation: D 441–37 T.[14] For the convenience of the reader the sample preparation and test procedure are quoted here:

"Preparation of sample

4. (a) A preliminary sieving of a representative portion, approximately 100 pounds of the gross sample shall be made, using square hole sieves with 1.06 and 1.50-in. openings. If this

preliminary sieving indicates that the lumps are mostly smaller than 1.50 in., successive representative portions of the gross sample shall be sieved until at least 25 lb. of the 1.06 to 1.50 lumps are obtained. If most of the lumps obtained by the preliminary sieving are larger than 1.50 in., sieving of representative portions of the gross sample shall be continued until at least 50 lbs. of the sieved material remaining upon the 1.06-in. sieve are available. The lumps so obtained that are larger than 1.50 in. shall then be broken with a hammer until they pass through the 1.50-in. sieve, avoiding as much as possible the production of lumps smaller than 1.06 in. Should the combined weights of the 1.06 to 1.50-in size, obtained by sieving before and after hammer breakage of the larger lumps, be less than the required 25 lbs., the amount shall be augmented by further sieving and breakage of additional representative portions, or the remainder of the gross sample, care being taken to discard all lumps in which noticeable cracks have developed by hammer breakage. Care should also be taken to provide lumps covering the whole range of the 1.06 to 1.50-in. size in both the 25-lb. composite sample, and in each 100-g. sample taken for test as in Section 5. This may be accomplished by the use of a 1.25-in. sieve to see that approximately half of the weight of the lumps comprising these samples will be between 1.06 and 1.25-in. and half between 1.25 and 1.50-in.

(b) The total quantity of the 1.06 to 1.50-in. size shall be thoroughly mixed and then resieved to pass the 1.50-in. sieve and be retained upon the 1.06-in. sieve. Only a thin layer of coal shall be placed on the sieve so as to allow the pieces to be in direct contact with the sieve openings. Individual pieces of coal not passing readily through the sieve shall be upended by hand to determine whether in any position they pass the sieve.

Procedure

5. (a) Approximately 1000 g. of the coal sample prepared in accordance with Section 4 shall be weighed and placed in the jar, and the jar rotated for 1 hr. in the tumbler test machine at 40 ± 1 r.p.m. In order to standardize the time of tumbling, a revolution counter should be used, either periodically or as permanent accessory equipment to the machine, to insure that the total number of revolutions during the test is approximately 2400. After tumbling, the coal shall be thoroughly graded as to size upon the sieves designated in Section 2 (c). The sieving shall be carried out in such small increments as to permit satisfactory contact between the individual pieces of coal and the sieve. On the two larger sieves, 1.06 and 0.750 in., individual pieces of coal not readily passing through the sieves shall be upended by hand to determine whether in any position they pass the sieve.

(b) Sieving may be carried out either by hand or mechanically, though the former method is preferable.

(c) At least four single-jar tests shall be made, and, provided sufficient sample is available, it is recommended that two or more four-jar tests be made. When only four single jar tests are made, the contents of each jar shall be sieved separately in order to be sure that there is satisfactory agreement between the results obtained. When two or more four-jar tests are made the contents of the four jars from each set may be mixed and sieved together. The weighings shall be made to the nearest 1 g.

Report

5. The results shall be reported to the nearest 0.5 per cent as friability, per cent, which is the percentage reduction in average size of the coal during the tumbler test.

Note.—A numerical example of the method of calculating friability is given in tabular form below, where the average of the openings of the retaining and passing sieves is expressed in inches to the nearest 0.001 in. . . . It is from the average of the sieve openings that the approximate relative size factors, shown as column (3), are derived. In the column to the extreme right, S represents the average size of the coal lumps before tumbling and s the average size of the tumbled coal, the value for S being arbitrarily chosen as 100 times its corresponding size factor."

TABLE XIII

TUMBLER TEST FOR SOLID FUELS

Date of Test: February 13, 1942 (27)

Fuel Index No. 5 Fuel Storage No. 7

Sieve Analysis of Fuel Using Square-Hole Sieves

Retained on	Passing	Weight Recorded gm.	Weight Per Cent (1)	Average of Sieve Openings		Product of (1) × (3)
				Inches (2)	Factor (3)	
Sample						
1.06 in.	1.50 in.	1000	100.0	1.280	1.00	100.00 = S
Tumbled Fuel						
1.06 in.	1.50 in.	650	65.0	1.280	1.00	65.0
0.750 in.	1.06 in.	154	15.4	0.905	0.70	10.78
0.530 in.	0.750 in.	53	5.3	0.640	0.50	2.65
0.375 in.	0.530 in.	31	3.1	0.452	0.35	1.09
0.0469 in.	0.375 in.	26	2.6	0.211	0.16	0.416
0.0117 in.	0.0469 in. (No. 16)	37	3.7	0.029	0.023	0.085
	0.0117 in. (No. 50)	49	4.9	0.006	0.005	0.024
Total (Sum of products (1) × (3) for tumbled fuel)						80.045 = s

$$\text{Friability, per cent} = \frac{100\,(S - s)}{S} = \frac{100\,(100 - 80.0)}{100} = 20.0\%$$

Dust Index = 5

Determination of Moisture Content Procedure:

In order to obtain satisfactory results a relatively large amount of lignite was used to secure a representative sample for each moisture determination. In every case the moisture determination was made soon after the sample was removed from storage. The only exception to this procedure was incurred in the case of the sample removed from storage involving submergence under water. In the case of that series of moisture determinations, the analysis was made at the time the other physical tests were conducted, i.e., after the passage of a sufficient period of time to eliminate the surface moisture which would otherwise have caused trouble in drop

shatter and tumbler tests. From this large gross sample a net sample approximately 250 grams was selected in the form of both coarse and fine lumps or particles. This net sample was placed in a 1 liter distillation flask containing kerosene. The weight of the distillation flask and content of kerosene had been determined in advance. The coarser particles of lignite were broken only to an extent sufficient to permit the passage of the broken pieces through the neck of the distillation flask. With the distillation flask and kerosene weight determined in advance, the procedure required to obtain a sample of 250 grams was, as may be observed, a very simple one. Care was, furthermore, exercised to see that the sample of lignite within the distillation flask was completely submerged under the kerosene.

With the weight of the lignite accurately determined, the distillation flask with its contents was mounted upon its supporting stand and connected to its condenser. A thermomenter was inserted into the distillation flask to such a depth as to provide a proper immersion through a stopper by means of which the vertical neck of the flask was sealed. The water was then permitted to flow through the condenser and heat was applied to the distillation flask and its contents. The vapors arising from the surface of the kerosene were permitted to flow out of the side neck of the distillation flask into the condenser. The heating apparatus was so shieled as to assure the fact that no moisture would condense in any part of the distillation flask. Upon entering the condenser these vapors were condensed and permitted to flow vertically downward in a manner counter-current to the flow of the cooling water. At the lower extremity of the condenser the condensed vapors were discharged into a glass funnel which in turn was placed into the neck of a calibrated glass measuring tube of a sufficient capacity to measure 100 cubic centimeters of liquid content. This measuring tube in turn was placed into a flask of materially larger cubage. The heating process was conducted in such a manner that a temperature of 225 deg. C. was reached in a period from 60 to 80 minutes.

When the end point temperature was reached the heat was removed from under the distillation flask and a careful examination was made to make certain that no moisture had been condensed within the flask. If such moisture was found a sufficient amount of heat was applied locally to that portion of the distillation flask to which the moisture adhered to evaporate it. The distillation flask and condenser were then disconnected and, if it was found that moisture adhered to any portion of the condenser, kerosene was poured through that member to discharge the moisture into the measuring tube. In the intervening period of time that more volatile portion of the kerosene which had been evaporated, condensed and discharged into the measuring tube was permitted to overflow into the flask into which the measuring tube was inserted.

The moisture content of the lignite was then determined by the simple expedient of dividing the number of cubic centimeters of water driven off in heating the lignite to 225 deg. C. or 437 deg. F. by 2.5. The answer resulting from this computation was regarded as the moisture content expressed in per cent by weight.

PART 6

RESULTS

In order to evaluate the results obtained in the course of this investigation appropriate consideration must be given to the meteorological conditions which prevailed during the 160 day test period. These data have, therefore, been assimilated in graphical form. An inspection of Figure 13 will reveal the fact that information with reference to sunshine, precipitation, relative humidity and temperature is provided in order that the results obtained may be considered in the entire fullness of their meaning. Among other facts, the following data should be borne in mind in the consideration of the results which are hereinafter presented.

1. The tests were begun in mid-winter and completed in the summer. Thus a wide variety of weather was experienced.
2. Temperatures as low as 17 deg. F. and as high as 100 deg. F. were experienced in the course of the test period. The mean monthly temperature increased steadfastly as the test period was extended from 48.5 deg. F. in January to 82.8 deg. F. in June.
3. The relative humidity varied through a very wide range from 8 per cent to 98 per cent. The mean daily relative humidity range approximated 25 per cent.
4. Rains of small magnitude were experienced upon frequent occasions, whereas, those of considerable magnitude were less frequent. The frequency of the heavier rains was greater in the late part of the test priod than in the early stages of the endeavor.
5. The percentage of possible sunshine per month ranged from 50 to 77 per cent. The greatest irregularity in the case of this factor occurred in the early part of the test period.

The entire meteorological data are not significant in the case of all results presented. In some cases the results obtained can be understood only when such data are taken into consideration. In other cases they are of comparatively little importance. The duration of the test period was of sufficient magnitude to embrace all types of weather which might need to be considered in the case of an investigation of this character.

The fact that the size degradation of lignite may not be discussed with propriety in terms of generalities is very clearly revealed by the graphical data presented in Figure 14, which portrays the size degradation tendencies of lignite stored under seven different storage conditions. Three facts are immediately apparent upon inspecting these data. They are as follows:

1. The extent of the size degradation of this fuel varies through a very wide range depending upon the class of the storage involved.

Class of Storage	Size Degradation at End of 160-Day Storage Period In Per Cent
Sample completely exposed	81.1
Sample protected from sunshine	70.0
Sample protected from rain	28.2
Sample protected from sunshine and rain	17.1
Sample stored in basement	9.6
Sample sealed in steel cans	8.8
Sample stored under water	5.2

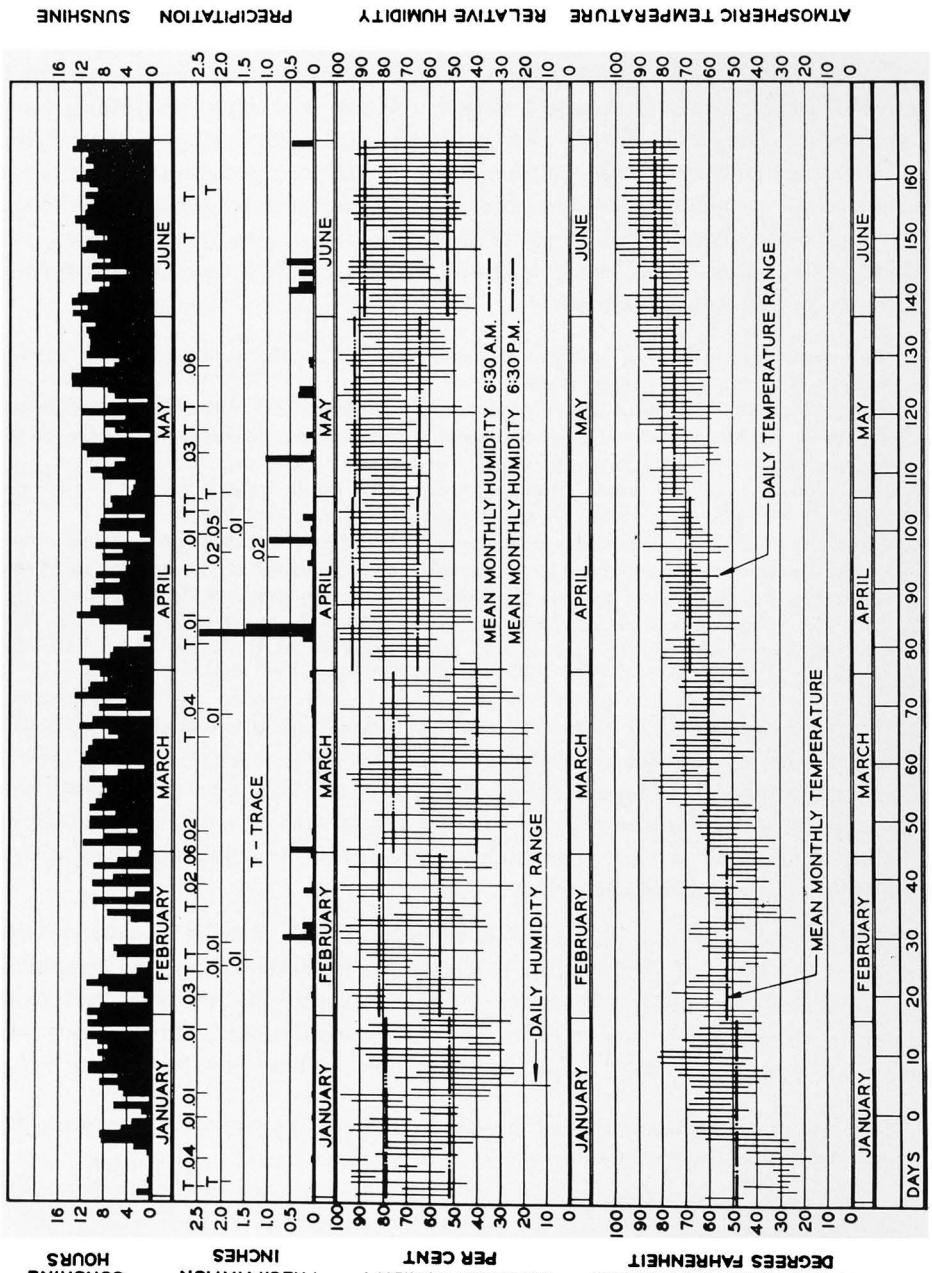

Fig. 13. Graph of meteorological data.

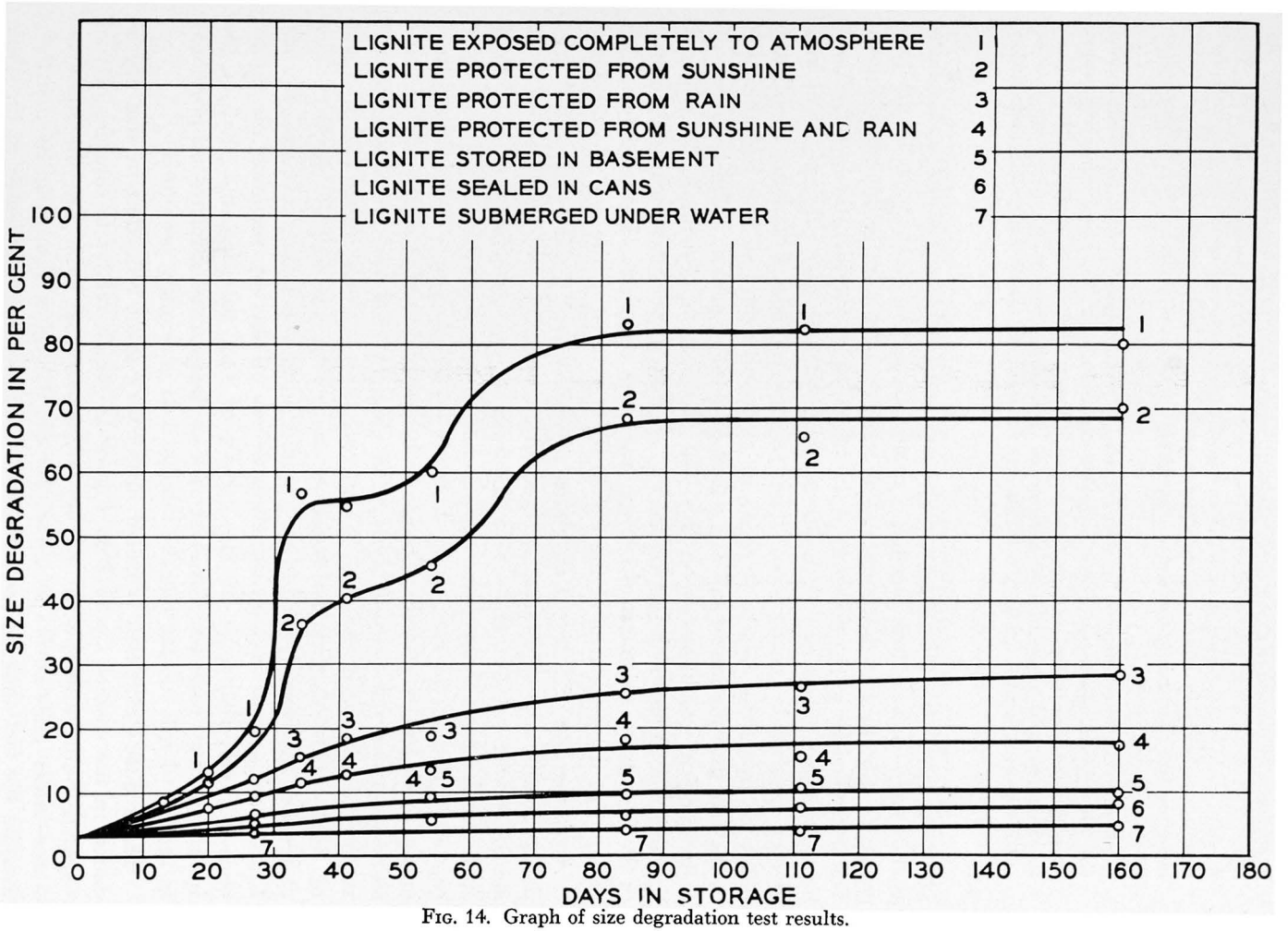

FIG. 14. Graph of size degradation test results.

2. Under certain classes of storage the duration of the storage period is of comparatively great significance. Under other storage conditions it appears to be of comparatively small importance. The sample stored in a basement reached the 10% degradation point in 160 days. The same point was reached by the completely exposed sample in 15 days. The shape of Curves 4, 5, 6, and 7, on the figure previously mentioned clearly indicates the fact that for those classes of storage the storage period may be extended materially without incurring size degradation tendencies appreciably in excess of those reached by the end of the 160-day test period.
3. Lignite can be stored successfully over extended periods of time without incurring serious size degradation tendencies under favorable circumstances. This may be accomplished by prohibiting the transportation of the initial moisture content out of the fuel particle to the atmosphere or by controlling the rate of subsequent moisture transportation into or out of the fuel particle in such a fashion as to retard the speed with which this action takes place.

The size degradation of lignite samples exposed completely to the atmosphere as shown by Curve 1 took place at a rapid rate in the early stages of the test period despite the fact that atmospheric temperatures were comparatively low. The irregularities in the first part of the curve under consideration were caused by two substantial rains. It should be observed here that rains of equal and greater magnitude in the later stages of the test period had no significant influence upon the lignite samples in storage because of the completeness of the size degradation in the early part of the test period. The influence of meteorological conditions upon the size degradation of completely exposed lignite is shown pictorially in Figure 15. As may be seen the slacking tendency of the fuel under this class of storage was quite complete. It varied from 3.2 per cent at the beginning of the test to 81.1 per cent at the end of 160 days.

An inspection of Curve 2 on Figure 14 will reveal the fact that the degradation in the case of samples exposed to the atmosphere but protected from sunshine was not as great as in the case of the completely exposed solid fuel. In the case of the former it reached an ultimate value of only 70 per cent, whereas, in the case of the latter it exceeded 81 per cent. This differential in degradation cannot properly be attributed to the absence of sunshine exclusively because in the case of cloth covered bins all of the precipitation did not reach the fuel in the case of substantial rains and in cases of light traces of rains no moisture may have reached the lignite. The absence of sunshine did retard the rapidity with which the moisture absorbed from precipitations was subsequently driven off thereby reducing the difference between shrinkage of the surface of fuel particles and that at the interior of such particles. An inspection of the pictorial information presented in Figure 16 will substantiate the tabular data previously presented.

The reader's attention is called to the very great reduction in size degradation in the case of Curve 3 on Figure 14 which relates to samples of fuel exposed to the atmospheric air but protected from rain, i.e., the fuel was stored under glass covers so as to prohibit the rapid absorption of moisture. Despite the fact that the last mentioned samples were subjected to the same atmospheric air as those of Curves 1 and 2, the size degradation in this case reached a value of only 28.2 per cent by the end of the 160 day test

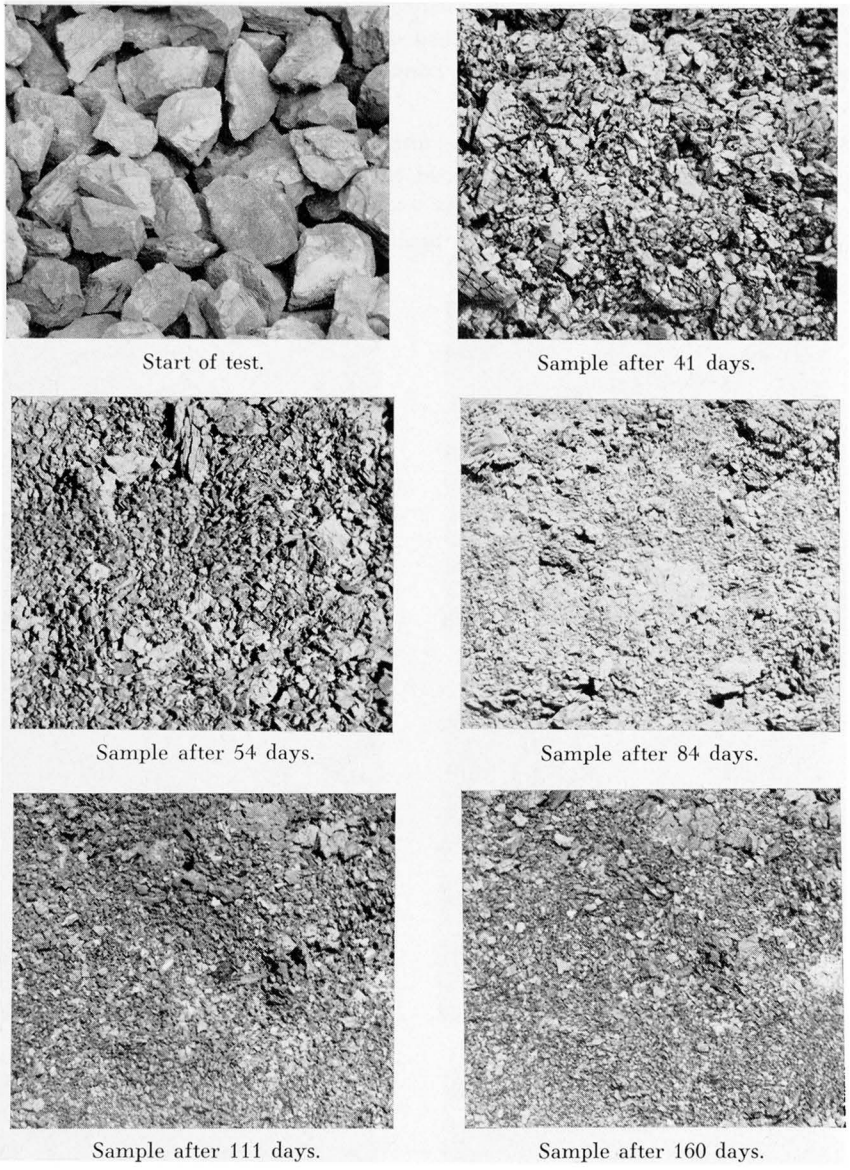

FIG. 15. Photographic record showing size degradation of lignite in the course of 160-day test period. Nature of storage: Completely exposed.

period. The remarkable improvement in the condition of the stored samples in this case can be observed pictorially in Figure 17.

A still greater improvement in fuel storage conditions is shown in the case of samples of fuel exposed to atmospheric air but protected from both sunshine and rain as shown by Curve 4 on Figure 14. For this type of storage the ultimate size degradation reached a value of only 17.1 per cent at the end of the 160 day test period. The pictorial data shown in Figure 18 relates to this series of samples. Inasmuch as the only difference in the

storage conditions of the samples represented in Curves 3 and 4 consisted of the absence of sunshine in the case of samples represented by Curve 4, a true indication of the differential caused by the sunshine is presented in this case.

By reducing the range of temperature and humidity variations the size degradation of lignite may be reduced to values even lower than those heretofore discussed. Curve 5 on Figure 14 reveals the fact that in the case of samples stored in a basement of a building the size degradation reached an

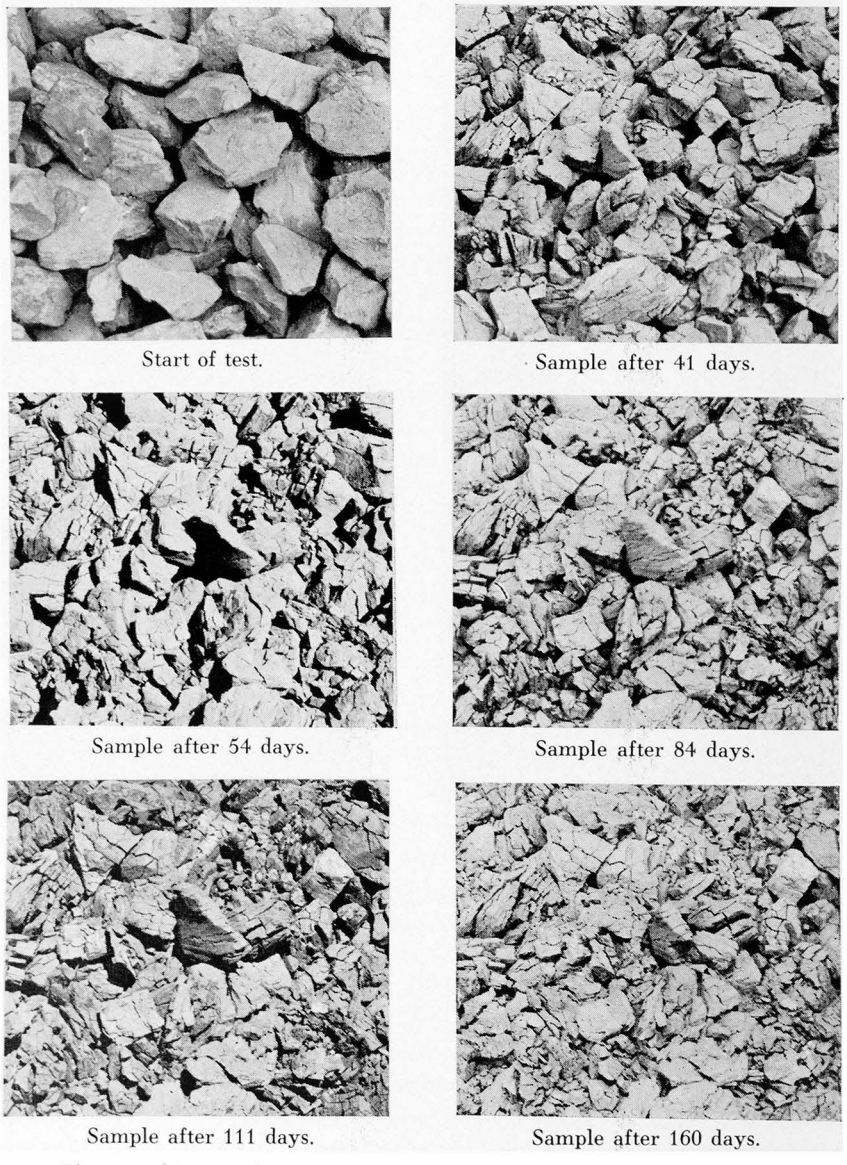

FIG. 16. Photographic record showing size degradation of lignite in the course of 160-day test period. Nature of storage: Exposed to atmosphere but protected from sunshine.

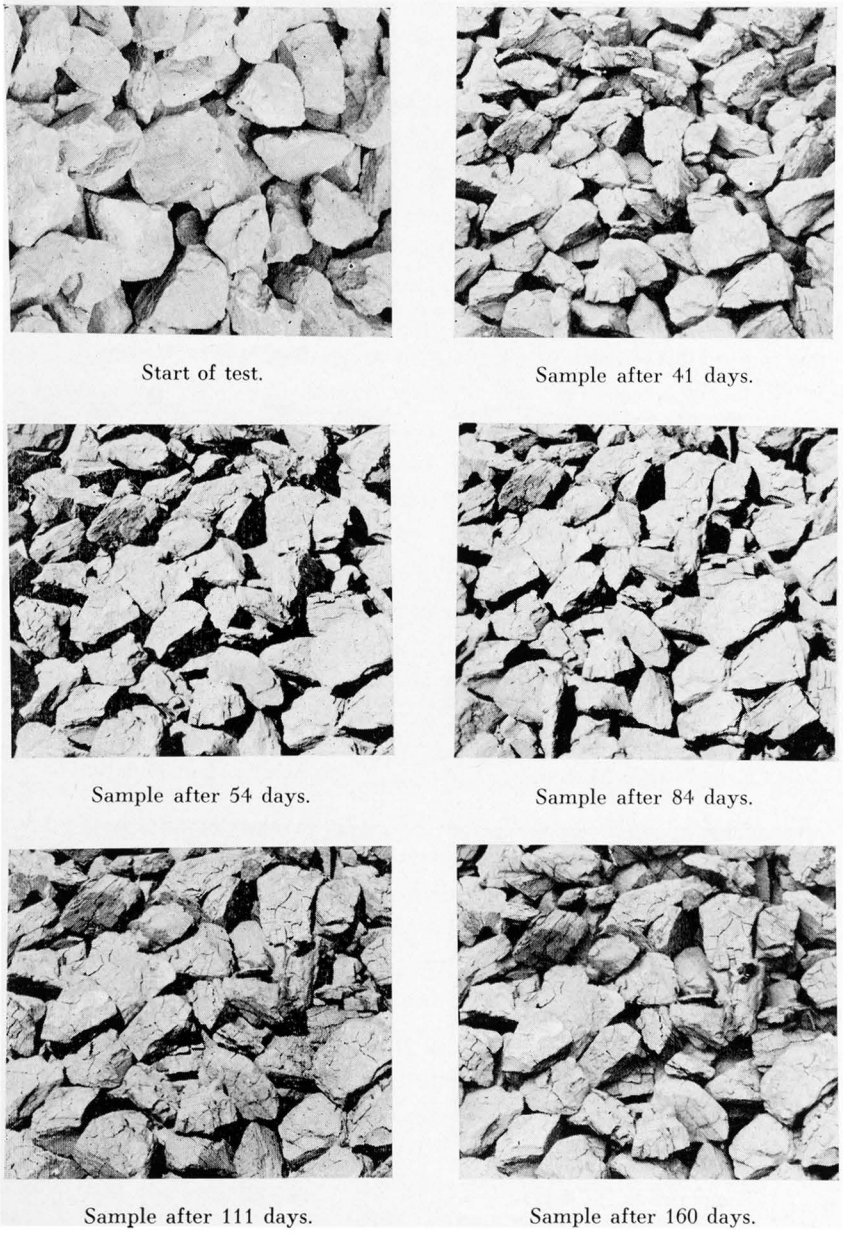

FIG. 17. Photographic record showing size degradation of lignite in the course of 160-day test period. Nature of storage: Exposed to atmosphere but protected from rain.

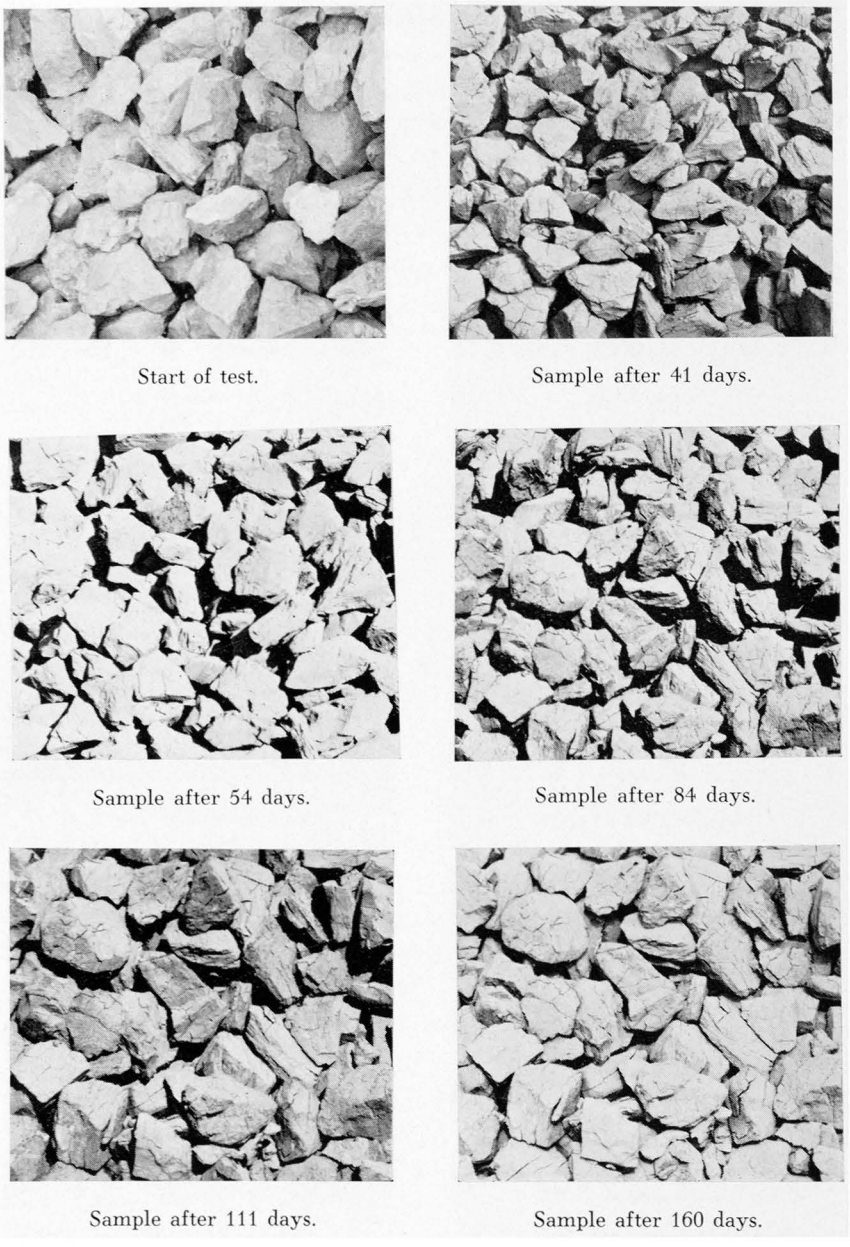

FIG. 18. Photographic record showing size degradation of lignite in the course of 160-day test period. Nature of storage: Exposed to atmosphere but protected from sunshine and rain.

ultimate value of only 9.6 per cent at the end of 160 days. The condition of such samples at the end of the storage period indicated is revealed in the upper picture shown in Figure 19. The Curve 6 on Figure 14 has been drawn to show the size degradation tendencies of lignite sealed in cans. The ultimate value reached in this case was 8.8 per cent. This value affords an interesting comparison with that of 17.1 per cent, the terminal point of Curve 4. The temperature of the fuel in both cases was the same. Neither series of samples was exposed to sunshine or rain. The samples of Curve 6 were subjected to no air changes throughout the test period, whereas, those of Curve 4 were subjected to highly variable conditions in so far as the air with which it came into contact was concerned. The condition of the lignite at the end of a 160 day test period while sealed in cans is shown in the center view of Figure 19. The last series of samples under consideration was stored in a submerged condition under water. The results obtained in the tests of these lignite samples are shown in Curve 7, Figure 14. In this case the least size degradation was experienced. The ultimate value reached was only approximately 3 per cent higher than the initial value. The final condition of the fuel stored in this fashion may be observed in the bottom view shown in Figure 19.

Despite the fact that samples completely exposed to the atmosphere for the greater storage periods were large samples, it was not possible to select from them the 50 pounds of lumps of lignite all of which passed through a 3 inch screen and all of which were retained upon a 2 inch screen after the samples had been in storage for 84 days. For the foregoing reason, it was not possible to conduct Drop Shatter Tests after that period for fuel in this type of storage. Curve 1, Figure 20, is shown as an incomplete curve. No direct comparison may be made between moisture loss and loss of size stability in the case of Curve 2 because the fuel stored in this manner received moisture in the form of rainfall. It is apparent, however, that the moisture absorption-rejection cycles of these fuel samples did not improve their size stability.

An inspection of Curves 3, 4, 5, and 6, on Figure 20 showing the size stability of samples of lignite under the storage conditions involved by these numbers and the same curves on Figure 21 showing the moisture content of the fuel samples tested will reveal the fact that these data are very closely related. The size stability of samples submerged under water shown by Curve 7 decreased to a very slight extent with the passage of time. The reduction in size stability from the beginning of the test period to the end of the 160 days involved was, in fact, no greater than the difference between the duplicate Drop Shatter Tests conducted for each sample tested.

Sample stored in basement after 160 days.

Sample sealed in cans after 160 days.

Sample submerged under water after 160 days.

FIG. 19. Photographs of lignite stored under special storage conditions at the end of 160-day test period.

An inspection of the graphical data presented in Figure 20 will reveal the extent of the ability of lignite to withstand a reduction in the size of its particles when handled after being removed from storage as revealed by Size Stability Tests. The following statements may be made with reference to the size stability of the lignite tested:

1. As in the case of the Size Degradation Tests, these Drop Shatter Tests reveal the fact that storage conditions have a very great influence upon the size stability of lignite. The range and the extent of this influence is as follows:

Type of Storage	Size Stability at the End of 160-Day Storage Period In Per Cent
Sample completely exposed	.....
Sample protected from sunshine	48.8
Sample protected from rain	59.9
Sample protected from sunshine and rain	58.8
Sample stored in basement	69.2
Sample sealed in cans	81.0
Sample submerged under water	87.5
Sample at beginning of tests	88.3

2. The general pattern of size stability is much like that of size degradation in the case of lignite, i.e., the factors which influence the breaking of particles of this fuel while in storage also influence the breakage of these particles while being handled after being removed from storage.
3. In the case of the samples which were protected from rain and to which no moisture was added, the size stability characteristics appear to have a very close relationship to the moisture content of the fuel.

Class of Storage	Reduction in Moisture Content in 160 Days Per Cent	Reduction in Size Stability in 160 Days Per Cent
Samples protected from rain	21.0	28.4
Samples protected from sunshine and rain	21.0	29.5
Samples stored in basement	18.7	19.1
Samples sealed in cans	1.3	7.3

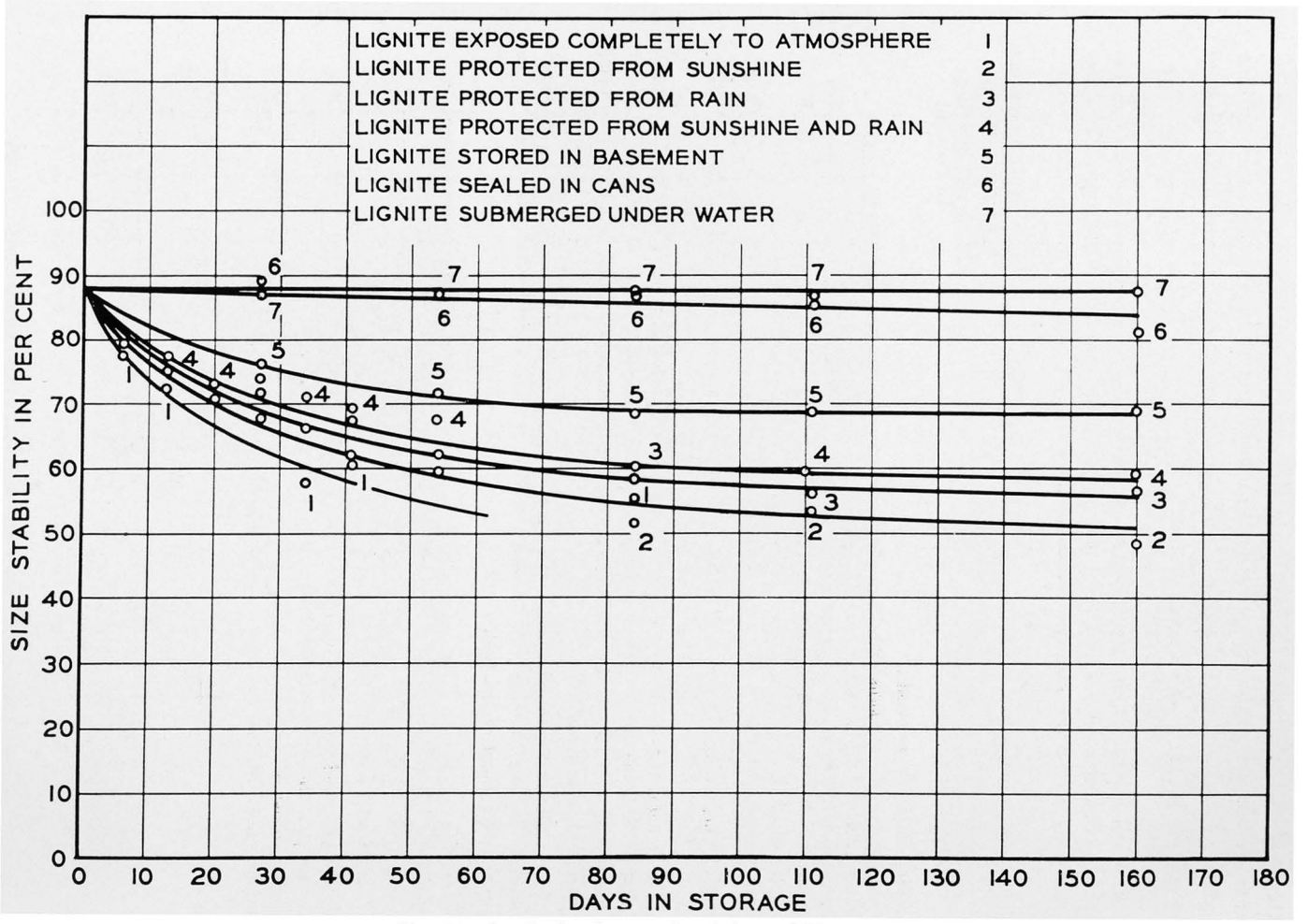

FIG. 20. Graph showing results of size stability tests.

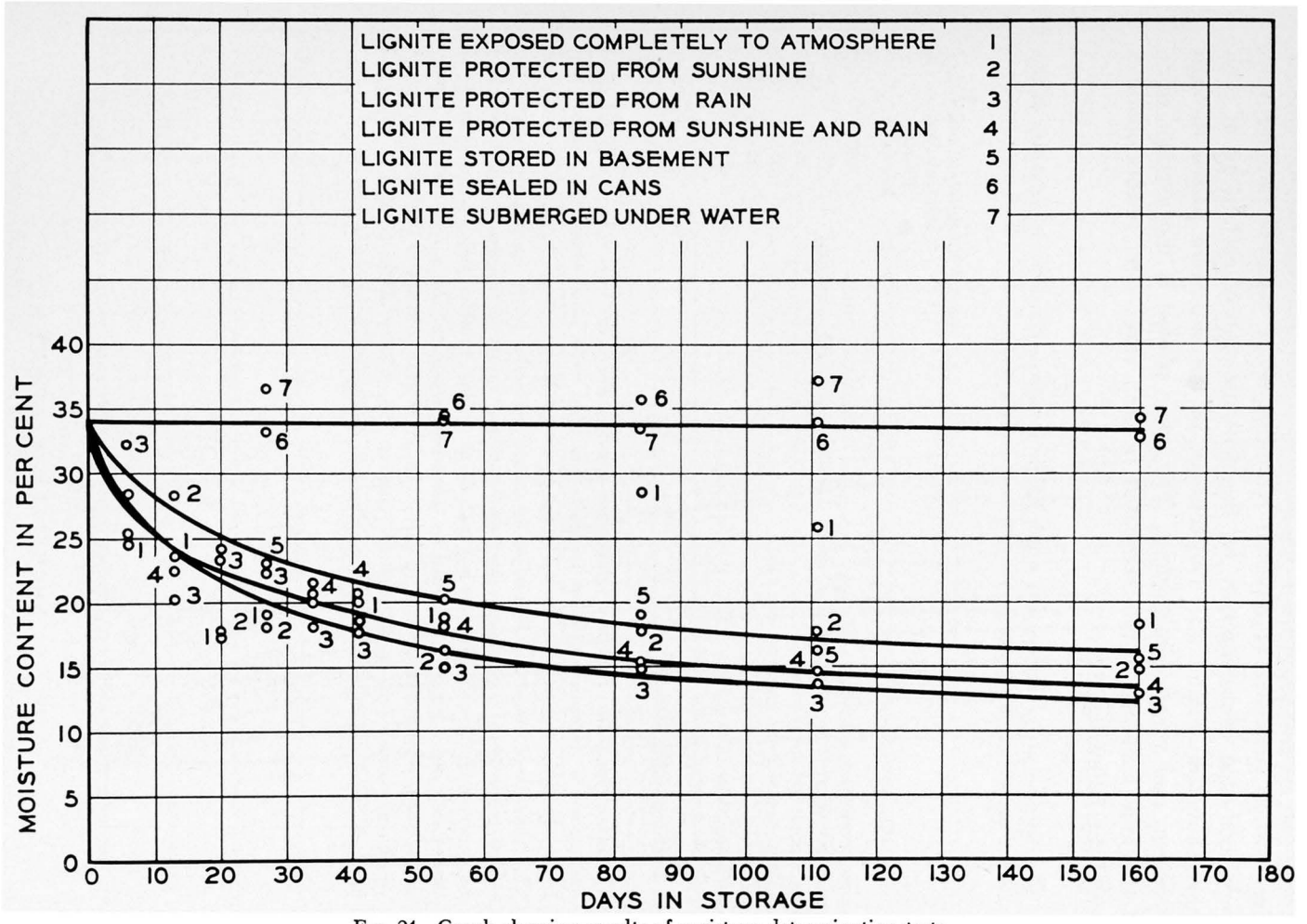

FIG. 21. Graph showing results of moisture determination tests.

The friability of lignite was determined in this case with the hope that it might be used as an index to the liability of this fuel to break into smaller pieces when subjected to repeated handling. Four separate tumbler tests were conducted simultaneously for the determination of each point of each curve shown on Figure 22. The contents of the jars were passed through the sieves and weighed separately. The point plotted is the average value of the four friability results computed in each case. The results obtained reveal the following:

1. The character of the storage into which lignite is placed influences the friability of this fuel at the end of the storage period to a very great extent.

Class of Storage	Friability at the End of 160-Day Storage Period Per Cent
Sample completely exposed	64.9
Sample protected from sunshine	42.4
Sample protected from rain	36.5
Sample protected from sunshine and rain	35.5
Sample stored in basement	32.6
Sample sealed in cans	21.1
Sample submerged under water	24.7
Sample at beginning of tests	15.7

2. The magnitude of the friability values were greatest where the least control was exercised over moisture absorption-rejection processes and they were least where the number and frequency of these cycles was limited to the greatest extent.
3. The friability of samples of lignite stored submerged under water appears throughout the test period to have been greater than corresponding values for similar samples sealed in containers with no water. It was not possible to conduct tumbler tests upon this material immediately upon removing it from its submerged condition. As a result of this circumstance it was permitted to give off its surface moisture until a moisture content was reached which approximated its initial moisture content. The ability of the lignite to withstand breakage in subsequent handling was reduced by the moisture reduction process.

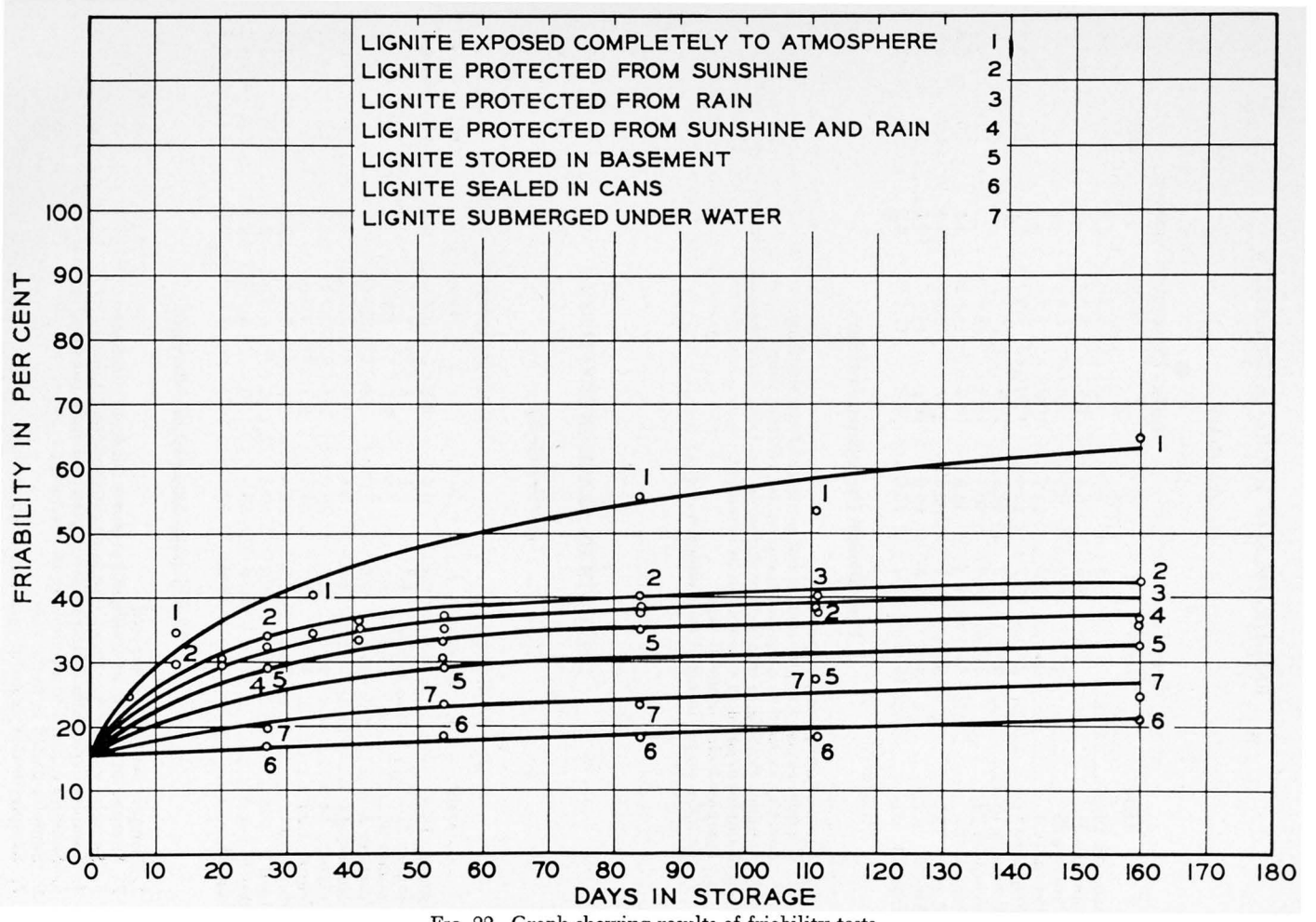

FIG. 22. Graph showing results of friability tests.

RESULTS OF SIZE DEGRADATION TESTS

(In Per Cent)

Date	Period Days	Storage Designation Number 1	2	3	4	5	6	7
January 15	0	3.2	3.2	3.2	3.2	3.2	3.2	3.2
January 21	6	5.6	6.4	7.5	5.2	....	....	....
January 28	13	8.2	8.1	7.8	6.4	....	....	....
February 4	20	13.4	11.7	10.6	7.5	....	....	....
February 11	27	19.7	12.4	12.0	9.6	6.7	3.4	5.2
February 18	34	56.9	36.9	15.9	11.4	....	....	....
February 25	41	54.9	40.1	18.5	12.5	....	....	....
March 10	54	60.3	45.6	18.9	13.1	9.1	5.5	5.8
April 9	84	83.1	68.5	25.7	18.2	9.4	4.0	6.2
May 6	111	82.6	65.6	26.5	15.5	10.7	7.5	3.8
June 24	160	81.1	70.0	28.2	17.1	9.6	8.8	5.2

Fuel Storage Designation Numbers

1. Samples completely exposed.
2. Samples exposed to atmosphere but protected from sunshine.
3. Samples exposed to atmosphere but protected from rain.
4. Samples exposed to atmosphere but protected from sunshine and rain.
5. Samples exposed to atmosphere in basement.
6. Samples sealed in metal cans.
7. Samples sealed in metal cans under water.

RESULTS OF SLACK INDEX TESTS

(In Per Cent)

Date	Period Days	Storage Designation Number 1	2	3	4	5	6	7
January 15	0	0.4	0.4	0.4	0.4	0.4	0.4	0.4
January 21	6	1.4	2.1	1.8	1.3	....	....	....
January 28	13	3.1	2.5	2.1	1.8	....	....	....
February 4	20	5.8	3.0	3.8	2.2	....	....	....
February 11	27	12.0	5.4	4.4	2.4	1.5	0.6	0.9
February 18	34	52.4	29.0	6.2	3.9	....	....	....
February 25	41	51.3	34.3	8.3	4.0	....	....	....
March 10	54	38.5	25.3	9.1	5.4	2.2	1.3	1.3
April 9	84	93.0	69.3	13.0	6.8	2.7	0.9	1.7
May 6	111	90.0	60.8	11.0	4.7	2.2	1.2	1.0
June 24	160	87.8	72.2	14.2	7.6	2.8	2.1	1.4

Fuel Storage Designation Numbers

1. Samples completely exposed.
2. Samples exposed to atmosphere but protected from sunshine.
3. Samples exposed to atmosphere but protected from rain.
4. Samples exposed to atmosphere but protected from sunshine and rain.
5. Samples exposed to atmosphere in basement.
6. Samples sealed in metal cans.
7. Samples sealed in metal cans under water.

RESULTS OF SIZE STABILITY TESTS

(In Per Cent)

Date	Period Days	Storage Designation Number 1	2	3	4	5	6	7
January 15	0	88.3	88.3	88.3	88.3	88.3	88.3	88.3
January 21	6	77.5	79.0	79.5	79.3	....	....	....
January 28	13	72.9	75.7	75.2	77.3	....	....	....
February 4	20	73.8	71.0	75.1	72.7	....	....	....
February 11	27	68.0	70.0	71.6	74.6	76.0	89.7	86.8
February 18	34	58.1	66.0	66.1	71.4	....	....	....
February 25	41	61.8	62.5	67.8	69.6	....	....	....
March 10	54	62.5	59.8	62.2	67.8	71.8	87.4	87.1
April 9	84	55.9	51.6	60.4	58.0	68.2	86.8	87.8
May 6	111	....	53.8	56.1	59.9	68.4	85.1	86.8
June 24	160	....	48.8	59.9	58.8	69.2	81.0	87.5

Fuel Storage Designation Numbers

1. Samples completely exposed.
2. Samples exposed to atmosphere but protected from sunshine.
3. Samples exposed to atmosphere but protected from rain.
4. Samples exposed to atmosphere but protected from sunshine and rain.
5. Samples exposed to atmosphere in basement.
6. Samples sealed in metal cans.
7. Samples sealed in metal cans under water.

RESULTS OF SHATTER INDEX TESTS

(In Per Cent)

Date	Period Days	Storage Designation Number 1	2	3	4	5	6	7
January 15	0	3.9	3.9	3.9	3.9	3.9	3.9	3.9
January 21	6	10.2	9.6	8.6	9.0	....	....	....
January 28	13	12.7	11.3	12.1	10.4	....	....	....
February 4	20	13.0	14.5	12.3	13.8	....	....	....
February 11	27	16.1	15.6	14.0	12.9	11.5	3.4	5.4
February 18	34	24.8	18.6	18.1	13.3	....	....	....
February 25	41	21.1	18.3	16.7	15.3	....	....	....
March 10	54	20.1	20.2	18.5	16.3	13.5	4.1	4.2
April 9	84	61.8	25.6	20.3	21.2	15.6	4.8	4.9
May 6	111	....	23.4	23.2	18.4	15.8	5.5	6.0
June 24	160	....	28.2	20.1	21.2	15.4	8.6	5.5

Fuel Storage Designation Numbers

1. Samples completely exposed.
2. Samples exposed to atmosphere but protected from sunshine.
3. Samples exposed to atmosphere but protected from rain.
4. Samples exposed to atmosphere but protected from sunshine and rain.
5. Samples exposed to atmosphere in basement.
6. Samples sealed in metal cans.
7. Samples sealed in metal cans under water.

RESULTS OF FRIABILITY TESTS

(In Per Cent)

Date	Period Days	Storage Designation Number 1	2	3	4	5	6	7
January 15	0	15.7	15.7	15.7	15.7	15.7	15.7	15.7
January 21	6	24.9	32.1	27.2	33.0	....	....	....
January 28	13	34.5	29.7	32.1	33.2	....	....	....
February 4	20	30.3	46.8	30.4	29.5	....	....	....
February 11	27	34.0	33.9	32.3	29.0	29.1	17.0	19.8
February 18	34	40.5	41.3	47.2	34.4	....	....	....
February 25	41	36.7	40.5	35.7	33.5	....	....	....
March 10	54	33.1	30.5	37.3	30.7	29.0	18.4	23.3
April 9	84	55.9	38.8	38.2	40.0	35.0	18.3	23.2
May 6	111	53.5	37.6	40.4	38.0	27.0	18.4	27.8
June 24	160	64.9	42.4	36.5	35.5	32.6	21.1	24.7

Fuel Storage Designation Numbers

1. Samples completely exposed.
2. Samples exposed to atmosphere but protected from sunshine.
3. Samples exposed to atmosphere but protected from rain.
4. Samples exposed to atmosphere but protected from sunshine and rain.
5. Samples exposed to atmosphere in basement.
6. Samples sealed in metal cans.
7. Samples sealed in metal cans under water.

RESULTS OF DUST INDEX TESTS

(In Per Cent)

Date	Period Days	Storage Designation Number 1	2	3	4	5	6	7
January 15	0	9.6	9.6	9.6	9.6	9.6	9.6	9.6
January 21	6	9.6	11.9	10.7	10.9	....	....	....
January 28	13	11.6	10.6	10.5	11.1	....	....	....
February 4	20	11.5	12.6	10.5	11.6	....	....	....
February 11	27	11.4	12.2	11.0	10.8	10.7	7.5	5.2
February 18	34	13.4	12.0	13.7	11.3	....	....	....
February 25	41	11.8	12.4	11.2	11.9	....	....	....
March 10	54	11.1	10.5	11.1	11.3	11.6	7.6	6.1
April 9	84	5.6	11.2	11.9	12.1	12.2	8.1	6.9
May 6	111	7.1	11.3	11.3	12.2	11.5	7.8	7.2
June 24	160	8.9	11.8	11.4	11.4	12.4	7.6	8.5

Fuel Storage Designation Numbers

1. Samples completely exposed.
2. Samples exposed to atmosphere but protected from sunshine.
3. Samples exposed to atmosphere but protected from rain.
4. Samples exposed to atmosphere but protected from sunshine and rain.
5. Samples exposed to atmosphere in basement.
6. Samples sealed in metal cans.
7. Samples sealed in metal cans under water.

RESULTS OF MOISTURE CONTENT TESTS

(In Per Cent)

Date	Period Days	Storage Designation Number 1	2	3	4	5	6	7
January 15	0	34.0	34.0	34.0	34.0	34.0	34.0	34.0
January 21	6	24.7	28.4	32.4	25.3	....	....	....
January 28	13	23.5	28.3	20.3	22.6	....	....	....
February 4	20	17.3	17.7	23.4	24.2	....	....	....
February 11	27	19.2	18.1	23.2	22.4	23.2	33.3	36.5
February 18	34	20.7	20.1	18.1	21.5	....	....	....
February 25	41	20.2	18.6	18.3	20.8	....	....	....
March 10	54	18.8	16.3	14.9	18.5	20.2	34.5	34.2
April 9	84	28.6	17.7	14.7	15.3	19.0	35.6	33.4
May 6	111	25.8	18.2	13.7	14.6	16.2	32.9	37.2
June 24	160	18.2	14.8	13.0	13.0	15.3	32.7	34.2

Fuel Storage Designation Numbers

1. Samples completely exposed.
2. Samples exposed to atmosphere but protected from sunshine.
3. Samples exposed to atmosphere but protected from rain.
4. Samples exposed to atmosphere but protected from sunshine and rain.
5. Samples exposed to atmosphere in basement.
6. Samples sealed in metal cans.
7. Samples sealed in metal cans under water.

RESULTS OF LOSS OF MOISTURE TESTS

(In Per Cent)

Date	Period Days	Storage Designation Number 1	2	3	4	5	6	7
January 15	0	....	....	....	....	....	....	....
January 21	6	9.3	5.6	1.6	8.7	....	....	....
January 28	13	10.5	5.7	13.7	11.4	....	....	....
February 4	20	16.7	16.3	10.6	9.8	....	....	....
February 11	27	14.8	15.9	10.8	11.6	10.8	0.7	—2.5
February 18	34	13.3	13.9	15.9	12.5	....	....	....
February 25	41	13.8	15.4	15.7	13.2	....	....	....
March 10	54	15.2	17.7	19.1	15.5	13.8	—0.5	—0.2
April 9	84	5.4	16.3	19.3	18.7	15.0	—1.6	0.6
May 6	111	8.2	15.8	20.3	19.4	17.8	1.1	—3.2
June 24	160	15.8	19.2	21.0	21.0	18.7	1.3	—0.2

Fuel Storage Designation Numbers

1. Samples completely exposed.
2. Samples exposed to atmosphere but protected from sunshine.
3. Samples exposed to atmosphere but protected from rain.
4. Samples exposed to atmosphere but protected from sunshine and rain.
5. Samples exposed to atmosphere in basement.
6. Samples sealed in metal cans.
7. Samples sealed in metal cans under water.

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