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An Investigation of the Grindability of Alberta Subbituminous Coals

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AN INVESTIGATION OF THE GRINDABILITY OF ALBERTA SUBBITUMINOUS COALS

by E. J. Jensen and J. F. Fryer

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Introduction

Grindability of coal has been the subject of many laboratory investigations, mainly in the United States and the United Kingdom. Several extensive studies were carried out with a view to having a method of determining the grindability of coal adopted as a standard method by the A.S.T.M. Eventually, in 1951, the Hardgrove test (1) was adopted by the A.S.T.M. as the sole standard method. This was probably due, to a large extent, to its simplicity and to the rapidity with which tests could be carried out. Calcott (2) made a detailed study of the performance of a slightly modified Hardgrove machine and its applicability to U.K. coals. Fitton, Hughes and Hurley (3) investigated various factors influencing the Hardgrove test. None of these workers offered any serious criticism of the Hardgrove machine.

All of these studies dealt with high-rank coals having fairly constant ash contents, and low moisture contents varying from 0 to 5 percent. The use of low-rank coals as pulverized fuel has increased rapidly in recent years; however, these coals behave differently from the high-rank coals in a grinding mill.

Samples of Alberta subbituminous coals submitted by mine operators and by power plant engineers have, from time to time, been tested on the Hardgrove machine in laboratories outside the province. The results of these tests have shown a disturbing lack of consistency, and the question has been raised as to what the grindability index really means in grinding practice. Brown (4), using high-rank coals, tried to relate the results of the Hardgrove test to practical grinding, but had to allow for a number of difficulties. It is conceivable that the Hardgrove test, which was designed for use with high-rank coals, would need considerable modification before it could be used successfully for subbituminous coals with high moisture contents.

The present investigation of the grindability of Alberta subbituminous coals was initiated as a result of the dissatisfaction and doubt which arose from the results of Hardgrove tests on these coals.

The Research Council of Alberta Grindability Apparatus

At the outset it was decided that it would be more desirable to have a test which would express grindability in terms of absolute units of energy required to produce a unit increase in surface area, rather than give an empirical relative value as obtained by the Hardgrove test. The Research Council of Alberta grindability apparatus described below was designed with this aim in mind.

The design and arrangement are shown in Figure 1. The crushing elements of the apparatus consist of two steel rolls having a surface hardness of 300 Brinell and with shafts in each end. The length of each roll is 6 inches and the diameter is 4 inches. The shafts run on bearings suspended in the walls of the apparatus in such a manner that the gap between the rolls can be adjusted to any size up to 1/8 inch. The rolls are placed one above the other so that the feed will enter horizontally. The feed is brought to the rolls by an electrically-vibrated feeding-table provided with a hopper, and two scraping knives to clean the rolls during grinding are mounted on the rear side of the rolls and held against the

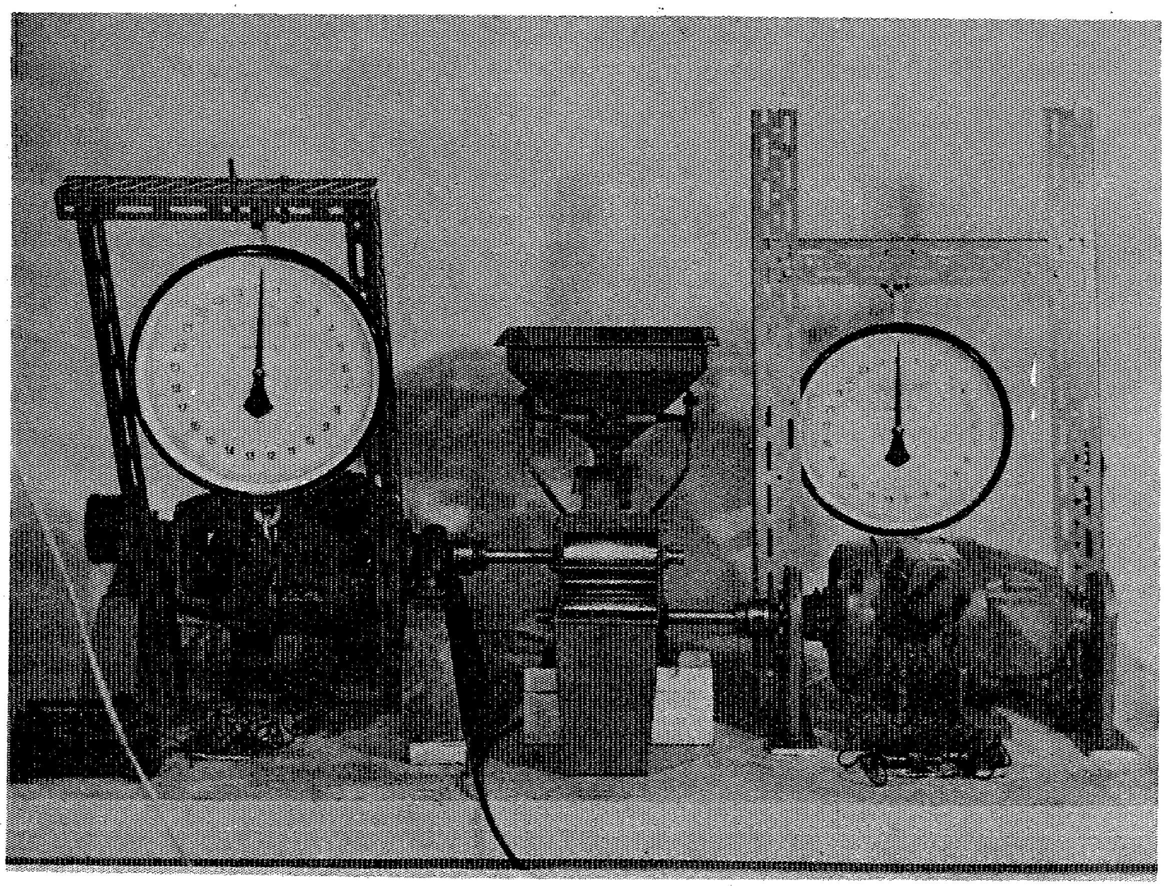

Figure 1 The Research Council of Alberta grindability apparatus.

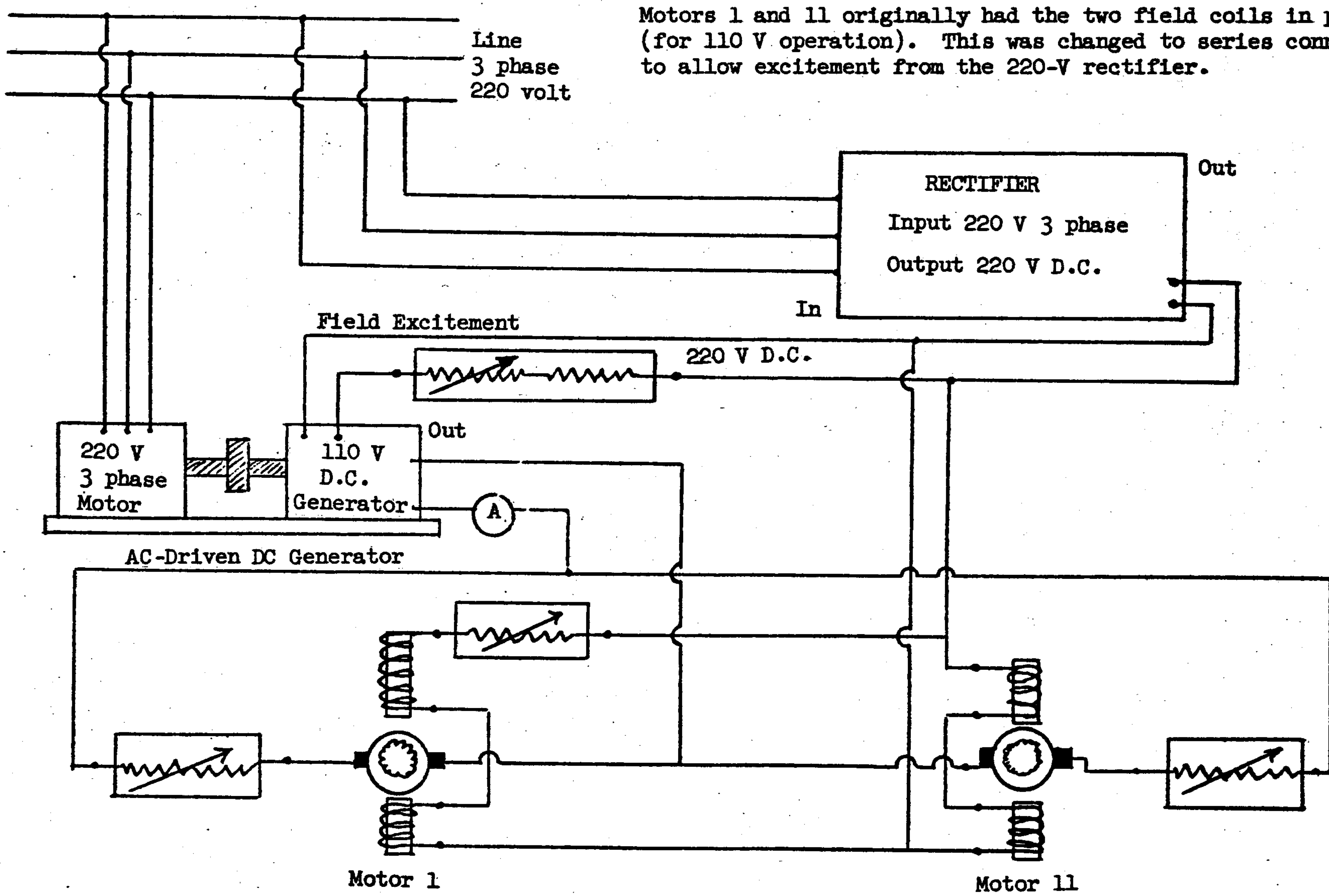

FIGURE 2

Circuit diagram for D.C. motors used in the Research Council of Alberta grindability apparatus.

rolls by springs. Each roll is turned by a motor attached to a shaft by means of a rigid coupling. Each motor is suspended in ball bearings so that the torque developed in the motor can be measured on a dynamometer attached to the motor by an arm 1 foot in length; D. C. shunt motors are used, and the electrical arrangement is shown in Figure 2.

It will be noticed that the armature and field of the motors are fed from two sources of different voltages. This is done because the motors were designed to run at 1200 and 1800 r.p.m., whereas speeds from 300 to 600 r.p.m. with maintained torque characteristics are desired. This complicated arrangement was chosen to avoid the expense of custom-built D.C. motors. Resistors cut into this armature circuit allow a variation in the r.p.m. of each motor of about 20 percent without impairing the torque characteristics.

Preliminary Tests

Optimum conditions for a number of variables had to be determined, and a large number of tests using different settings were necessary before a standard procedure was worked out. The variables involved were: (a) size of feed, (b) rate of feed, (c) constancy of rate of feed, (d) gap between rolls, (e) velocity of rolls and the ratio of the velocities of the rolls.

(a) The size of feed was chosen as -14 +28 mesh Tyler (-16 to +30 U.S.) as this size is used in the Hardgrove test and thus facilitates the making of comparisons. Other sizings were tried but did not prove more advantageous.

(b) and (c) A 200-gram sample fed through the apparatus in 80 $\pm$ 30 seconds was found to be the most convenient. It was necessary to feed the apparatus somewhat below capacity to avoid excessive spilling at the back of the rolls.

Too slow feeding led to low readings on the dynamometers.

(d) It was found that, as the distance between the rolls was decreased, a finer product and higher readings on the dynamometers were obtained. However, a gap smaller than 0.004 inch caused extreme flaking of the product.

(e) A velocity of 600 r.p.m. for the upper roll and 500 r.p.m. for the lower roll was found to produce the best results. When the rolls rotated at equal speeds the product was flaky.

Six runs were made with the same sample under identical conditions.

Speeds: Upper roll 600 r.p.m. $\pm$ 3

Lower roll 500 r.p.m. $\pm$ 2

Gap: 0.007 inch

The results obtained are shown in Table I.

TABLE I

Results of six identical test runs on the Research Council of Alberta apparatus

Run No.	Torque, ft.lbs. Upper roll Empty	Upper roll Loaded	Upper roll Net	Lower roll Empty	Lower roll Loaded	Lower roll Net	Duration of run, sec.	Weight of product recovered gm.
I	0.80	2.20	1.40	0.55	-0.35	-0.90	31.7	193
II	0.80	2.30	1.50	0.55	-0.40	-0.95	32.9	195
III	0.80	2.25	1.45	0.60	-0.35	-0.95	32.9	196
IV	0.80	2.30	1.50	0.60	-0.40	-1.00	31.3	195
V	0.80	2.20	1.40	0.50	-0.40	-1.00	31.3	196
VI	0.85	2.15	1.30	0.55	-0.35	-0.90	32.3	196

Sieve analysis of product, %

Sieve	I	II	III	IV	V	VI	Av.
+35	11.6	11.9	12.8	12.0	13.0	12.5	12.3
+48	32.9	33.8	33.6	33.6	34.0	33.8	33.6
+65	24.5	23.9	23.8	23.7	23.7	23.6	23.8
+100	17.4	16.1	15.4	15.9	15.1	15.3	15.5
+150	4.5	5.2	5.7	5.7	5.7	5.7	5.4
+200	4.8	4.7	4.6	4.7	4.4	4.7	4.7
-200	4.3	4.4	4.1	4.4	4.4	4.4	4.3
	100.0	100.0	100.0	100.0	100.0	100.0	99.6

Table I shows that the sieve analyses of all six runs were practically identical, indicating that consistent results can be expected from this apparatus, providing the correct procedure is followed.

Standardized Procedure

The coal sample, made up of big lumps in order to prevent loss of moisture, is crushed in a hammer-crusher with a 1/8-inch bottom screen. The crushed sample is then screened in batches of approximately 250 grams between -14 and +28 mesh Tyler for 20 minutes using a Ro-tap machine. The material is kept in closed containers. When a sufficient amount of sized coal for the experiment has been produced, it is mixed thoroughly and kept in containers with tight covers until used.

A 200-gram sample of the -14 +28 mesh Tyler material is weighed to the nearest 0.5 gram and transferred to a sealer. The feeder is started and the hopper is adjusted to deliver the 200 grams in approximately 60 seconds. The gap is set at 0.004 inch, the roll crusher is started and the speed regulated at 600 and 500 r.p.m. for the upper and lower rolls respectively The dynamometers are now read and this reading is referred to as "empty". The coal is dumped into the hopper, and when the front of the coal stream reaches the rolls a timer is started. After a few seconds the dynamometer pointers oscillate around an equilibrium position. Readings are then taken and are referred to as "loaded". When the end of the coal stream reaches the rolls, the timer is stopped. Coal adhering to the frame of the apparatus is brushed into the container with the ground coal. The ground product is weighed to the nearest 0.5 gm., and this weight is taken to be the weight of feed. This procedure was adopted due to the observation that the losses that were encountered occurred at the back of the rolls and thus never reached the rolls. The ground, weighed coal is transferred to a nest of Tyler sieves consisting of 35, 48, 65, 100, 150, 200 mesh sieves and screened for 20 minutes using a Ro-tap machine. The sieves were weighed before and after sieving. From the readings on the Research Council apparatus and the sieve analysis, the energy in ft.lbs. required to produce a square foot of new surface was calculated. The methods for calculating both the energy used in grinding and the increase in surface area are given in the Appendix to this report.

The Hardgrove Machine

During the time that the preliminary tests were being conducted on the Research Council of Alberta apparatus, a Hardgrove machine was obtained by the Research Council. It was hoped that some of the reported shortcomings of the Hardgrove machine when applied to subbituminous coals could be investigated, and that a comparison between the performances of the Hardgrove machine and the Research Council apparatus could be made.

The Hardgrove machine is described by the A.S.T.M [1] and, in more detail, by Hardgrove [5]. Details of the machine are shown in Figure 9.

Procedure for Hardgrove Test

The procedure prescribed in the A.S.T.M.[1] standard was followed with a few exceptions. The sample was prepared as described above, and sieved on a Ro-tap machine for 20 minutes, but brushing of the sieve was omitted. It was found that a straight 20-minute sieving period led to the same results as the procedure described by the A.S.T.M. standard. The coals under investigation do not stick to the sieves, which explains why brushing was unnecessary. Where a definite moisture content was desired, air-drying was omitted.

To check the machine's performance three samples were tested on the Hardgrove machine, and the results compared with those obtained on identical samples submitted to the Fuel Research Laboratories of the Department of Mines and Technical Surveys at Ottawa. The comparative results are shown in Table II.

TABLE II

Hardgrove indices of coal samples as obtained by the Research Council of Alberta (R.C.A.) and by the Fuel Research Laboratories (F.R.L.), Ottawa

	F. R. L.		R. C. A.		
Sample	Moisture content of coal %	Hardgrove index	Moisture content of coal %	Hardgrove index	Loss during test g.
A	0.8	99	-	102	0.31
B	22.8	29	23.3	28	0.12
C	0.6	79	-	79	0.26

According to the A.S.T.M., the permissible variation in Hardgrove indices obtained by two laboratories is 3 percent. The results shown in Table II indicate that our Hardgrove machine would give satisfactory results.

Experimental Work

As the moisture content was thought to be one of the major factors affecting the grindability of subbituminous coals, it was decided to investigate the relationship between these two qualities.

Coals Tested

All coals tested were from coal fields in the Edmonton horizon. One sample was from the Castor area, and other samples were collected from a mine in the Pembina area. Samples from different seams and locations (as indicated by Figure 3) were taken. It is known that the coal in a given mine can vary from seam to seam, and also from location to location along a seam.

The samples comprising about 100 lbs. each were taken from points three feet behind the coal face, to avoid any conflicting results which might arise from weathering effects on the coal. The samples were kept in closed containers until tested. Analysis figures for the samples are given in Table III.

Preparation of Samples for Grindability Tests

The samples were crushed in a hammer-mill fitted with a 1/8-inch outlet screen. The crushed material was sieved until sufficient material of size -14 +28 mesh Tyler to conduct a series of tests was obtained. This sized material was stored in sealed jars.

In all tests on samples of less than natural moisture content, the moisture in the coal was reduced by drying in an oven at about 70°C. until the desired initial moisture content was reached. After drying, the samples were hand-sieved on a 28 mesh Tyler screen to remove any fines formed during drying, and transferred to sealed containers for at least 24 hours.

Grindability tests were conducted on these samples by both the Research Council of Alberta apparatus and the Hardgrove machine using the procedures described previously. Immediately before carrying out the grindability tests, samples of the sieved coal were taken for moisture determination.

Determination of Moisture

Five-gram samples of coal were heated at 108°C. for 2-1/4 hours in a

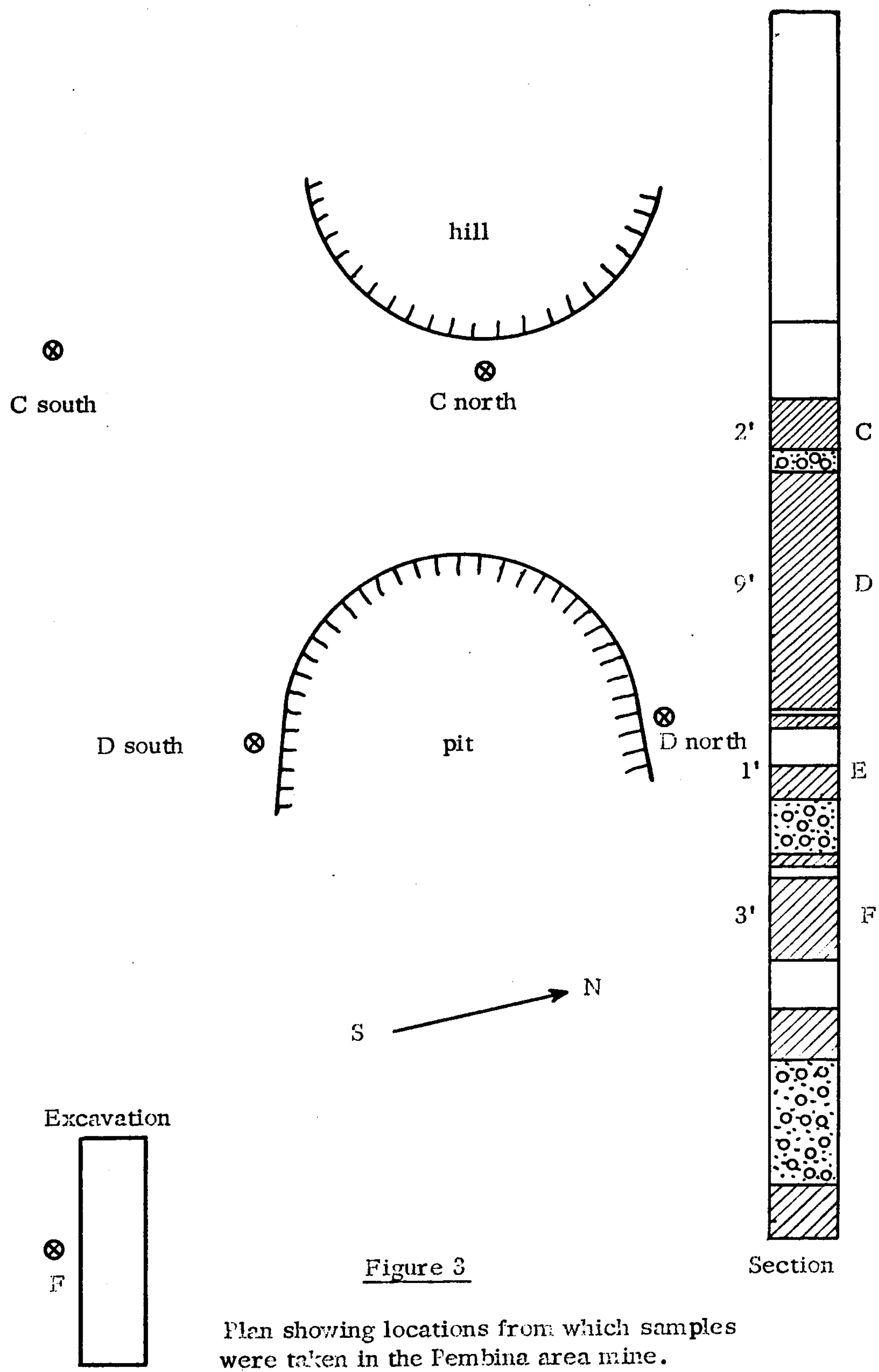

Figure 3

Plan showing locations from which samples were taken in the Pembina area mine.

TABLE III

Analysis of coal samples used in grindability tests

		Castor	Pembina F Seam 797-57	Pembina C South 800-57	Pembina C North 950-57	Pembina D South 900-57	Pembina D North 849-57
CAPACITY MOISTURE BASIS							
Moisture,	%	25.6	21.5	22.4	22.3	22.0	21.4
Ash,	%	7.3	10.2	7.0	6.9	6.1	5.6
Volatile matter,	%	27.7	26.2	28.5	27.0	29.5	29.7
Fixed carbon,	%	39.4	42.1	42.1	43.8	42.4	43.3
Carbon,	%		51.7	52.9	53.95	53.95	54.60
Hydrogen,	%		3.1	3.3	3.00	3.40	3.45
Calorific value,	B.t.u./lb.	8620	8490	8790	8930	9130	9290
AS RECEIVED BASIS							
Moisture,	%	27.3	22.0	22.8	23.9	23.7	22.0
Ash,	%	7.2	10.1	7.0	6.8	6.0	5.5
Volatile matter,	%	27.1	26.0	28.3	26.4	28.8	29.5
Fixed carbon,	%	38.4	41.9	41.9	42.9	41.5	43.0
Carbon,	%		51.4	52.7	52.80	52.75	54.20
Hydrogen,	%		3.0	3.3	2.90	3.35	3.40
Calorific value,	B.t.u./lb.	8420	8440	8740	8740	8930	9220
DRY BASIS							
Ash,	%	9.8	13.0	9.0	8.9	7.8	7.1
Volatile matter,	%	37.3	33.4	36.7	34.7	37.8	37.8
Fixed carbon,	%	52.9	53.6	54.3	56.4	54.4	55.1
Carbon,	%		65.9	68.2	69.40	69.15	69.50
Hydrogen,	%		3.9	4.2	3.85	4.35	4.35
Calorific value,	B.t.u./lb.	11,590	10,820	11,320	11,490	11,710	11,820

nitrogen atmosphere at an absolute pressure of about 10 cm. of mercury. The percentage of moisture was calculated from the loss in weight.

Precision:

For coals over 5% moisture - 0.3% absolute,

For coals under 5% moisture - 0.2% absolute.

Experimental Results

The results showing the grindabilities at various moisture contents as determined by both machines for the coal sample from the Castor area are given in Table IV and shown in Figure 4.

TABLE IV

Grindability of coal from the Castor area at different moisture contents

(a) Hardgrove machine

Sample No.	Moisture, %	Hardgrove index
701	27.3	39.4
706	22.4	37.2
711 (air dried)	15.9	33.4
716	11.7	35.5
721	22.1	37.6
726	4.5	40.2
731	0.5	37.0
760	6.6	40.7

(b) Research Council apparatus

Sample No.	Moisture, %	ft.lbs./sq.ft.
739	27.5	24.3
742	22.5	26.9
745	18.2	27.3
748	14.5	23.9
751	8.9	21.3
754	6.6	21.7
757	3.1	21.8

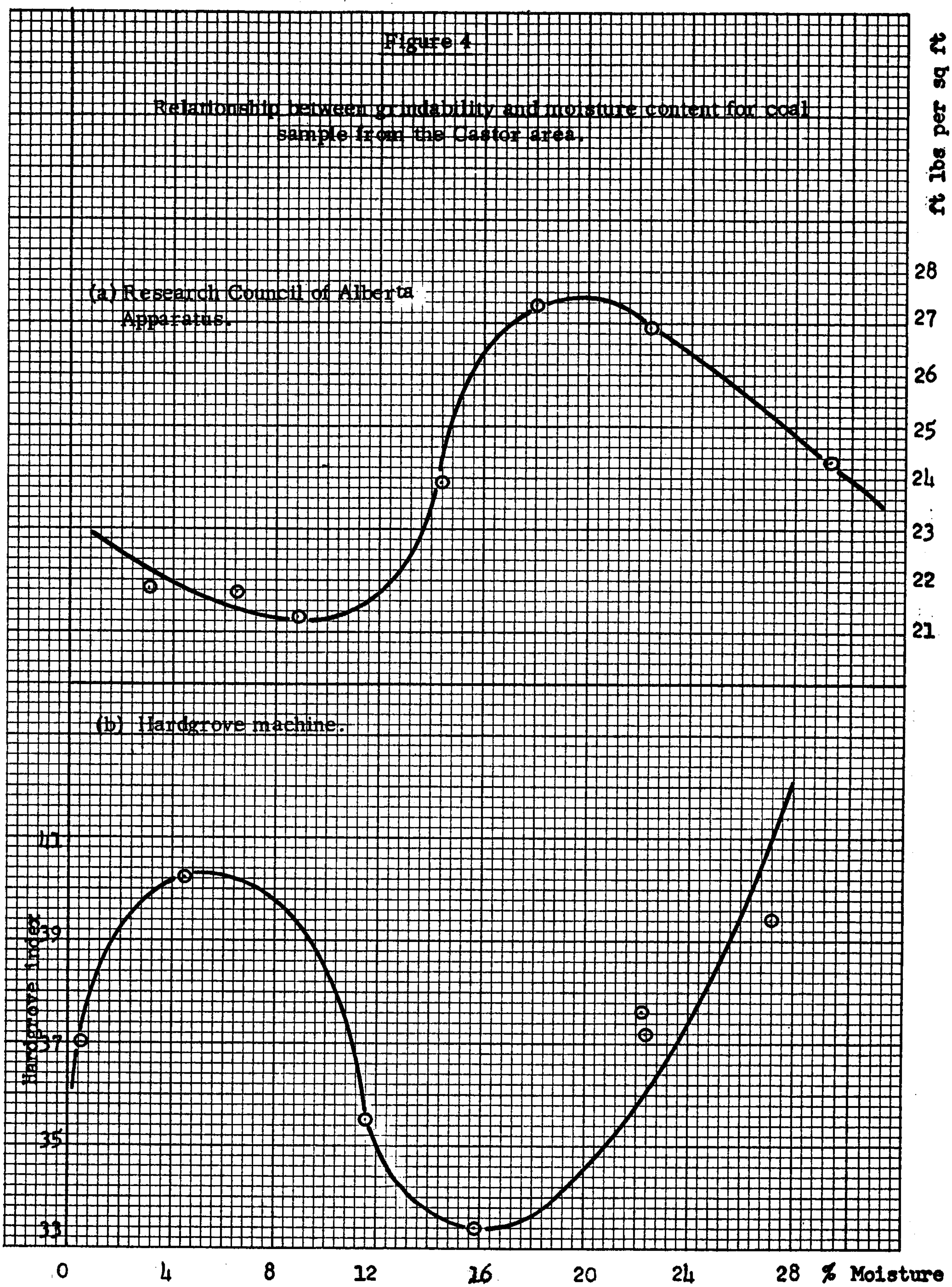
Figure 4
Relationship between grindability and moisture content for coal sample from the Castor area.
ft lbs per sq ft
28
27
26
25
24
23
22
21
(a) Research Council of Alberta Apparatus.
(b) Hardgrove machine.
Hardgrove Index
41
39
37
35
33
0
4
8
12
16
20
24
28
% Moisture

Table V gives the results for the different samples obtained from the mine in the Pembina area. These results are plotted in Figures 5, 6, 7 and 8. Each result is the average of duplicate values, and the agreement between duplicates for the Hardgrove index was of the order of 0.5 units, and for the Research Council of Alberta apparatus between 5 and 10 percent.

TABLE V

Relationship between grindability and moisture content for five samples of coal from the Pembina area

Seam and location	Sample No.	Moisture, %	Hardgrove index	ft.lbs./sq.ft.
	765 - 795	22.2	70.1	16.4
	771	1.2	58.8	20.9
F	776 (air dried)	14.2	58.3	14.5
	781	15.1	60.7	14.7
	785	9.7	63.3	16.4
	790	6.8	62.4	18.4
	801	23.5	59.0	22.2
	806 (air dried)	16.1	53.4	24.4
C	811	0.8	50.3	21.9
South	820	13.9	52.4	18.7
	825	10.7	55.6	18.3
	830	18.2	52.4	18.5
	850 (air dried)	14.1	49.3	39.8
	855	0.6	44.5	25.6
D	860	21.8	45.5	41.7
North	865	11.6	49.8	27.6
	870	8.8	47.6	35.7
	875	16.4	47.3	41.1
	901	23.6	55.9	-
	904	0.6	53.0	-
D	907 (air dried)	13.0	55.6	-
South	910	11.5	55.9	-
	913	9.9	57.2	-
	916	16.8	57.8	-
	925	6.0	55.8	-
	990	23.3	53.9	-
	991	21.2	49.4	-
C	992 (air dried)	15.2	51.7	-
North	993	9.7	53.5	-
	994	11.4	53.2	-
	995	6.7	56.3	-
	996	17.1	51.6	-
	997	1.9	56.2	-

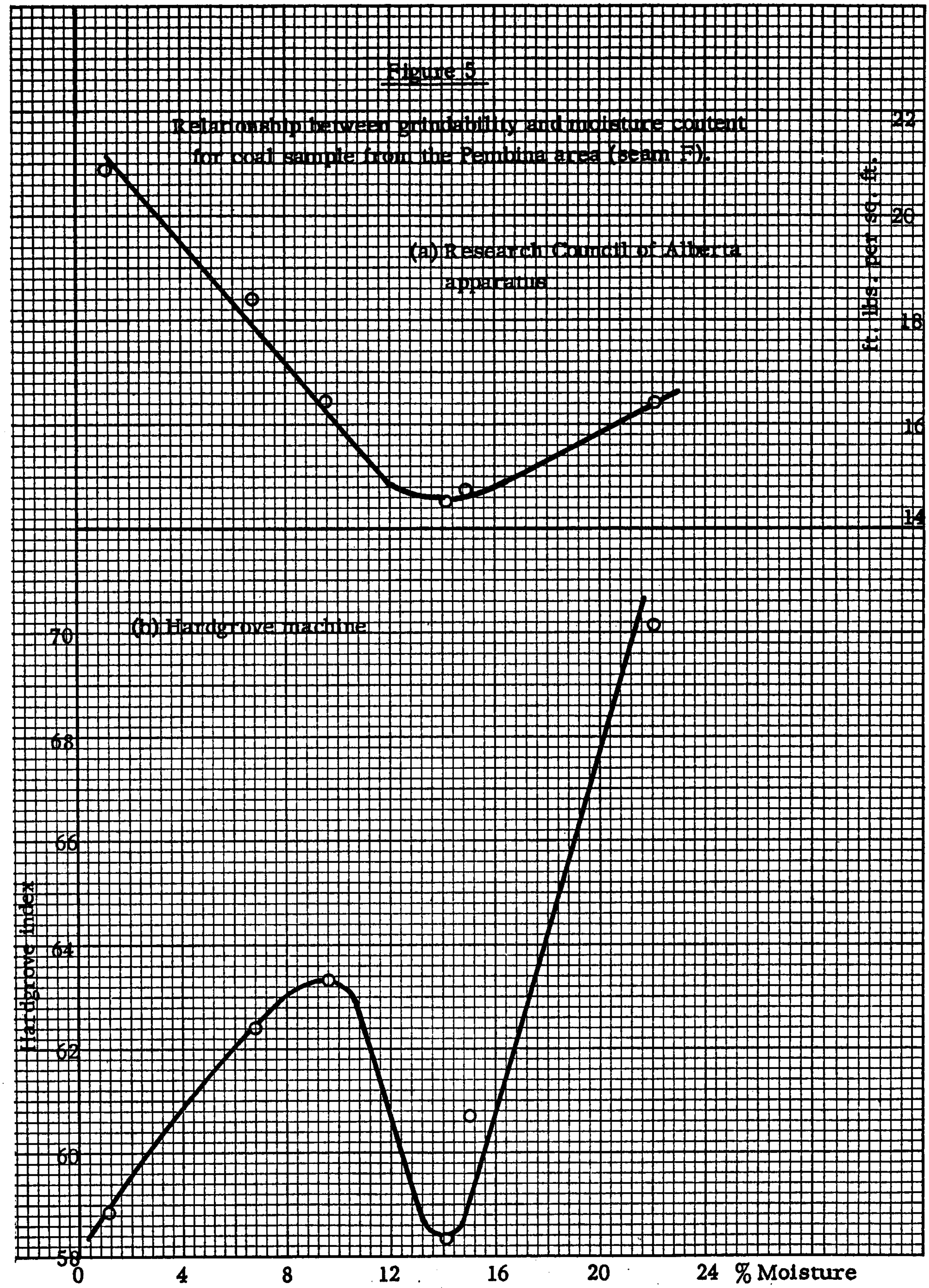
Figure 5
Relationship between grindability and moisture content
for coal sample from the Pembina area (seam F).
(a) Research Council of Alberta
apparatus
(b) Hardgrove machine
Hardgrove Index
ft. lbs. per sq. ft.
22
20
18
16
14
70
68
66
64
62
60
58
0
4
8
12
16
20
24 % Moisture

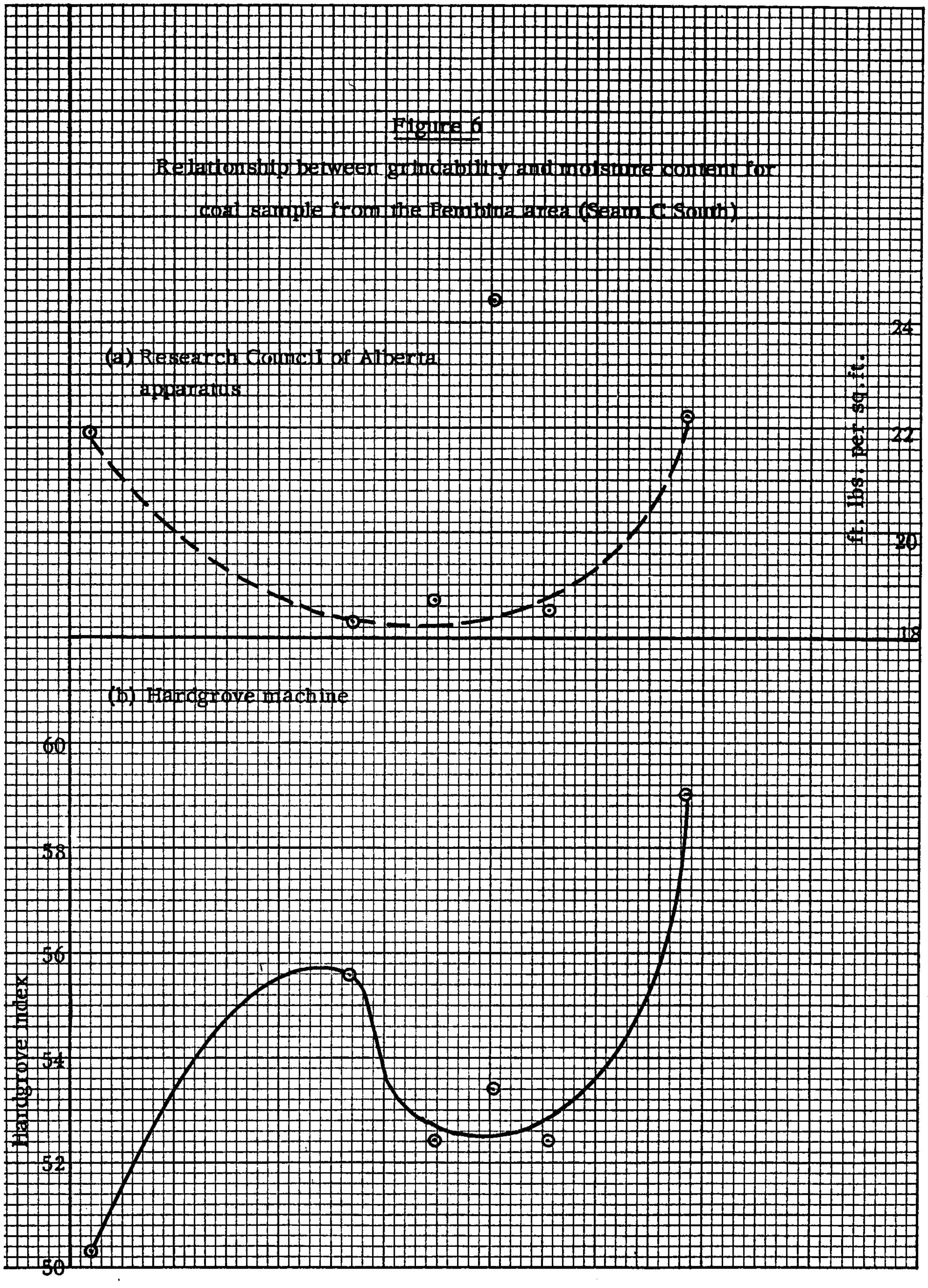
Figure 6
Relationship between grindability and moisture content for
coal sample from the Pembina area (Seam C South)
(a) Research Council of Alberta
apparatus
(b) Hardgrove machine
ft. lbs. per sq. ft.
24
22
20
18
Hardgrove index
60
58
56
54
52
50

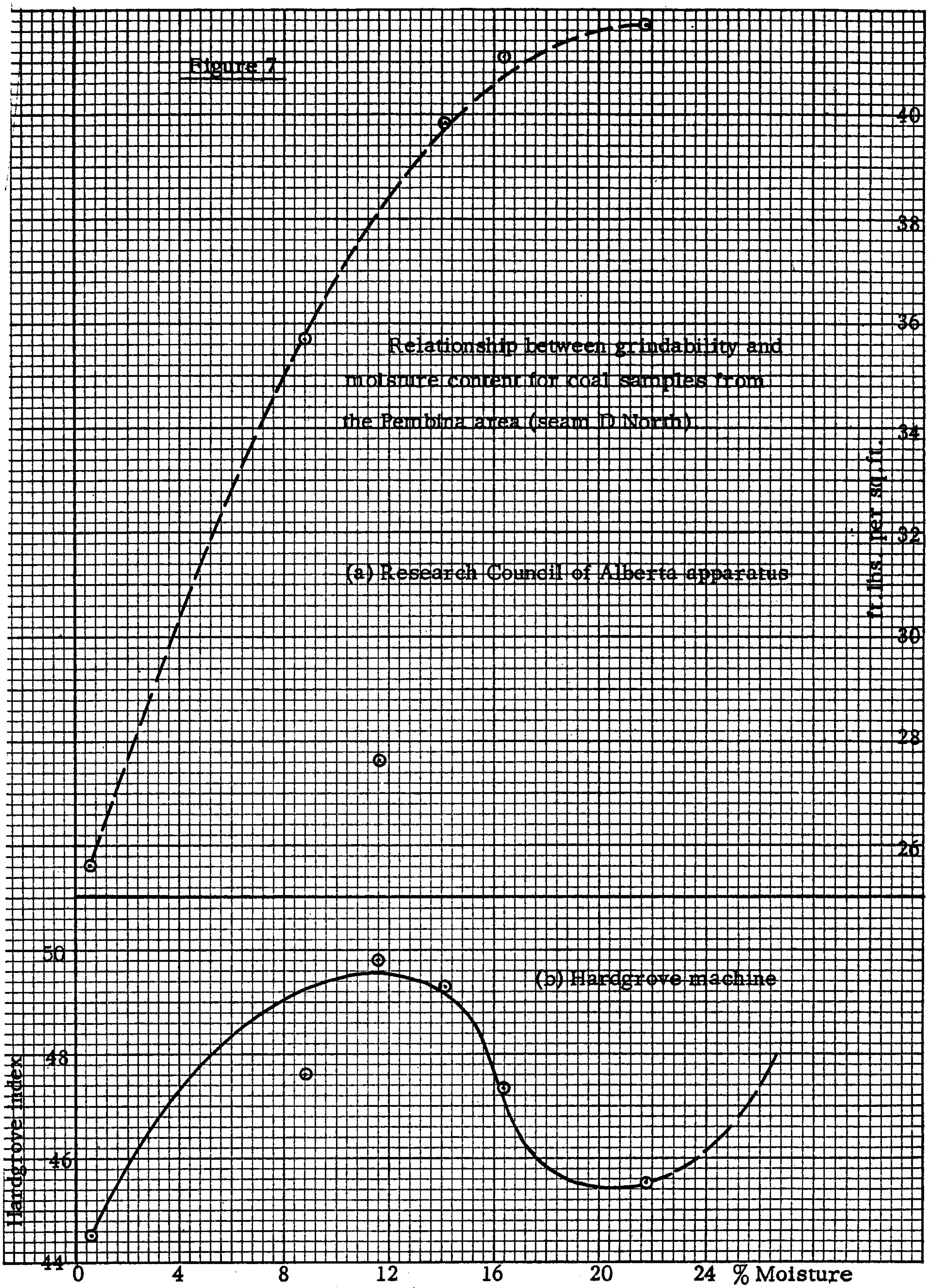
Figure 7
Relationship between grindability and moisture content for coal samples from the Pembina area (seam D North)
(a) Research Council of Alberta apparatus
(b) Hardgrove machine
ft. lbs. per sq. ft.
40
38
36
34
32
30
28
26
Hardgrove index
50
48
46
44
0
4
8
12
16
20
24
% Moisture

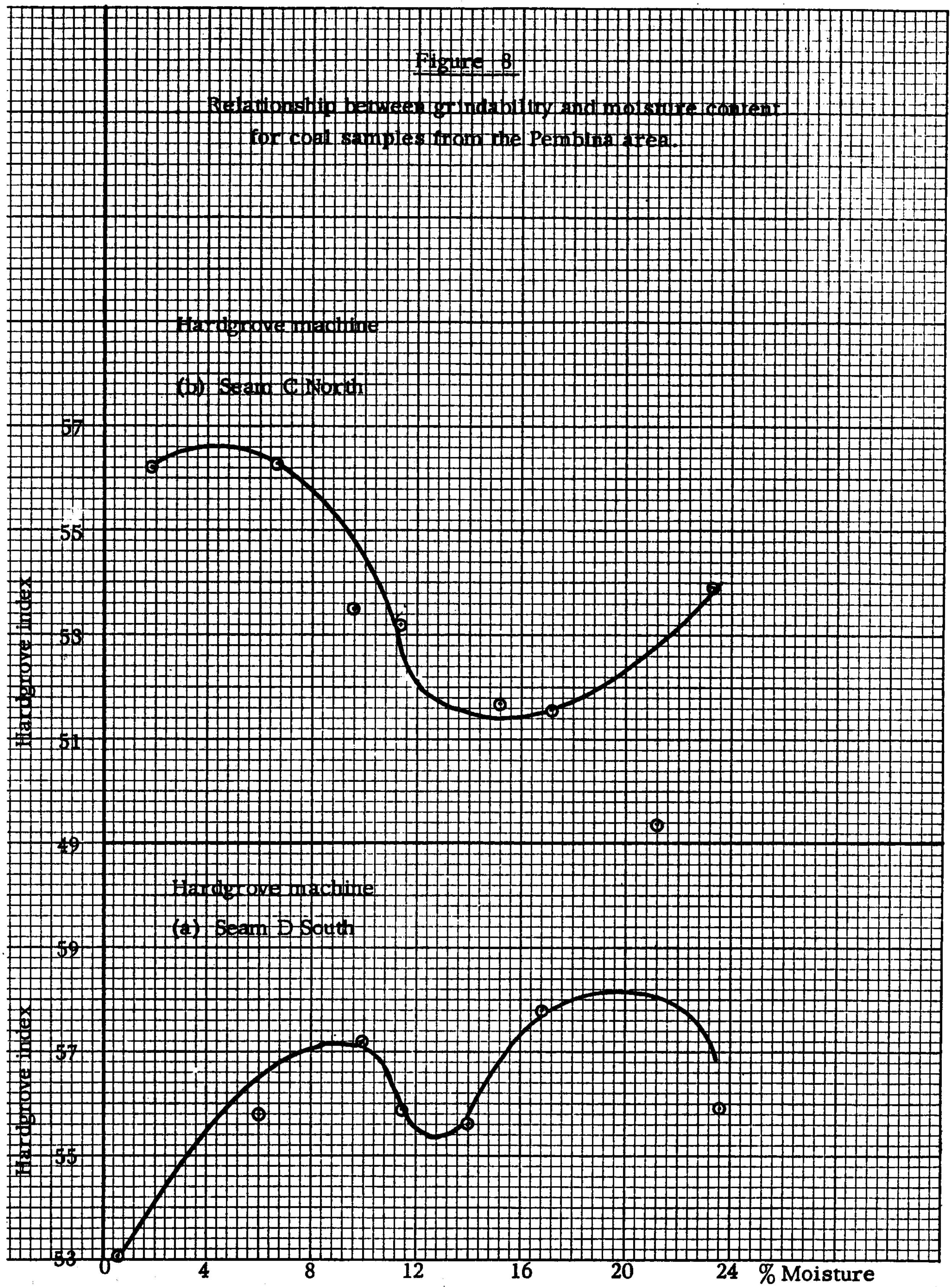
Figure 8
Relationship between grindability and moisture content
for coal samples from the Pembina area.
Hardgrove machine
(b) Seam C North
Hardgrove machine
(a) Seam D South
Hardgrove index
Hardgrove index
57
55
53
51
49
59
57
55
53
0
4
8
12
16
20
24
% Moisture

A check was made on how the moisture content varied during the grinding. In experiments with the R.C.A. apparatus, the moisture in the -200 mesh fraction was analysed, while in the Hardgrove tests the moisture in both the +200 mesh and the -200 mesh fractions was determined. Since the results showed the same tendency in all samples, only results for one series are given. These are shown in Table VI. All determinations were made in duplicate.

TABLE VI

Variation in moisture content during grindability tests

Sample No.	850	855	860	865	870	875
Moisture in feed	14.1	0.6	21.8	11.6	8.8	16.4
R.C.A., -200 mesh	13.5	2.7	18.7	10.9	9.1	15.1
Hardgrove, -200 mesh	12.3	1.6	21.0	10.3	8.7	13.9
Hardgrove, +200 mesh	14.4	0.8	21.7	11.8	9.3	16.3

Table VI shows that small variations in the moisture content of the coal occur during grinding tests. However, in the majority of cases, allowance for this change in moisture would not affect the result to any large extent, and for the Hardgrove machine the change in the Hardgrove index would still be within the tolerance in the Hardgrove index allowed by the A.S.T.M.[1]. Ellman & Belter[6] have made a fairly detailed study of the effect of allowing for this small change in moisture content during grinding. Their various methods of calculation led to slightly different grindability values, but did not alter the main issue of their investigations.

Experimental Observations

It was observed while carrying out the grindability tests that, with both machines, samples containing close to capacity moisture behaved differently to samples with lower moisture contents. In the Research Council apparatus the samples containing about capacity moisture flowed poorly, necessitating an adjustment to the hopper; increased flaking was also observed.

In the Hardgrove machine a sample, after grinding, will normally appear evenly distributed around the balls in a level layer as shown in Figure 10 (a). However, a sample with close to capacity moisture appeared, after grinding, as a ring of coal pressed outwards and upwards against the wall of the bowl, leaving a relatively clear path for the balls. This effect is clearly shown in Figure 10 (b). Further mention of this observation will occur in the discussion.

Discussion of Results

Figures 4 to 8 indicate that the grindability varies in a nonlinear way with moisture. Allowing for obvious deviations, the general pattern for the Hardgrove curves is an S -shape, with a minimum around "air-dryness" and a maximum generally around capacity moisture content and around 6 - 10% moisture content. The curves obtained with the Research Council apparatus differ from this pattern except in one example; hence it is not possible to establish a correlation between the results obtained with the two machines and in this way interpret Hardgrove index in absolute units.

In the case of the three samples from the Pembina field which were tested on the Research Council apparatus, seams F, C (south) and D (north), both machines placed the air-dried samples in the same order of grindabilities. This is probably

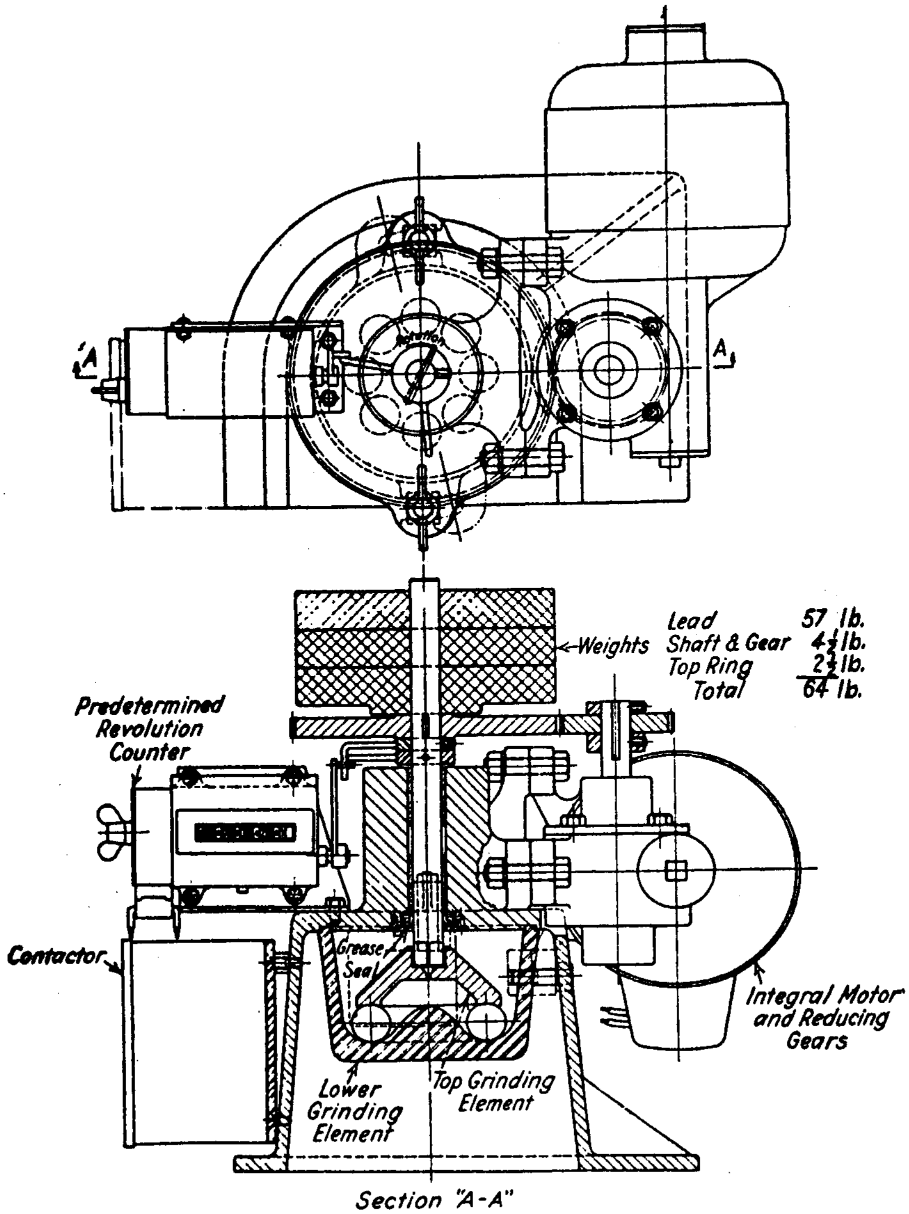

Figure 9 Hardgrove grindability machine.

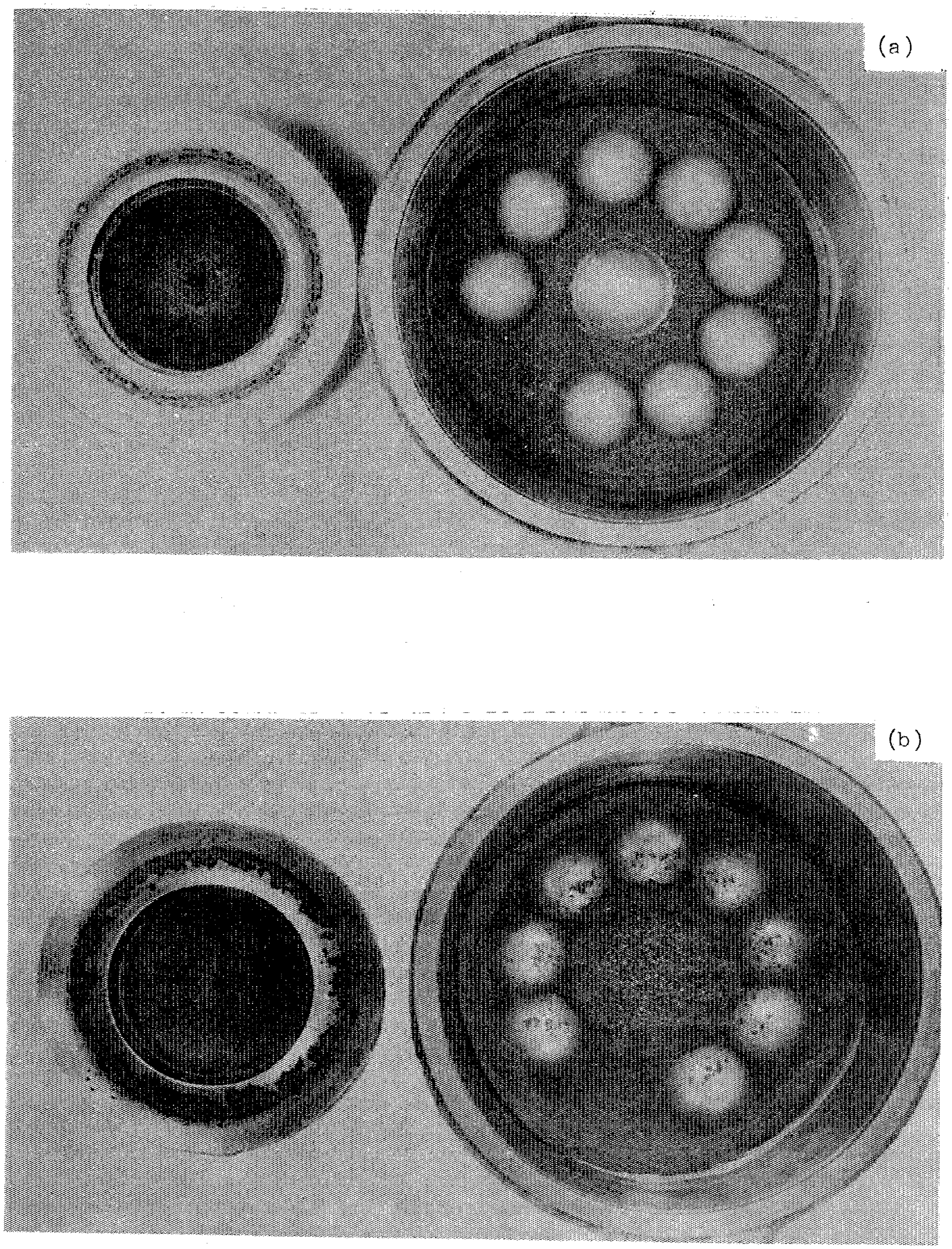

Figure 10 Views inside the grinding elements of the Hardgrove machine after grinding,
(a) Air dried coal,
(b) Coal with close to capacity moisture content.

mere coincidence because, if the results shown in Table IV for the Castor area coal are also considered, then the order of grindabilities differs for the two machines. Bangham[7] has pointed out that the type of machine used is a factor in comparing grindabilities, and Heywood[8], in his classic study, showed that the four machines he considered placed the coals tested in varying orders of grindability.

The curves shown in Figures 4 to 8 for the Hardgrove machine are similar to those obtained for North Dakota lignites by Ellman and Belter[6] in a recent detailed investigation.

The shape of the Hardgrove curves at high moisture contents gives cause for some concern as to whether the Hardgrove test is suitable for coals with high moisture contents. The highest moisture contents shown in Figures 4 to 8 are all slightly beyond capacity moisture. Since the relative humidity in the laboratory was between 40 and 60 percent, it means that some evaporation would take place during a test. In some instances the curves obtained from the Hardgrove tests appear to indicate that it is easier to grind a coal at capacity moisture than at air-dryness; this is in direct contradiction to practical grinding experience in which it is found impossible to perform satisfactory grinding without drying the coal somewhat. One possible explanation is offered by the observation mentioned earlier and shown in Figure 10(b). If a ring of coal is formed, it means that the coal is not true flowing and that fresh coal is not flowing into the path of the balls. In other words, some coal particles are ground over and over again resulting in too many fines, and, therefore, an apparently high Hardgrove index is obtained.

The increase of about 6 Hardgrove index units above the minimum at the center part of the curve may possibly be explained as due to the weakening of the coal structure through removal of moisture. Whether the reason for the drop in grindability as the moisture content approaches 0% is due to the nature of the ash content in the dry state, is a matter of mere speculation at this stage.

It should be remembered that the Hardgrove test prescribes that the sample be air-dried before being submitted to the test. When the moisture content ranges from 0 - 5 percent, a slight variation in moisture content will not appreciably influence the test. But when air-dryness can mean a moisture content between 10 - 16 percent, depending on the atmospheric conditions, conditions not foreseen by the designers of the Hardgrove machine are involved. A further minor criticism of the Hardgrove test as outlined in the A.S.T.M.[1] procedure, is that no means are offered of adjusting the machine to grind the standard coal to a Hardgrove index of 100.

Turning to the results obtained with the Research Council apparatus, the regularity of the results is much less pronounced. The magnitude of the results checks readily with those of Heywood[8] although they are somewhat higher, probably due to the different method of calculation involved.

In Figure 4 for the coal sample from the Castor area there appears to be good agreement between the results obtained on both grindability machines in that the curve for the Hardgrove machine follows inversely the curve for the Research Council apparatus. However, Figures 5, 6 and 7 for the samples from the Pembina area do not substantiate this agreement. The curve shown in Figure 5 for seam F, for results obtained using the Research Council apparatus, conforms more readily with what is found in practice, and suggests that a subbituminous coal of this type should be ground at about 17 percent moisture. It seems hardly worthwhile to venture into an interpretation of the curves in Figures 6 and 7.

Part of the lack of conformity of these results may be ascribed to certain failings in the present apparatus and its inherent error. With a standard procedure now worked out, it would seem natural to fix the apparatus to these conditions, to replace the two motors by one motor of suitable size, and to couple the rolls using a suitable set of gear wheels. The dynamometers should be replaced by a single recording instrument. Refinements of this nature would no doubt increase the accuracy of the apparatus and might remove the uncertainty with which one is almost bound to view the present results. Although such improvements could be implemented and further experiments carried out before discussing the matter of grindability, it seemed desirable to halt the investigation temporarily.

A continuation of the work along the lines outlined in this report, even if it led to a perfect method and nice smooth curves, would still not solve the problem of practical grinding. The real problem would still be left unsolved, and that is to devise a laboratory test that can interpret grinding in practice and predict the results to be expected. In recent years few attempts have been made to solve this problem, and no real success has been reported.

It is felt that the Research Council of Alberta method has certain inherent advantages in its approach to the problem. It represents the first time since Heywood[8] that an attempt has been made to measure grindability in absolute terms. However, before any further work is done it is felt that the problem must be reassessed and the terms of reference clearly defined.

Conclusions

1. The Research Council of Alberta apparatus, with a few modifications suggested by initial experience in operating the apparatus, could be used to determine the grindability of coal in absolute units. So far, the evidence indicates that reliable and consistent results should be obtainable.

2. Grindability of Alberta subbituminous coals varies with the moisture content in a nonlinear way.

3. The relationship between the moisture content and the Hardgrove index provided the same pattern for all samples tested.

4. The energy required for grinding is between 15 and 40 ft.lbs per sq.ft. of new surface produced for coals having Hardgrove indices of 60 to 40.

5. The A.S.T.M. Hardgrove grindability test is not directly applicable to Alberta subbituminous coals without some modification.

6. Variations in the Hardgrove index for a particular subbituminous coal, which have been reported in the past, have been due to:

   (a) Lack of definition of the moisture content at which the determination was carried out, and

   (b) Variations in the coal from seam to seam and from location to location along a seam.

With these findings in hand, it has been decided to submit this report to various parties who might be interested. Decision as to whether further work on this project is warranted will depend to a large extent upon the reaction to the report and suggestions received.

APPENDIX

Methods used for calculating the energy consumed in grinding and the increase in surface area produced during grindability tests using the Research Council of Alberta apparatus

Energy Measurements

The torque produced by a D.C. motor is given by the equation:

$$D = \frac{KEi_a}{N}$$

where, D is the torque,

K is a constant, approx. = 1 (any deviation from 1 is due to small electrical losses in the motor),

E is the electromotive force,

i_a is the armature current,

N is the number of revolutions per minute.

Thus $E \cdot i_a = DN$ (Assuming K = 1)

but $E \cdot i_a = W$,

where W is the energy per minute utilized as useful work.

Hence $W = DN$.

If D and N are measured, then W can be calculated.

The energy to be determined is the energy used in grinding the coal, or, the difference between the energy required when the apparatus runs empty ($W_e = D_e \cdot N_e$) and the energy required when it runs loaded ($W_L = D_L \cdot N_L$), that is,

$$W = W_L - W_e = D_L N_L - D_e N_e$$

where subscripts L and e refer to loaded and empty conditions respectively, and W is the energy per minute, from one motor, used for grinding.

In any given test the value of N is maintained constant for each roll, therefore

$$W = W_L - W_e = N(D_L - D_e)$$

The total energy per minute required for grinding (W_G) is the sum of the energies from both rolls, that is,

$$W_G = W_1 + W_2 = N_1 (D_{L_1} - D_{e_1}) + N_2 (D_{L_2} - D_{e_2})$$

where subscripts 1 and 2 refer to the separate rolls.

W_G is calculated from this equation, measuring D in pound-feet.

The energy in ft. lbs. (F) required to grind one pound of coal is given by:

$$F = \frac{W_G \times t}{M}$$

where t is the time in minutes taken to grind the samples, and

M is the weight of the sample in pounds.

Surface Area Determination

The surface area to be determined is the external surface of the coal. Several methods have been suggested in the literature (9, 10, 11, 12, 13, 14, 15, 16), but it should be noted that it is impossible to measure accurately the external surface of a pulverized coal. The quoted methods are all based on one or more assumptions, and since an exact answer is unobtainable they can all claim to be equally right. When assumptions have to be made in order to arrive at comparable figures, the assumptions might just as well be such that they make the method workable and simple. The method described below is based on a particle-size analysis, as are most known methods. It appears to assume that the coal particles are cube-shaped, though, in fact, it only assumes that the geometrical configuration is the same for all sizes of particles.

If a cube with a side-length "a" is split into cubes of side-length "b", the number of cubes obtained is:

$$\frac{a^3}{b^3}$$

The surface of the original cube is $6a^2$ and of each new cube $6b^2$. Thus the increase in surface is:

$$6b^2 \cdot \frac{a^3}{b^3} - 6a^2$$

$$= \frac{6a^3}{b} - 6a^2$$

If the number of particles in one gram of the original coal is "n", the new surface per gram is:

$$n\left(\frac{6a^3}{b} - 6a^2\right)$$

Assuming that the particles are cubical, then

$$n = \frac{1}{\alpha a^3}$$

where "a" is measured in centimeters and α is the specific gravity of the coal. Figure 11 shows that coal is far from cube-shaped when crushed. However, "n" can be determined experimentally. If a crushed coal is screened on a nest of standard sieves, the number "n" of particle-size "x" (where x is the average particle-size of the fraction obtained between two sieves with apertures x_1 and x_2) can be determined by counting and weighing.

The ratio of the calculated "n" and the experimentally-determined "n" is a measure of the deviation from the assumed cube-shape, i.e., a shape-factor. If this factor remains constant from fraction to fraction, it can be used as a correction factor in the calculation of the number of particles per unit weight.

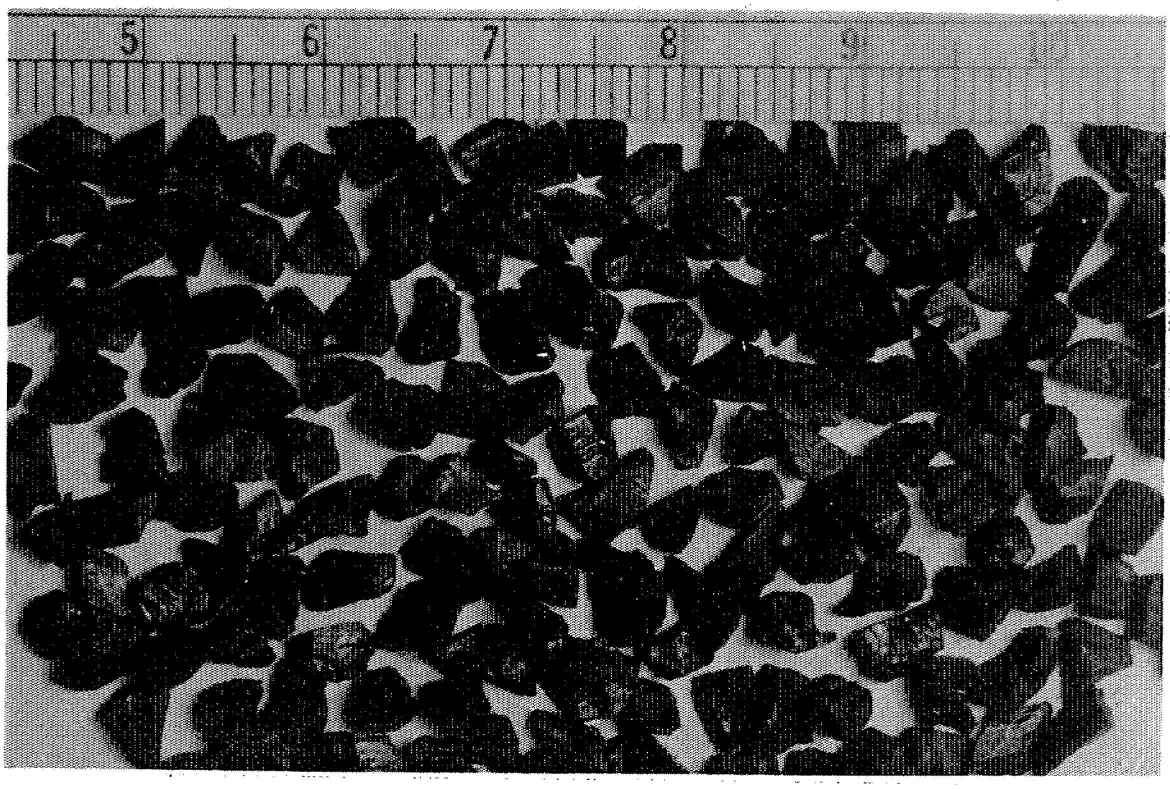

Figure 11 Magnified photograph of sized coal particles.

An example will illustrate how the method is applied to calculate the surface increase from a sieve analysis:

The coal used for grinding is sized between -14 and +28 mesh Tyler, and therefore the average particle-size of the feed (side-length of cube) is 0.879 mm.

The surface area of one particle of feed is $6(0.879^2) = 4.63 \text{ mm}^2$.

The specific gravity of the coal is 1.40 gm. per ml.

Therefore, the number of particles per gm. of feed, calculated as cubes

$$= \frac{10^3}{1.40 \times 0.879^3} = 1{,}052$$

The shape factor = 0.58 (see Table VIII).

Thus, the actual number of particles per gram of feed $= \frac{1{,}052}{0.58} = 1{,}814.$

TABLE VII

Calculation of the new surface area given by one particle of feed after grinding

Tyler sieve (mesh)	Size of opening, mm.	Average diam. of particle, mm.	Surface area in mm^2 $\left(\frac{6a^3}{x}\right)$	Sieve analysis, wt. % retained	Surface area x wt. % retained (mm^2 x 100)
35	0.417	0.648	6	9.4	56.4
48	0.295	0.356	9	15.9	143.1
65	0.208	0.252	16	27.7	443.2
100	0.147	0.178	23	21.9	503.7
150	0.104	0.126	32	8.7	284.8
200	0.074	0.089	46	7.8	358.8
-200	-0.074	0.037	110	8.4	924.0
		Total		100.0	2714.0

Table VII indicates that one particle of feed yielded, on the average, a new surface of 27.14 mm^2. Since the surface area of the original particle of feed was 4.63 mm^2, the new surface produced is:

$$(27.14 - 4.63) \times 1800 \times \frac{453.6}{(25.4 \times 12)^2} = 198.5 \text{ sq.ft./lb.}$$

Experimental Determination of "n"

To determine "n" (the number of particles in one gram of coal), the coal is ground in the same way as it is for grindability tests. A representative portion of the ground coal is then sieved on a nest of successive Tyler standard sieves, and the number of particles in a weighed portion of a fraction is counted. The counting is repeated four times in each fraction. The specific gravity of the coal is determined according to the method of Oberholtzer[12].

Example of Detailed Calculation of Shape Factor

Sieves: -6 +7 mesh Tyler; average size of particles = 3.061 mm.

Weight of sample	Number of particles	Particles per gm.	
1.5056 gm.	65	43	
1.5149 gm.	71	47	av. 45
1.2012 gm.	57	47	
1.4883 gm.	67	45	

Theoretical number of particles per gram $= \frac{10^3}{3.061^3 \times 1.40} = 25.$

Therefore, shape factor $= \frac{25}{45} = 0.56.$

TABLE VIII

Calculation of the shape factor of coal particles of various sizes

Sieves	Average size of particles, mm.	Actual number of particles per gm. 1	2	3	4	Average	Theoretical number of particles per gm.	Shape factor
-6+7	3.061	43	47	47	45	45	25	0.56
-7+8	2.578	79	79	77	74	77	42	0.54
-8+9	2.172	124	127	121	116	122	69	0.59
-9+10	1.816	191	200	190	186	192	119	0.62
-10+12	1.524	336	343	324	337	335	202	0.60
-12+14	1.283	593	560	582	564	575	338	0.59
-14+16	1.080	1077	1114	1092	1080	1088	567	0.53
-16+20	0.912	1670	1637	1659	1656	1656	942	0.57
-20+24	0.767	2660	2804	2762	2641	2717	1582	0.58
-24+28	0.645	4078	4554	4251	4103	4247	2667	0.63
-24+28	-	4312	4431	4437	4092	4318	-	0.62

Average of all observations: 0.58 ± 0.05

It should be noted that for the determination of "n", a $\sqrt[4]{2}$ series of sieves rather than a standard $\sqrt{2}$ is used. This closer sieving enables a sufficiently accurate determination of "n" to be made, even though fewer particles are counted.

As indicated in Table VIII, the theoretical number of particles in one gram when calculated as cubes is, for example, 338 particles for the -12 +14 fraction. On the other hand, for the same fraction, the number of particles when calculated as spheres amount to:

$$\frac{10^3}{1.40 \times \frac{\pi}{6} \times 1.283^3} = 646$$

This indicates that the shape of crushed coal particles is somewhere between spheres and cubes.

It is also interesting to note that the shape factor arrived at in this way for the coals investigated can be expressed as:

$$\frac{0.84}{\alpha} \pm 0.04$$

where α is the specific gravity of the coal. This value of 0.84 is an interesting one because it is the factor generally used to assess the particle size that will pass a square aperture in a sieve, and it is also the factor used to relate square-hole screens to round-hole screens.

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