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FUEL RESEARCH INSTITUTE

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ONDERWERP:
SUBJECT: DETERMINATION OF THE ABRASIVENESS OF COAL WITH THE APPARATUS OF YANCEY, GEER AND PRICE.

plus addendum

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DIVISION:

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FUEL RESEARCH INSTITUTE OF SOUTH AFRICA

REPORT NO. 14 OF 1971

DETERMINATION OF THE ABRASIVENESS OF COAL WITH THE APPARATUS OF YANCEY, GEER AND PRICE

1. INTRODUCTION

Coal, in its various stages of mechanical handling during the processes of winning, preparation and utilization, causes wear of the metal surfaces with which it makes contact.

For example, in the preparation of coal as a power station fuel different types of wear are caused on the equipment during the following stages of handling:

a) Transport from the mine to the power station bunkers by conveyor belt.
b) Crushing and milling to powder size.
c) Pneumatic transport of the coal dust to the burners.
d) Spreading and firing in the boiler combustion chamber.
e) Pneumatic transport of some of the incombustible fraction of the coal as fly ash in the flue gas to the stack.

In each of the above-mentioned stages the coal handled or its solid incombustible residue cause a wearing action of diversified nature.

For instance, during crushing the wear of mechanical surfaces achieving the comminution is mainly due to gouging.

The scarring of the boiler tubes is due mainly to the hard constituents of the ash, e.g. quartz and silicates, while the effect of abrasion is mainly of a superficial nature.

Definitions

In order to avoid any misunderstanding the terms "abrasion" and "abrasiveness" are defined as follows:

/Abrasiveness .....

<u>Abrasion</u> is the action of a specified material (in the present context coal) to abrade, i.e. to remove by rubbing, grinding or gouging or by any other means of mechanical contact, particles from the material with which mechanical contact is made.

<u>Abrasiveness</u> is the property of the material to cause abrasion. (In this study abrasiveness is expressed as the milligrams of iron lost or abraded from test plates during the abrasiveness test.)

Abrasion in the technical literature is somewhat arbitrarily divided into the following classes[1,2]:

1) Gouging abrasion;
2) Grinding or high stress abrasion;
3) Scratching or low stress abrasion.

An ideal abrasiveness measuring machine ought to be able to measure separately, with one test, all the types of wear caused by the three kinds of abrasion mechanisms listed above. How this can be done, even if only approximately, will be discussed later.

After having classified abrasion in its various mechanical forms, let us consider the influence of the properties of the metal of which the abraded specimen or apparatus is made, and of the properties of the abrading material.

Among the physical parameters affecting the wear of a metal, hardness seems to be the most important.

Dependence of abrasion on hardness must be linked both to hardness of the metal and to the hardness of the particulate material causing abrasion.

The case of coal is, in this respect, more complex because although of relatively low hardness (2 to 2,5 Mohs), it can embed very hard minerals like quartz (7 Mohs) and pyrite (6-6,5 Mohs) in various concentrations and sizes.

The care which one has to exercise in measuring abrasiveness is illustrated by the wear rate diagrams of <u>Figure 1</u>[1].

In this figure the rate of wear of certain metal surfaces is plotted against hardness of the minerals which are processed in certain rotary mills.

Three kinds of steel were checked against wear rate:

Pearlitic steel (270 D.P.H.*)
Heat treated steel (400 D.P.H.)
Martensitic steel (760 D.P.H.)

The wear of the pearlitic steel proved to be of the same order as that of the martensitic steel when processing quartz (7 Mohs), i.e. a hard mineral, but did not decrease appreciably for a mineral (unspecified on the figure) of hardness 4 (Mohs).

Figure 1 also proves that wear is a property relevant to the metal subjected to the mechanical action, to the particulate material causing it, and to the mechanism by which abrasion is produced.

In the design of an abrasiveness testing machine, one can only standardize the abrasion according to the conditions present in the machine. Therefore, while ideally one should endeavour to measure the effect of abrasion in the three classes defined above, and for many combinations of metal and particulate material causing abrasion, in practice one has to choose certain standard conditions and keep them as constant as possible.

Results obtained in a machine when testing a particular material such as coal, must be related to facts observed and/or expected in the field, because of the complicated phenomena determining the wear, as described above.

2. SOME CONSIDERATIONS ABOUT COMMINUTION

Comminution is defined here as the reduction in size of particles because of breakage by mechanical action.

Comminution is the typical action which is exerted in mills. It is mentioned here because the abrasiveness

/measuring .....

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*Diamond pyramid hardness

measuring apparatus, i.e. the Yancey, Geer and Price model, causes comminution of a coal sample in the early stage of the coal grinding process.

The energy required for the reduction in particle size is transferred mechanically to the material, and after causing breakage, appears ultimately and almost totally as heat produced. In fact the fraction of the energy stored by the material as surface potential energy, is very small.

It is worth while mentioning some of the theories so far developed for an explanation of the process of breakage:

The fundamental equation controlling this process is the following:

$$\frac{dw}{dD} = -CD^{m} \qquad (1)$$

where dw is the energy required for an infintesimal reduction of particle diameter dD, D is the particle diameter, C is a constant embodying various physical parameters.

The minus sign expresses the condition that energy is required for reducing D by dD.

Exponent m can acquire values between -1 and -2, according to the modes of fracture occurring in the particle.

The two limiting values correspond to the ideal theories of Kick (for m = -1) and von Rittinger (for m = -2).

Kick assumes that a particle fractures when the energy stored in the particle exceeds the ultimate elastic energy.

This statement is equivalent to saying that the fracture energy is proportional to the particle volume (D^3).

This theory is approximately true for brittle materials.

Von Rittinger assumes breakage of a particle to occur when the shear stress between contiguous faces inside the solid element (which faces define the plane of cleavage) has reached its ultimate strength.

/According .....

According to von Rittinger's theory, the energy required for the fracture is proportional to the particle's newly created surface (i.e. proportional to D^2).

A more recent theory was developed by Bond, and this theory may be regarded as an empirical compromise between the two previously mentioned theories. Bond's theory fixes the exponent in Eqn. 1 at the value $m = -\frac{3}{2}$[13].

3. THE PHENOMENON OF SURFACE SCRATCHING

Wear due to surface scratching is typical of that caused by a grinding stone. The physical quantities involved in this phenomenon are very simply related as the following experiment will prove[3]:

The apparatus (see Figure 2) consists of a metal probe, M, contained in a casing and loaded with a weight, P, which presses the probe against a rotating disc, B, providing the power. A suspension of water and silicon carbide made of uniform particles (D = 0,1 mm) is fed, at a constant flow rate, through vertical channels provided in the casing.

The carbide particles act as grinding medium between disc and probe.

In order to avoid scarring of the rotating disc surface, this is also provided with a translational periodical motion as indicated by the arrows, A.

It was proved that the wear rate obeys the very simple law:

$$v = cnPko \qquad (2)$$

where v is the volume of the abraded material, c is the effective circumference of the disc, P the weight, n the total number of revolutions, and ko a constant.

The constant ko groups the effect of many variables, which were of particular interest in these studies which included, inter alia, the influence of various metals and various wetting liquids on the parameter ko.

/4. .....

4. THE YANCEY, GEER AND PRICE MODEL TESTING MACHINE

4(a) Constructional Details

Although the machine has been illustrated in F.R.I. Bulletin No. 66, 1965[9], a brief description follows with emphasis on what has been observed in more recent experiments.

The machine represented in Figure 3 incorporates a mortar, 1, containing a sample of coal of 4 kg.

A shaft, directly coupled to an electric motor, carries four arms on which steel wearing plates, 3, are mounted.

The whole assembly of motor and shaft can be lowered along suitable guiding columns (not shown), into the mortar.

After the shaft and arm assembly has been lowered into the mortar, this is closed by a lid, 4.

The shaft end is hemispherically shaped, and fits into a bearing, 5, placed on the base, 6, of the mortar.

The purpose of this bearing is to prevent shaft deflections.

Initially, there is a gap of ca. 5 mm (in original model, 0,2") between the surfaces of the plates and the cylinder wall, into which the coal particles are dragged and crushed by impact and pressure. The plates are curved so as to allow, during the rotation, a gradual flow of coal towards the throat of the passage.

The plates are made of four curved strips of mild steel with flat dimensions 50,5 x 38 mm (2 x 1½"), the curves being at a radius of 16 mm (5/8"). (More details are available in Appendix I.)

The vertical position of the shaft-arms assembly is fixed by allowing a clearance of ca. 5 mm (0,2" in original model) between the edges of the plates and the bottom of the mortar.

The exact adjustment of these two gaps is obtained through the following procedure:

/1) .....

1) The vertical adjustment by means of a ring-shaped spacer, having exactly the thickness of ca. 5 mm (0,2" in original model) which is placed on the bottom of the mortar.

   The shaft-arm assembly is lowered against it, and the thrust bearing cup is screwed upward till in contact with the hemispherical head, and locked.

   The ring spacer is then removed and the shaft is lowered again into position.

2) The radial adjustment by placing feeler gauges between each plate and mortar wall, and shifting the arms radially to their correct position and then securing each individual arm in its socket on the shaft.

Experience has shown that the setting of the machine must be accurately performed to obtain reproducible results.

4(b) Testing Procedure

This is as follows:

The plates are accurately weighed, then secured by means of brass screws onto the arms and the assembly lowered into the mortar.

The machine is then charged with coal (4 kg) of a specified size range, the lid is placed in position and the electric motor is switched on and allowed to run until a certain number of revolutions are totalized on a Veeder-Root counter.

Moreover, in certain cases it was of interest to determine the electric power and the current absorbed during the experiment. (For more details see Appendix II.)

The machine is automatically stopped after having completed a pre-set number of revolutions

The shaft is then lifted, the abrasion plates are removed, cleaned thoroughly, e.g. with carbon tetrachloride, and weighed. The abraded metal is determined as the difference between the two mass readings.

A set of four abrasion plates is used up to a cumulative wear of 2 grams, after which the set is discarded. This is (being considered) as the maximum tolerance allowed.

5. MODIFICATION OF THE YANCEY, GEER AND PRICE MODEL TESTING MACHINE FOR SURFACE ABRASION MEASUREMENT

The investigation of surface abrasion was carried out by applying a new head (shown in Figure 4) to the shaft of the original abrasiveness testing machine.

A cylindrical head, 1, 101 mm (4") in diameter by 101 mm (4") in height was mounted to the shaft.

The cylindrical head consisted of a hollow brass cylinder on which three lining segments, 2, made of a tempered steel plate, were screwed on the outside surface. (For mechanical details of the plate material see Appendix I.)

The cavity of the cylinder was filled with water by means of a small hole, 3. On the inside of the shaft a small vent hole, 4, was provided.

The head was lowered into the mortar, 5, in the usual way with a clearance of 50 mm (2") from the mortar bottom. An amount of coal sufficient to fill the mortar up to 50 mm (2") above the cylinder's upper face was then charged, followed by an amount of water just sufficient to cover the coal surface.

The addition of water to the coal and the filling of the inner space of the head was undertaken to prevent local overheating and consequent change of metal properties (mainly hardness) during the abrading process.

The testing procedure followed the same pattern as described before, viz:

Setting of the machine.
Preliminary weighing of the lining segments.
Mounting of the segments.
Running of the machine.
Re-weighing of the segments.

6. EXPERIMENTAL RESULTS RELATIVE TO THE YANCEY, GEER AND PRICE MODEL MACHINE

In an early stage of the investigation particular care was taken to arrive at a testing technique which would be acceptable both as a correct measurement of the wear and for good duplication of the results.

The results are presented in Figure 5.

The amount of abraded metal (cumulative of 4 plates) was plotted against the total revolutions of the shaft. Test values were collected during a discontinuous procedure by stopping the machine intermittently after a pre-set number of revolutions.

The motor-shaft assembly was then raised, the four wearing plates removed, cleaned, and weighed as already described, yielding the results shown as points on the graph.

The diagram illustrates the abrasion process as it proceeds with increasing revolutions.

The slope of the curve at any point indicates the intensity of the abrading action, which has been expressed in milligrams of abraded metal per revolution. The tangents drawn are averages for two experiments.

The coal sample was prepared according to the following procedure:

A sample of coal - Waterpan small nuts size - (analysis given below) was taken from a bulk sample and divided mechanically into two batches (sub-samples) which separately underwent the following stages of preparation:

a) milling;
b) screening to a size 4,76 mm to zero (-3/16" BS);
c) collection of a sample of 4 kg as charge.

Analytical details of the coal are summarized in Table 1.

/TABLE 1 .....

TABLE 1

ANALYSIS OF COAL SAMPLES

Sub-sample reference	Coal type	Size	Ash, %	Pyrite, %	Free quartz, %
C_1	Bituminous	4,76 mm to zero	12,8	0,51	1,4
C_2	Bituminous	4,76 mm to zero	12,8	0,51	1,4

The preparation described above is that followed in the procedure already in use at the Fuel Research Institute for routine testing.

Results obtained on the two sub-samples C_1 and C_2 are shown in Figure 5 by means of two sets of points which, for practical purposes, can be considered to coincide. (This provided an indication of the repeatability of the results.)

The intensity of the abrading process (represented by the slope of the curve) is high at the beginning of the process ($1,0 \times 10^{-2}$ mg/rev), and then decreases towards a constant value (reached at about 3×10^4 total revolutions and equal to $0,062 \times 10^{-2}$ mg/rev).

The abrading action in the machine can be interpreted in the following way:

Just after starting the machine, the metal loss from the blades is mainly due to gouging and high stress abrasion because of the process of comminution of the coal and impurities.

At the end of the run, i.e. after some 30×10^3 to 40×10^3 revolutions have been totalized by the counter, the loss of metal is due only to low stress abrasion (scratching), whilst the sample has been reduced in the meantime to a powder.

Abrasiveness of a certain coal can, therefore, be measured in this machine by two co-efficients of abrasion (expressed, e.g. in milligrams/revolution):*

/One

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*These abrasiveness coefficients are typical of the machine model under discussion.

One determined at the beginning of the test (A_c), expressing abrasion mainly due to comminution, the other (A_s), at the end of the test (say after 40 x 10^3 total revolutions) expressing low stress abrasion (scratching)*.

The repeatability of results already suggested by the data of Figure 5, was further investigated with relation to the mechanical properties of the machine and of the metal used for the abrasion plates.

A sample of Waterpan coal was prepared and divided into nine representative sub-samples of 4 kg each.

Preparation followed the procedure already described.

Nine tests, all using the same set of abrasion plates, were performed in the machine. Each test consisted of 12 000 total revolutions; abrasion figures were obtained as mass difference of the plates before and after each run, respectively. Results have been summarized in Table 2.

TABLE 2

RESULTS OBTAINED FROM REPEATED TESTS

Test No.	1	2	3	4	5	6	7	8	9
Abrasiveness, mg iron	87,0	88,0	96,4	79,8	93,6	97,7	85,3	84,8	88,[illegible]
Mean value, mg iron	89,0								
Standard deviation, mg iron	5,21								
Standard deviation as % of mean	5,85								

/The .....

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*In a more precise determination of abrasiveness due to comminution, A_c, one should subtract the surface abrasion coefficient, A_s, (see example later).

The numerical analysis of the figures again illustrat that the machine has good repeatability characteristics.

Quantitatively, one can say that the probability of a test result falling within one standard deviation bracket (i.e. ± 5,85 per cent of the mean value) is about 69 per cent, provided that test results are "normally" distributed.

Properties of repeatability were also assessed for the plate material with regard to its hardness (determined as microhardness) according to the following procedure:

Two sets of plates, P_1 and P_2, were sampled from the same batch of plate steel supplied, and a third set, P_3, from a different batch.

Plate microhardness tests were carried out on each set before running abrasiveness trials and thereafter on successive performances of one, two, and three abrasiveness trials.

The testing procedure and the coal type were the same as those described above for repeatability.

Results are plotted in Figure 6, using a magnified scale for the microhardness in order to make the slight increase in hardness more visible.

The diagrams illustrate that the hardness of a plate tends to increase slightly with its "use", a fact that can be ascribed to a hardening process due to successive heating and cooling of the metal and work hardening.

Because the selected steel has a low carbon content, the increase in hardness is limited and no influence was noticed on the abrasiveness figures.

The hardness test results also illustrated that the figures for hardness varied little from one batch to another, a fact that, in practice, should be checked before accepting a steel as being suitable.

In the work reported so far the charge was always 4 kg of coal cut out from the bulk sample of coal after this had been crushed by a standardized procedure to a top size of

5 mm (3/16" BSS). This produced results of acceptable reproducibility.

To obtain a better insight into the operation of the apparatus, a few experiments were also performed with smaller batches, viz. of 3, 2 and 1 kg, respectively. These sub-samples were prepared by crushing a quantity of Waterpan nuts, screening the product at 3/16" BS and cutting out samples of 4, 3, 2 and 1 kg by means of a mechanical divider.

There are no definite rules laid down for the minimum size of the representative sample of -5 mm material, but a quantity of 5 lb, say 2,5 kg, is generally considered to be adequate.

The 1 and 2 kg batches may thus be rather small but it is considered that for the purpose of these experiments, the samples would still be sufficiently representative in respect of ash content and particle size distribution.

The abrasiveness figures (in milligrams of iron) are plotted against total revolutions in Figure 7.

It may be noted from Figure 7 that the tangent to the curve for the 1 kg charge has a slope of $0{,}45 \times 10^{-3} \frac{mg}{rev}$.

This value was taken as a measure of the abrasiveness coefficient, A_s, of the coal due to surface scratching, i.e. the abrasion occurring when the coal is already in a powder form and irrespective of the amount charged.

In fact, experiments carried out at a later stage proved that abrasiveness due to surface scratching is invariant with the coal charge, at least as a statisticsl average.

A specific abrasiveness index, i, for comminution has been derived from Figure 7 and plotted in Figure 8.

The specific abrasiveness index is defined as the ratio between the weight of iron abraded against the weight of coal charged.

This index, i, is therefore expressed by a pure number.

/The ......

The index expresses abrasiveness caused by comminution of particles only.

The effect of surface abrasion due to scratching has been eliminated from the values plotted, according to the following numerical example for point P of Figures 7 and 8

The abrasiveness value read for P in Figure 7 is 29,5 mg, obtained after 14 000 revolutions.

The abraded iron due to surface scratching is calculated as follows:

$$14\ 000 \times 0{,}45 \times 10^{-3} = 6{,}5 \text{ mg}$$

where $A_s = 0{,}45 \times 10^{-3} \frac{\text{mg}}{\text{rev}}$ is the abrasiveness coefficient due to surface scratching obtained in one revolution.

By subtracting the last value from the total iron abraded, i.e.

$$\begin{array}{rl} 29{,}5 - & \text{mg} \\ \underline{6{,}5} & \text{mg} \\ 23{,}0 & \text{mg} \end{array}$$

and by dividing this figure by the weight of the coal charge (in this case equal to two kg), one gets:

$$i = \frac{23 \times 10^{-6}}{2} \ \frac{(\text{kg})}{(\text{kg})} = 11{,}5 \times 10^{-6}$$

This figure is plotted at 14 000 revolutions as shown by point P in Figure 8.

In this figure the plotted points group around two exponential curves: one for the results relative to a coal charge of one kg, the other for two, three and four kg.

The first exponential curve (for one kg of coal charge) has a revolution constant n_1 = 4 000 rev or a time constant T_1 = 160 s.

The second exponential curve as a revolution constant n_o = 9 000 rev or a time constant T_o = 360 s.

The time scale has been derived from the revolution scale by assuming that the motor operated at its synchronous

/speed .....

speed of 1 500 rev/min. The small error introduced by this assumption is unimportant in the present context.

Both exponential curves approach asymptotically the same horizontal at a value of 15×10^{-6}.

This proves that the specific amount of iron abraded (i.e. referred to a unit mass) of -3/16" coal sample charged is in all four instances the same. The much smaller value of the time constant in the case of one kg of coal charge is due to the faster feed rate of the coal to the blades, i.e. to the region where comminutation takes place.

In fact, one kg of coal fills the mortar up to a height just covering the blades, leaving the space above free for unimpeded mixing and feeding.

Expressing these concepts analytically, let G (kg) be the amount of coal charged, g (kg) the amount of iron abraded, n the total revolutions, t the time.

No symbol is introduced for the mass of the large particle component undergoing comminution. In fact, as this is proportional to the coal charge, G_*, it can be expressed by the same symbol.

Consequently, if dG indicates the mass of particles comminuted in an incremental number of revolutions dn, under the assumption that the amount of particles comminuted is proportional to the amount of particles present G, one can write:

$$dG = -Gdn \qquad (3)$$

where the minus sign expresses the fact that the large particle are reduced in number.

By integration

$$G = G_* \; e^{-\frac{n}{no}}$$

where G_* is an integration constant, expressing the mass of the charge.

G tends to the value 0 which means that after a sufficient number of revolutions all the coal is reduced to powder.

/The .....

The amount of abraded iron, g, is obviously proportional to the mass of particles comminuted $G_x - G$; therefore, one can write

$$k(G_x - G) = g \qquad (4)$$

Substitution into the previous equation yields

$$\frac{g}{k} = G_x(1 - e^{-\frac{n}{n_o}})$$

The value $\frac{g}{G_x}$ = i has been defined in Figure 8 as the specific abrasiveness index due to comminution.

The value of the constant k is: $k = 15 \times 10^{-6}$. It represents the kilograms of iron abraded by one kg of coal (sieved -3/16" BS) after being fully comminuted to powder.

The previous expression written either in revolution or time representation finally becomes:

$$i = \frac{g}{G_x} = k(1 - e^{-\frac{n}{n_o}}) \qquad (5)$$

$$i = \frac{g}{G_x} = k(1 - e^{-\frac{t}{T_o}}) \qquad (5 \text{ bis})$$

where n_o and T_o must be substituted by n_1 and T_1 as may be applicable.

The value of i tends to the value of k when n or t become very large.

7. ABRASION STUDIED ON A COAL SAMPLE OF "CONSTANT" SIZE - EFFECTS OF SILICA POWDER ADDITION

At this stage of the investigation it was decided to modify the procedure of coal sample preparation in the sense that only a charge having particles screened within narrow size limits was used in subsequent tests. The purpose was to refer abrasion effects due to comminution to a material of initially constant size.

/Any .....

Any coal sample prepared in this way will subsequentl be referred to as a sample of "constant" size. Such samples were obtained by screening a batch of ground coal between 4,76 and 3,18 mm (-3/16 and +⅛" BS).

The coal used for this series of tests was the same bituminous coal used in previous tests, i.e. collected from the same bulk sample but screened to "constant" size as mentioned above.

The chemical analysis of this sample is summarized ir Table 3.

TABLE 3

ANALYSIS OF COAL SAMPLE

Sample reference	Coal type	Size	Ash, %	Pyrite, %	Free quartz, %
C_3	Bituminous	-4,76 mm +3,18 mm (-3/16" +⅛" BS)	12,8	0,88	1,4

A group of tests covered a sample of relatively clear coal, another group of tests a sample of this coal to which 1,7 per cent (by weight) silica was added. The silica was added ir powder form (-270 mesh A.S.T.M., i.e. grain size less than 53 µm).

The results are presented in Figure 9, where the lower curve, C_3, refers to pure coal and the upper curve (C_3 + SiO_2) to silica and coal.

The investigation also covered the aspect of power consumption (Figure 10).

The plotted values of the power give only indicative averages, due to the fact that for each point plotted the machine had to be started from rest, and instantaneous power indications were not constant.

A better determination of the power was done in a later stage without stopping the machine.

/The .....

The two diagrams of Figure 9 show the same trend as those of Figure 5.

The final coefficient of abrasion, A_s, for clean coal (curve C_3) is 0,08 x 10^{-2} mg/rev, i.e. of the same order as the corresponding value of Figure 5, amounting to 0,062 x 10^{-2} mg/rev.

The initial coefficients of abrasion (A_c approximately) are 0,67 x 10^{-2} mg/rev for Curve C_3 of Figure 9 and 1,0 x 10^{-2} mg/rev for Figure 5.

Curve (C_3 + SiO_2) of Figure 9 yields values of the coefficient of abrasion which are considerably higher both at the beginning (2,5 x 10^{-2} mg/rev for Curve (C_3 + SiO_2) as against 0,67 x 10^{-2} mg/rev for Curve C_3) and at the end A_s (0,30 x 10^{-2} mg/rev for Curve (C_3 + SiO_2) as against 0,08 x 10^{-2} mg/rev for Curve C_3).

This means that crushing of coal particles when surrounded by much smaller silica particles produces a much more intense abrasion than when the coal grains are surrounded by similar coal grains of the identical hardness.

The large increase in the initial coefficient of abrasion, A_c, from Curve C_3 to (C_3 + SiO_2) is in qualitative agreement with the results shown in Figure 1 for the curve of a pearlitic steel, when abrasions caused by calcite (3 Mohs) and quarts (7 Mohs) are compared.

The use of coal screened to constant size was done for research purposes only.

In practice it should be avoided because of the danger of removing (during screening) the relatively small grains of abrasive material (quartz and pyrite) potentially present in the coal.

8. EXPERIMENTAL RESULTS WITH THE CYLINDRICAL HEAD (SURFACE ABRASION)

Tests were carried out in conformity with the technique already described in Chapter 5.

/One .....

One purpose of the test was to check the validity in principle of Eqn. (2) for coal; the other was to study the influence of coal size, if any.

The lining segments mounted on the cylindrical head consisted of three hardened steel plates with hardness 852 HV_{10kg} (Vickers hardness).

Hardened steel plates were used for the purpose of measuring particularly the abrasiveness of the hard constituent of the coal (e.g. quartz and pyrite), according to the interpretation of the diagram in Figure 1.

Two typical samples of coal as per Table 4 were tested and results plotted in Figure 11 (sample reference C_4) and Figure 12 (sample reference C_5).

TABLE 4
ANALYSIS OF COAL SAMPLES

Sample reference	Coal type	Size	Ash, %	Pyrite, %	Free quartz, %
C_4	Bituminous	-4,76 mm +3,18 mm (-3/16" +⅛" BS)	12,8	0,99	1,4
C_5	Bituminous	-0,50 mm +0,26 mm (-30 +60 mesh BS)	13,6	0,41	2,4

The abrasiveness figures yield points which lie practically on a straight line.

The two coefficients related to surface abrasion are the same for both experiments (i.e. 0,27 x 10^{-2} mg/rev). This indicates that coal size has little influence in this surface abrasion testing method.

Summarizing, one can say that wear due to surface abrasion (scratching) is governed by a law of proportionality between total revolutions and weight of material abraded.

9. COMMINUTION STUDIES

The Yancey, Geer and Price model machine was also studied experimentally with regard to its performance as comminution device.

As reference a Hardgrove grindability tester was operated using the same kind of coal, analysis of which has already been given in Table 1.

As is well known, the Hardgrove machine is widely used for testing the grindability of coals.

It consists essentially of a mortar, containing five steel spheres resting between an upper disc which can be loaded by different weights, and a stationary base. The upper disc revolves dragging along the spheres.

The comminution of a certain material can be studied for various conditions of contact pressure of the steel spheres, as determined by the superimposed weights.

Instead of this specified procedure the sample of 50 g of coal of the specified size grading was loaded.. Milling took place under a constant load of 29,1 kg for a cumulative total of 60 revolutions, with intermediate stoppages at 15, 30, 45, and 60 revolutions.

At each stoppage the whole sample was extracted for screen analysis and then recharged into the mill.

The various sieve analysis results are plotted in Figure 13 as a family of five curves relative to the values of 15, 30, 45, and 60 total revolutions.

Each point of the curve was obtained by plotting the aperture size of the sieve against the weight percentage of material retained.

During the process of comminution, the lower curve is moving into the next curve above it, and so on. The shape of the curve is approximately constant.

These can be approximately described by the well-known Rosin Rammler equation (see Reference 12):

$$R = 100e^{-\left(\frac{D}{D'}\right)^N} \qquad (6)$$

where R is the weight fraction retained on a sieve or aperature D; N is an exponent typical of a certain material and milling process; D' is a characteristic diameter*.

By calculating the double logarithm of Eqn. 3 one gets:

$$\log \log R = N \log \left(\frac{D}{D'}\right)$$

This is the representation used in Figure 13 where the values of N are geometrically expressed by the slope of the line.

Large values of N, i.e. lines almost vertical, correspond to a material with almost constant grain size diameter (e.g. the line n = o of the graph has an N value equal to 9, the sample is practically made of particles between diameters D_1 = 3,18 mm and D_2 = 2,06 mm.)

As is well known, the Rosin Rammler distribution curve frequently provides a rather faithful numerical description of the comminution process in mills.

In a second stage of the experiment the Hardgrove machine was replaced by the discussed abrasiveness testing machine, which was operated in steps as described below.

After predetermined numbers of revolutions, representative samples were taken from the charge and sieved, for instance, after 5 000, 10 000, and 25 000 revolutions. The results are shown in Figure 14.

The initial charge consisted of coal particles of practically constant diameter (D = 3,18 mm ($\frac{1}{8}$")).

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*D' is the aperture of the sieve in which 36,8 per cent (e.g. the fraction e^{-1}) of the original charge is retained.

The representative curve of the coal as charged, is a vertical line. This curve progresses during milling into 5 000, 10 000, and 25 000 total revolution curves.

The behaviour of the standard abrasiveness machine is highly anomalous in the Rosin Rammler representation.

Let us split each curve into two branches, B_1 and B_2. Branch B_1 is characterized by a large value of N; branch B_2 by a small value of N.

Considering each branch as an independent line segment, the graph shows that branch B_1 corresponds to a size distribution function which is very narrow (i.e. with a small value of the standard deviation), while branch B_2 corresponds to a size distribution function with wide scattering of particle diameters (i.e. with a large value of the standard deviation).

Because of the milling action of the machine, particles are continuously transferred from branch B_1 (which is initially a vertical line) to branch B_2.

It appears also that the population of particles belonging to a certain branch B_2 (e.g. that for n = 5 000 total revolutions) decreases only slowly by further milling action and added revolutions.

In other words, this means that the machine poorly comminutes particles below a certain size. This was to be expected in view of the openings left purposely between the moving wearing plates and the inside of the mortar.

The comminution along the B_1 branch follows more or less the same pattern as that of the Hardgrove mill.

10. POWER REQUIREMENTS

The abrasion process was also studied in relation to the power absorbed by the machine.

The efficiency curve of the electric motor was determined for this purpose using a procedure described in Appendix II.

The power curve as obtained from wattmeter readings can be reduced to the actual power absorbed in the grinding process by multiplying the wattmeter readings by the electric motor efficiency reported in Figure 17.

This power, transferred to the mass of coal, can be considered for any practical purpose as fully dissipated into heat, because of the very low efficiency of the milling process.

Two tests were carried out: one represented in Figure 15 for bituminous coal size -4,75 mm +3,18 mm (-3/16 +$\frac{1}{8}$" BS), and the other in Figure 16 for the same bituminous coal but with 1,7 per cent of silica added (silica ground to -0,053 mm).

In both cases the power and current values were plotted against the total revolutions.

Both figures show power diagrams which decrease from the beginning of the test up to 12 000 revolutions and then remain constant from there onward.

A practically constant power "base" line represents friction losses arising inside the mass of comminuted coal because of the mixing action of the machine.

What is above the "base" line may be taken approximately to represent power spent for comminution and breakage of particles.

Assuming a torque exists in the machine for the mixing action, and an additional torque (measured from the base line upwards) is present and available for the comminution and breakage of particles, this torque becomes practically zero at about 12 000 revolutions in Figure 15.

Moreover, final abrasiveness values in the two tests were determined as follows:

Figure 13	:	127,8 mg for 40 000 total revolutions
Figure 14	:	282,1 mg for 40 000 total revolutions.

11. CONCLUSIONS

The Yancey, Geer and Price apparatus is suitable fo measuring coal abrasiveness both in the form of high stress abrasion and surface abrasion, as defined in paragraphs 1, 3, and 6.

High stress abrasion is determined only in the earl stage of operation of the machine, when the large particles are being comminuted.

Low stress abrasion is determined in a later stage when the coal charge has practically been reduced to powder.

The machine yields repeatable results when represent tive samples of coal are used, in conjunction with abrasion plates, having approximately the same mechanical and metallurgical properties.

It is advisable to select a metal for the abrasion plates which does not undergo any hardening effect because of temperature rise or any work hardening.

Although a small change in properties of the metal like that due to hardening is in practice unavoidable during the use of the machine, it has been proved that within certain limits this change does not have any noticeable effect on the results.

This holds at least for the particular mild steel used during the experiments.

The repeatability of the results is further affected by the proper setting of the machine before use.

This incorporates:

a) side clearance between abrasion plates and mortar wall,

b) bottom clearance between abrasion plates and mortar surface.

One aim of the present investigation was to provide basic information for the possible drafting of a standard for determining abrasiveness.

/Small .....

Small constructional improvements might still be added to facilitate adjustment, the setting operation and, generally, the use of the machine.

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RESEARCH OFFICER

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PRINCIPAL RESEARCH OFFICE

PRETORIA.
9th November, 1971.
/TW

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APPENDIX I

MECHANICAL PROPERTIES OF THE ABRASION PLATES

Abrasiveness tests were performed with two kinds of abrasion plates.

The test method proposed by Yancey, Geer and Price requires four abrasion plates of mild steel as described in Chapter 4.

They were cut from a hot-rolled "mild steel plate" 16 SWG ISCOR, commercial quality.

A strip of this material, named herein Specimen S_1 was subjected to the mechanical tests specified in Table 5.

The steel used in the surface abrasion tests consisted of three lining segments as described in Chapter 5, made out of a plate of flat-ground stock, USA imported steel, having the following commercial specifications: A.I.S.I. 01: A.S.M. 410.

These three segments and a test specimen, named S_2, were heated together in a furnace up to 800°C, kept at this temperature for one hour, then tempered by quenching in oil.

From tests performed by the National Mechanical Engineering Research Institute (C.S.I.R.) in Pretoria, the results presented in Table 5 were obtained.

TABLE 5

MECHANICAL PROPERTIES OF SPECIMENS S_1 AND S_2 (254 mm LONG)

Specimen	Material	Yield point stress, $(\frac{N}{mm^2})$	Stress at failure, $(\frac{N}{mm^2})$	Elongation at failure, %	Vickers hardness
S_1	Mild steel	399	451	$\frac{7,1}{254} = 2,8$	132
S_2	Hardened steel	-	-	-	853

/One .....

The microhardness testing method mentioned in the text was performed at the Fuel Research Institute as follows:

A diamond pyramid was forced into a clean, polished zone of the metal surface by application of the weight of a mass of 0,034 kg.

The diagonal dimension of the impression was then measured by means of a microscope.

The microhardness was calculated according to the following formula:

$$H_m = \frac{1\,854{,}4 \times 10^3}{g_s} \frac{Mg}{a^2}$$

where H_m is the value of microhardness in kg/mm^2;

M is the applied mass in kg

a is the (absolute) diagonal dimension of the penetration impression in μm;

g is the acceleration due to gravity, m/s^2; and

g_s is the standard value of the acceleration of gravity, i.e. 9,80665 m/s^2.

APPENDIX II

CHARACTERISTICS OF THE ELECTRIC MOTOR

The motor used was a three-phase, delta connected, Asea induction motor rated for 2,6 kW at 1 440 RPM, 5,8 A and 440 V.

In the specific case of the investigation it was connected to a 380 V supply, which is approximately the same as that applied during abrasiveness tests.

Determination of the motor characteristic curves covered:

1) Electrical determination of power, line current and calculation of total electrical input power and power factor. The connection of the various meters is shown in Figure 17.

2) Mechanical determination of the output power by means of a dynamometer.

For each torque reading, the revolutions of the shaft were measured and the corresponding power calculated.

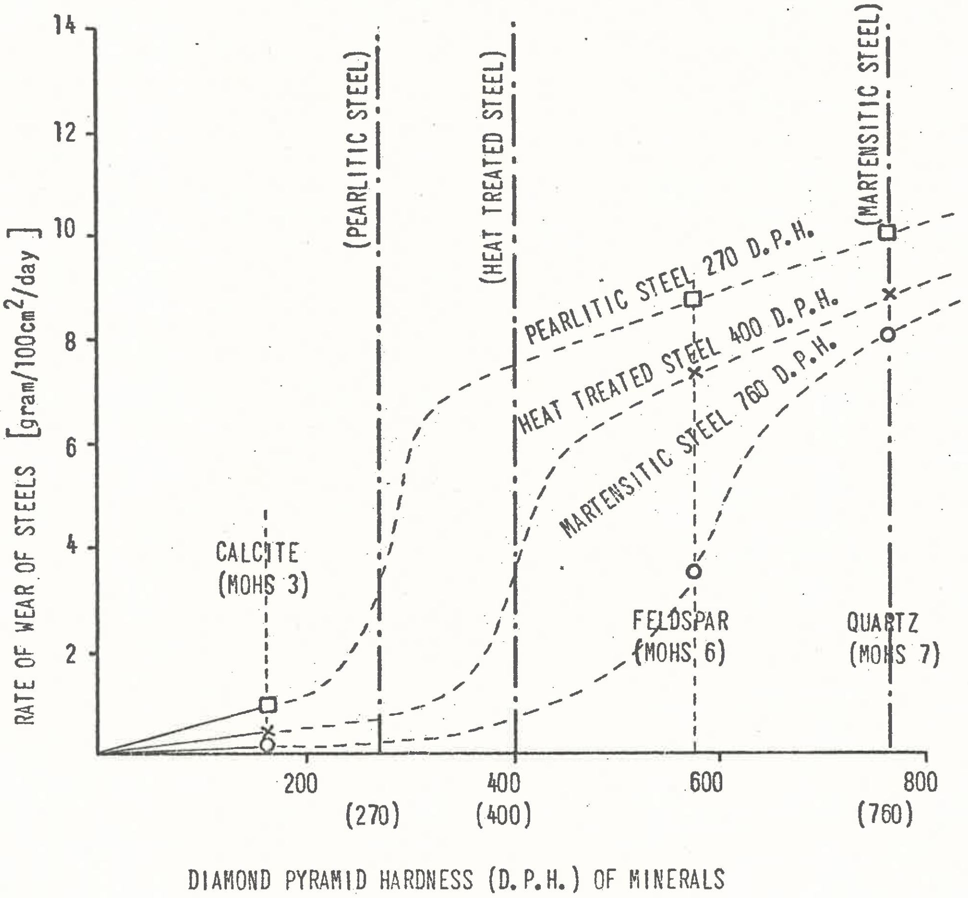
14. NOMENCLATURE, SYMBOLS, AND UNITS

(SI units are used except when indicated by an *)

a	Absolute diagonal of penetration impression*	* (μm)
c	Disc circumference	(m)
d	Symbol of differentiation	
g	Acceleration due to gravity	$(\frac{m}{s^2})$
g	Abraded iron	(kg)
k	Constant relative to comminution	
k_o	Constant relative to surface abrasion	$(\frac{ms^2}{kg})$
i	Specific abrasiveness index due to comminution	
m	Exponent	
n, n_o, n_1	Total number of revolutions, revolution constants, respectively	
t	Time	(s)
v	Volume of abraded material	(m^3)
w	Energy	(N x m)
A_c, A_s	Abrasiveness coefficients due to comminution and surface scratching, respectively	$(\frac{\text{mg iron}}{\text{rev}})$
C	Constant	$(\frac{N}{m})$

/D .....

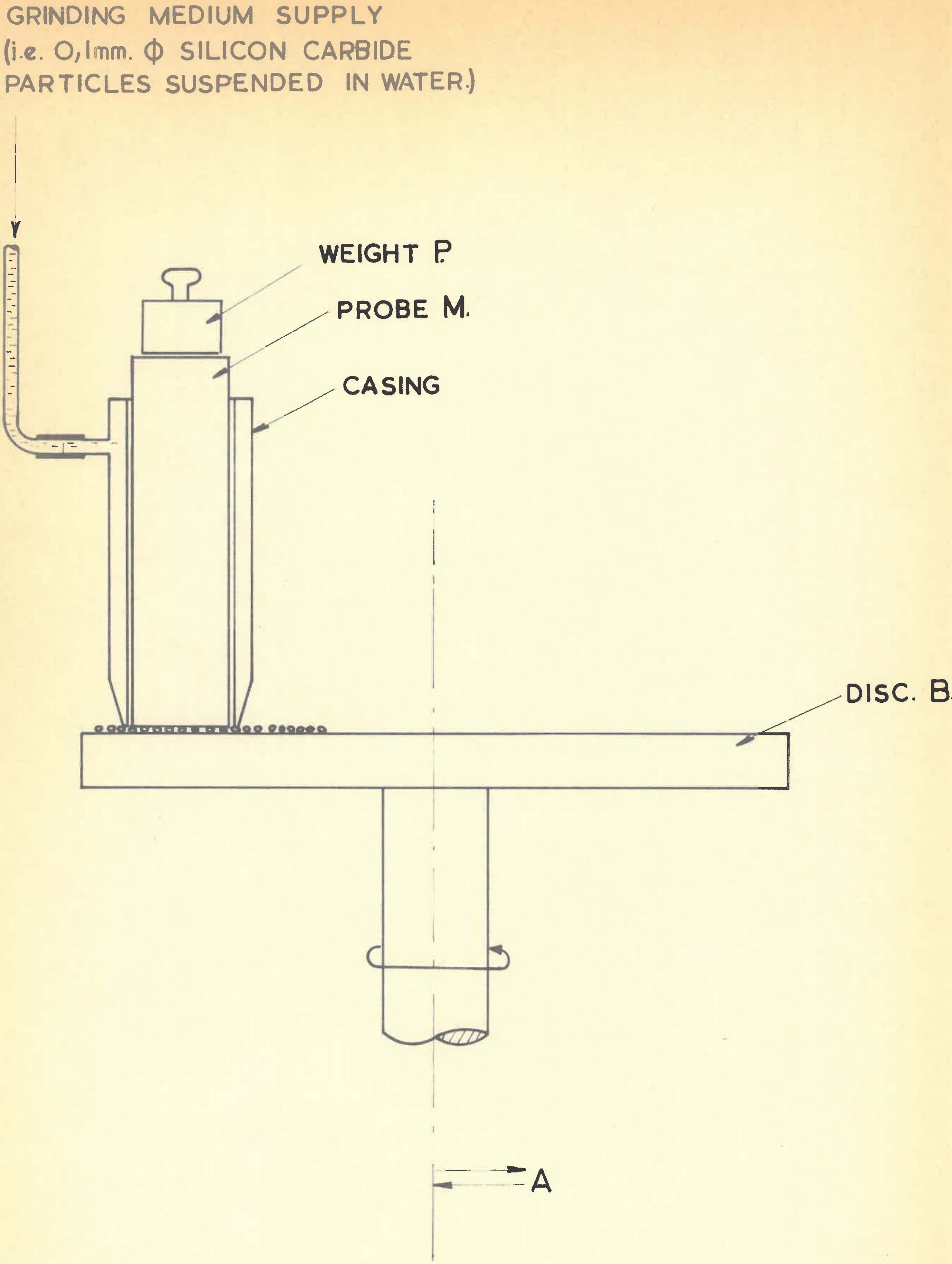
D	Particle diameter	(m)
G	Mass of particles undergoing comminution	(kg)
G_{x}	Coal charge	(kg)
H_m	Microhardness*	*($\frac{\text{kg force}}{\text{mm}^2}$
M	Mass	(kg)
N	Exponent	
P	Force on specimen	(N)
R	Weight fraction retained on sieve	(%)
T_o, T_1	Time constants	(s)



RELATIONSHIP BETWEEN WEAR RATE OF STEEL AND HARDNESS OF MINERAL GROUND

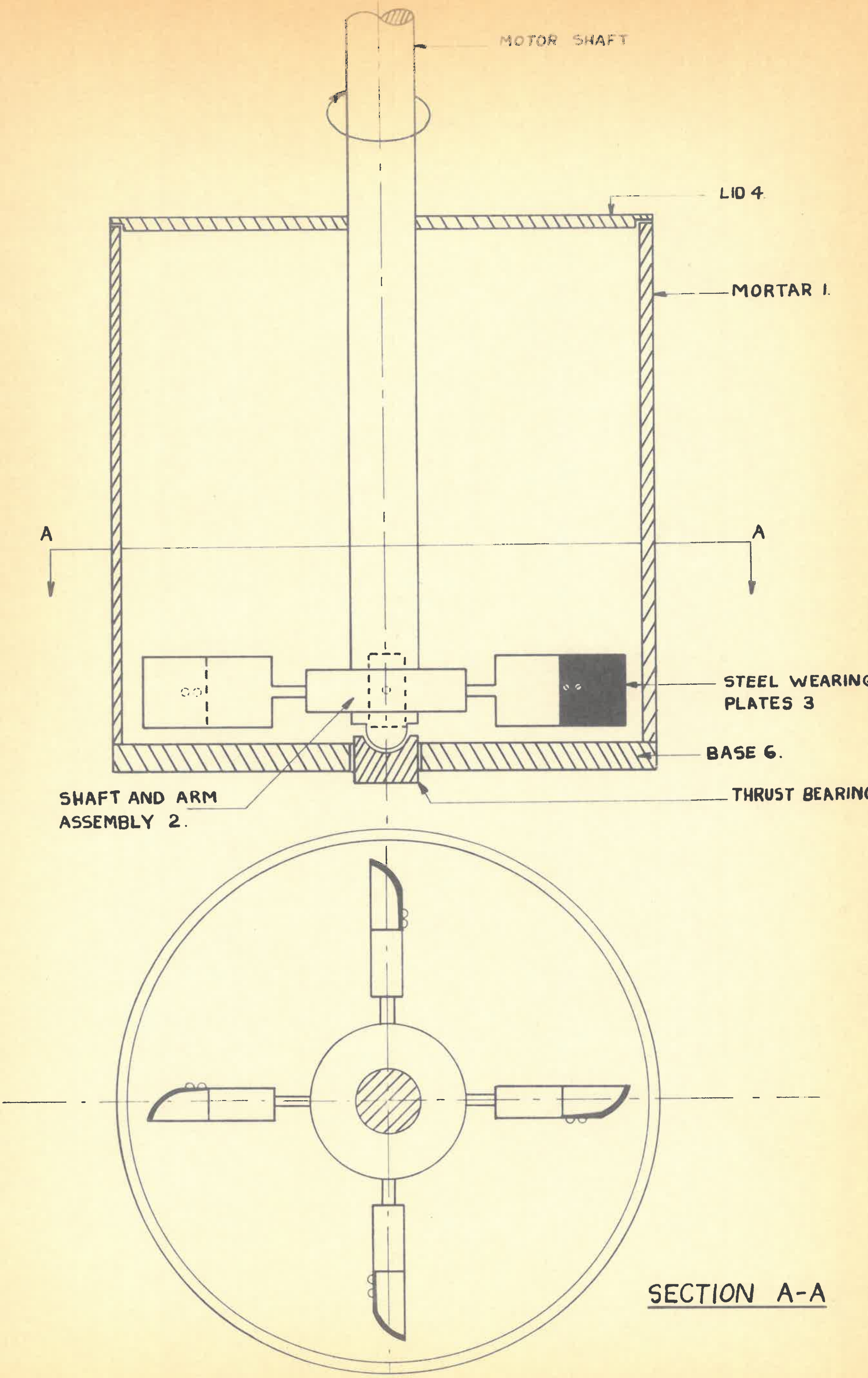
(AFTER NORMAN) (REF. 5).

FIG. 1

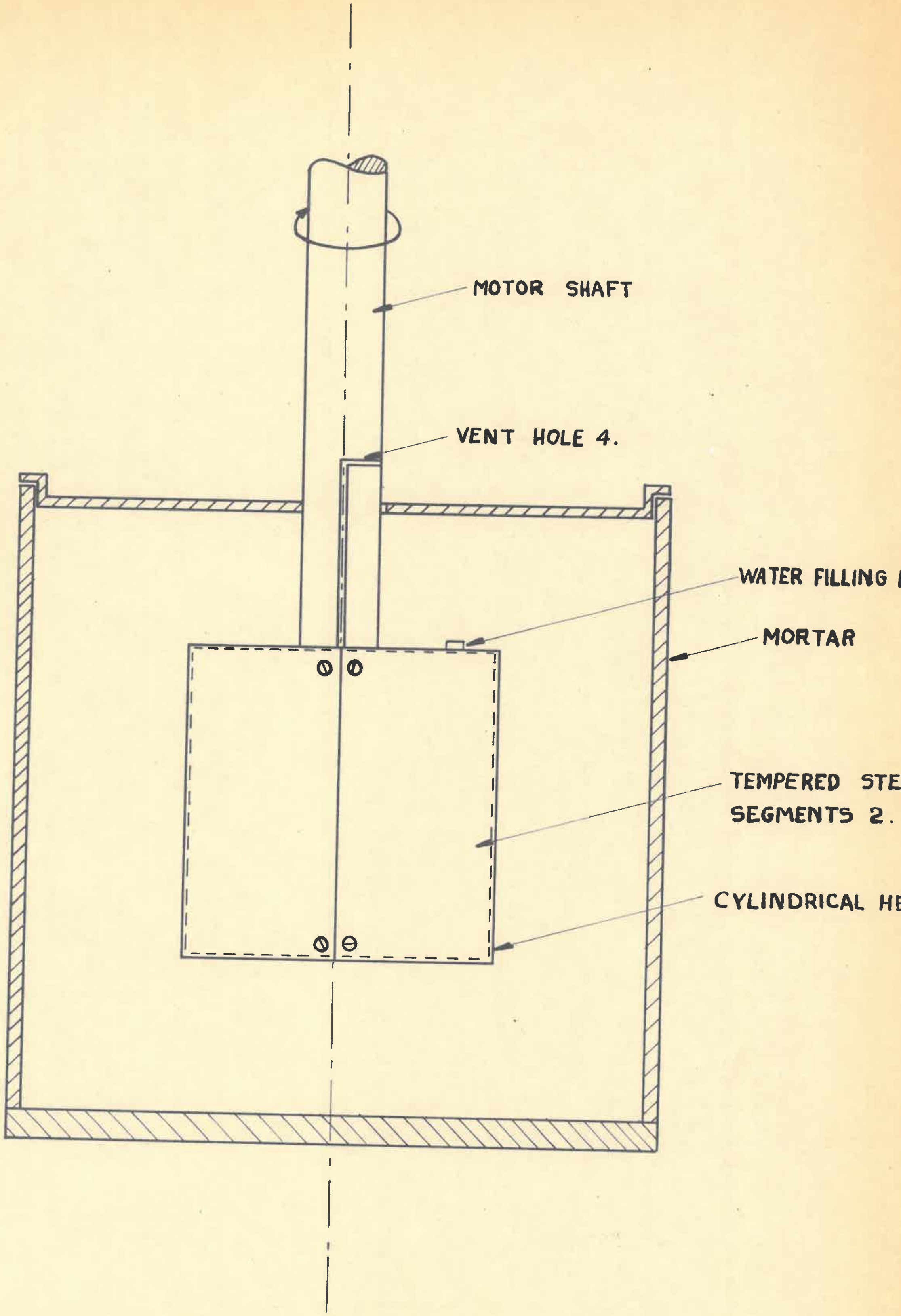


DEVICE FOR MEASURING SURFACE ABRASIVENESS

FIG. 2



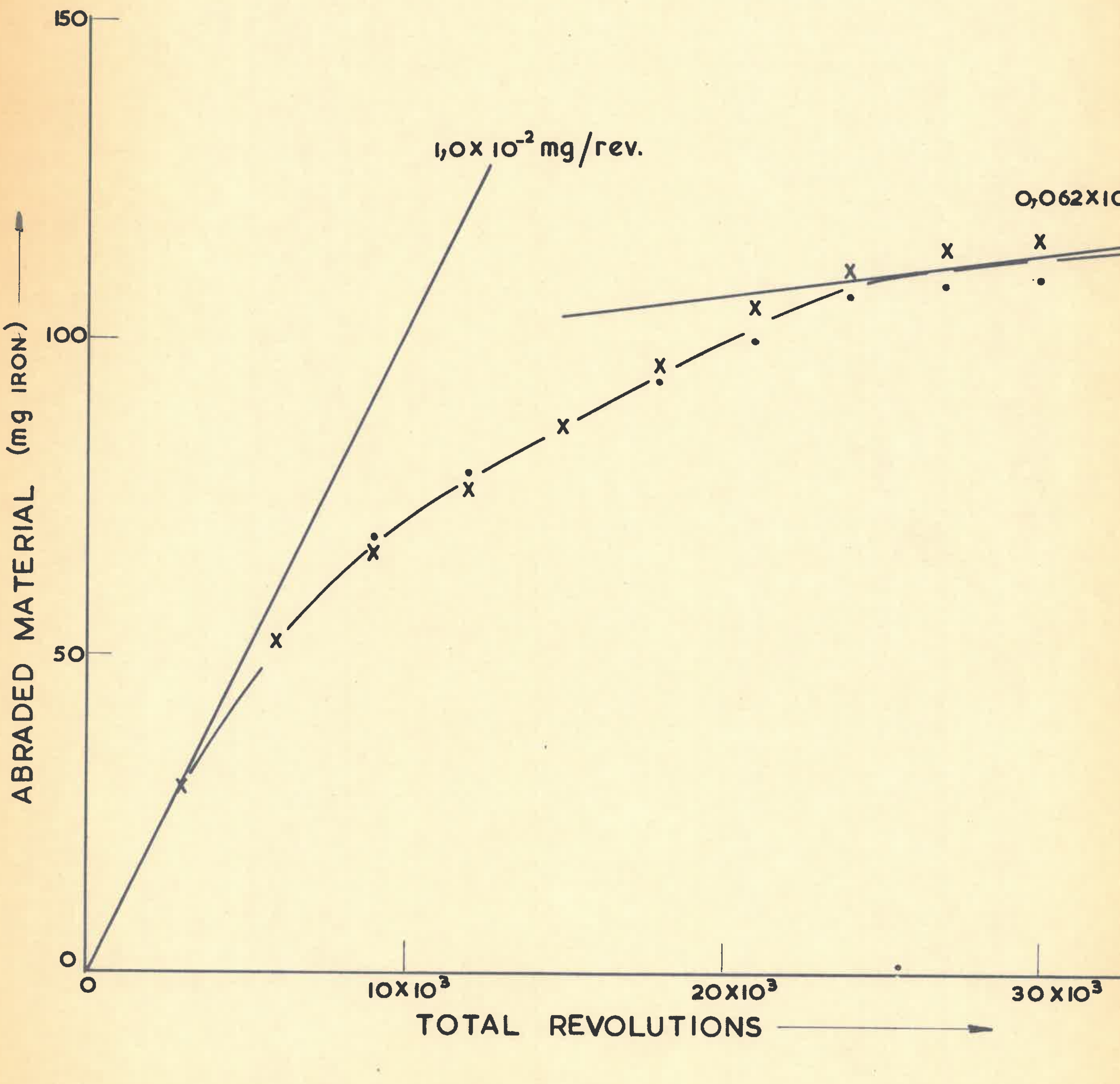
THE YANCEY GEER AND PRICE MODEL TESTING MACHINE.



EXPERIMENTAL HEAD FOR SURFACE ABRASIVENESS MEASUREMENT

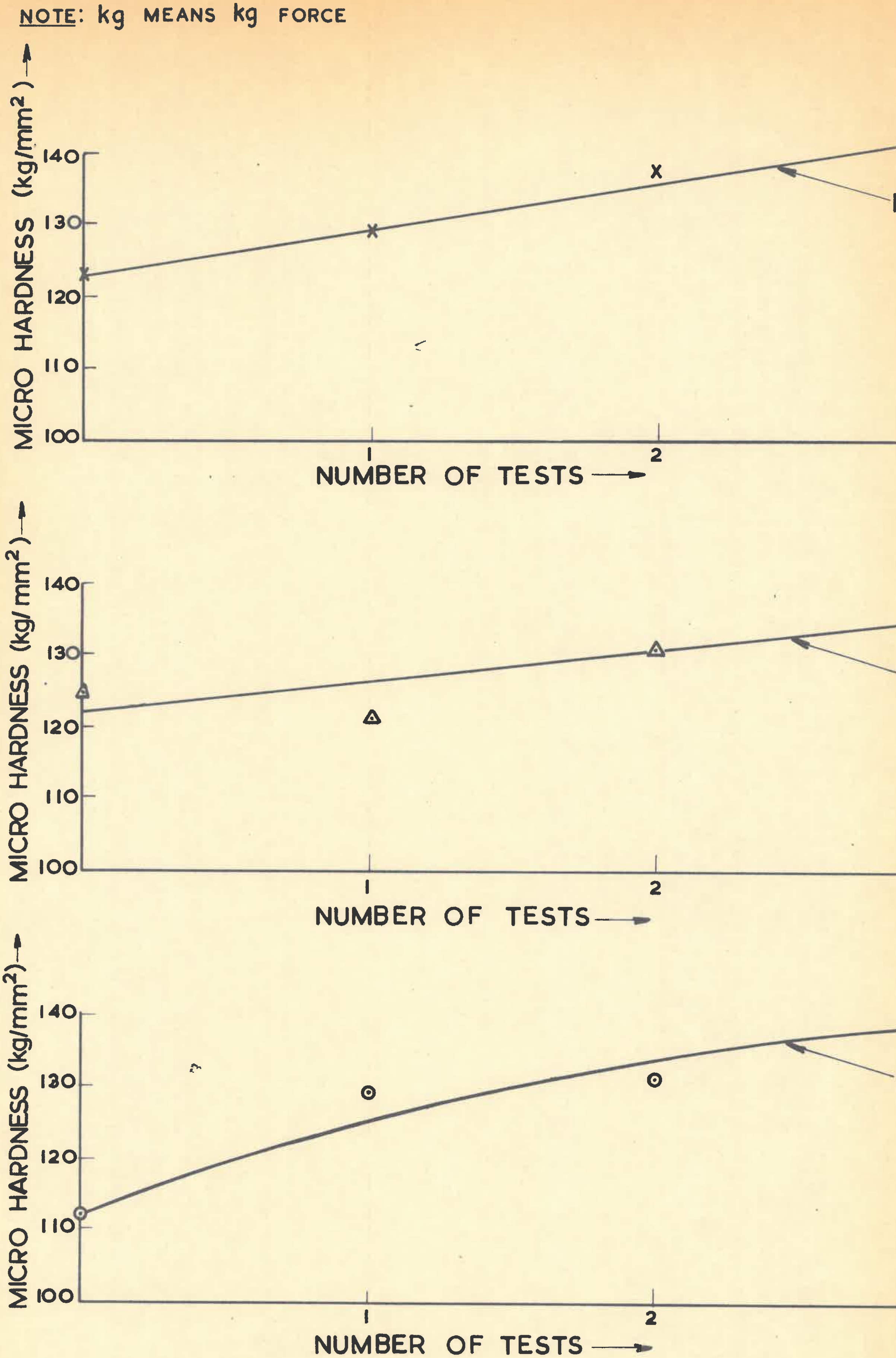
FIG. 4

SUB-SAMPLE REF.	COAL TYRE	SIZE	ASH %	PYRITE %	FREE QUARTZ %
•••• C_1	BITUMINOUS	4,76 mm TO ZERO	12,8	0,51	1,4
XXX C_2	DITTO	4,76 mm. TO ZERO	12,8	0,51	1,4



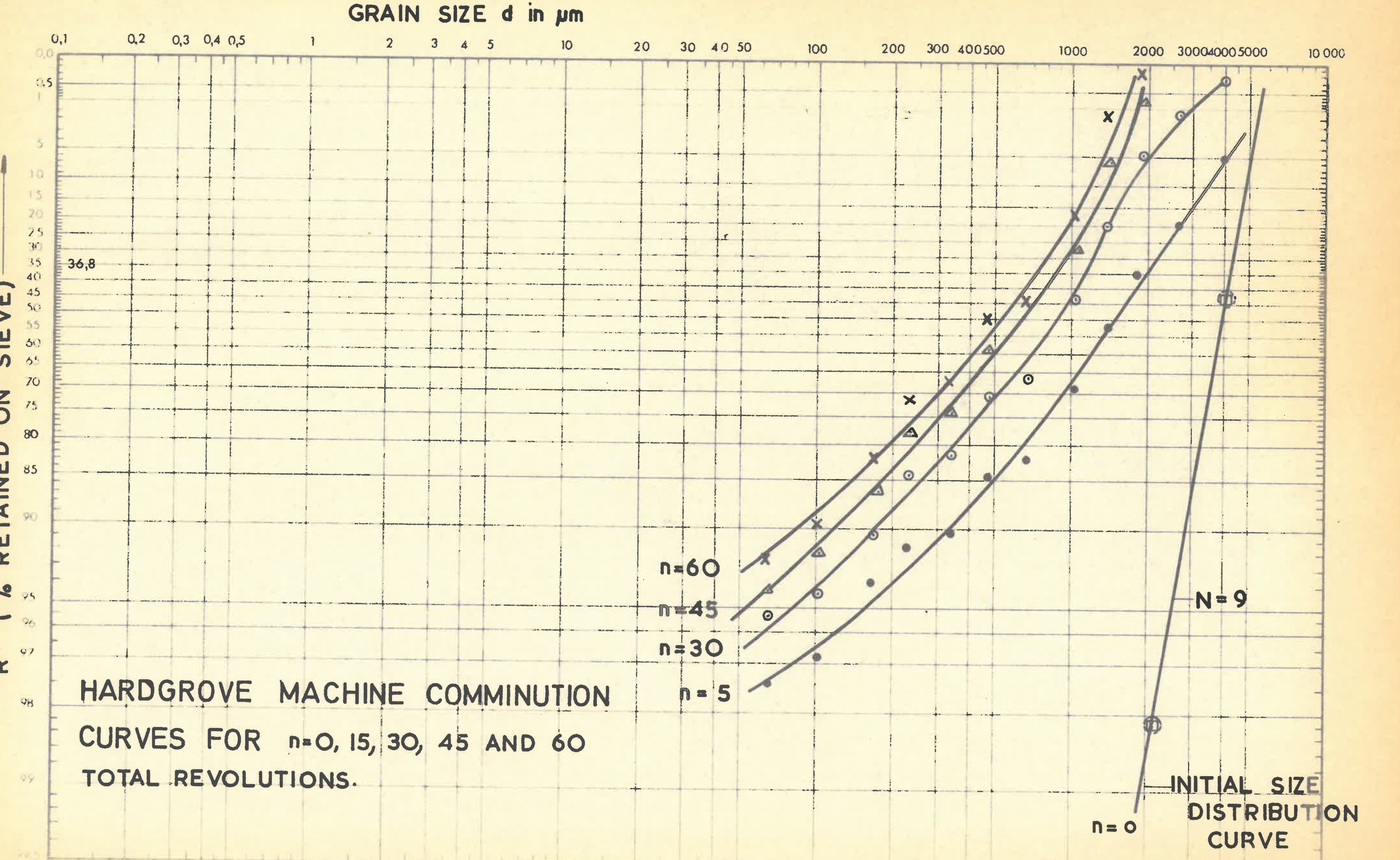
ABRASIVENESS DIAGRAM FOR STANDARD MACHINE

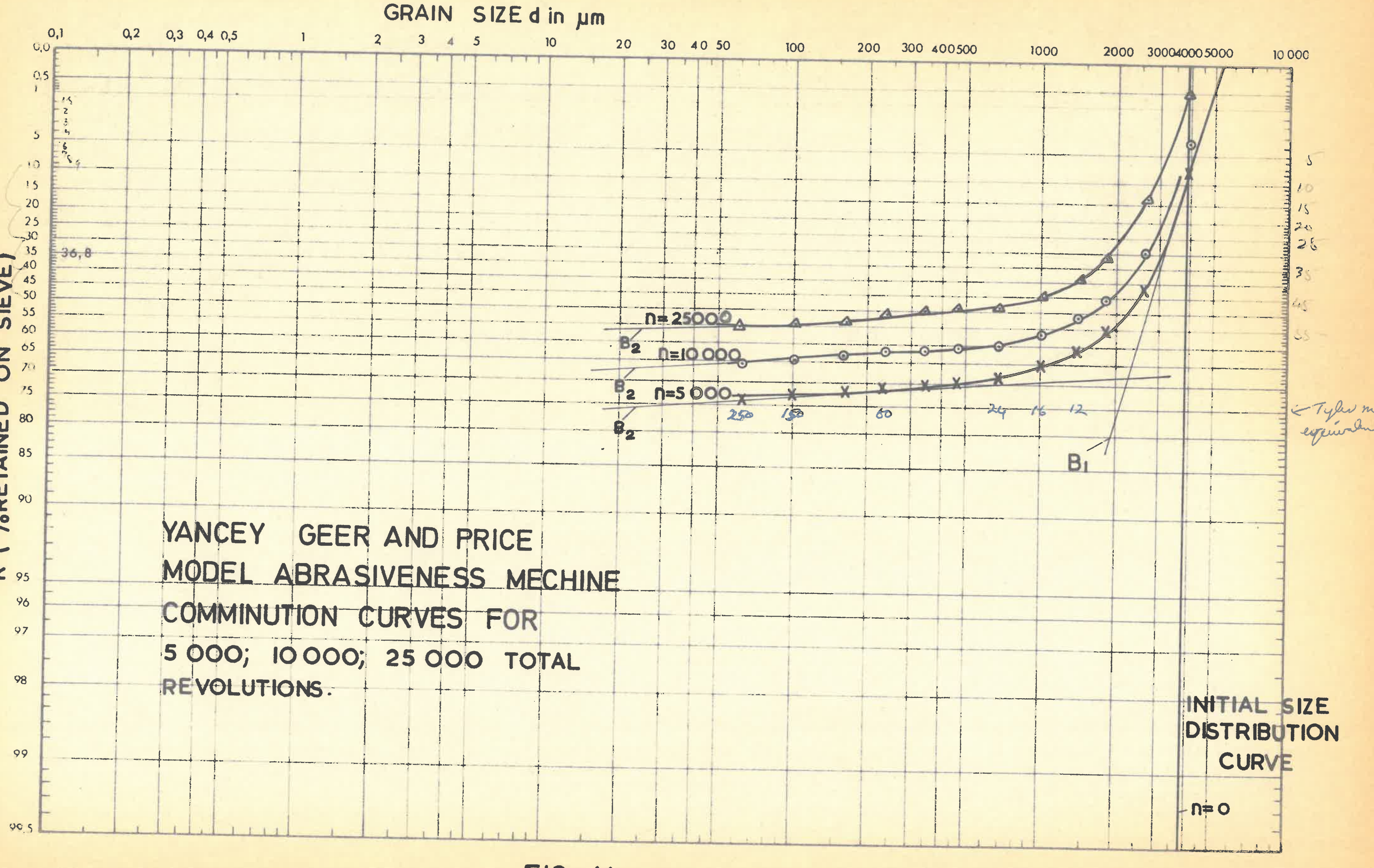
FIG. 5



VARIATION OF PLATE HARDNESS

FIG. 6


GRAIN SIZE d in µm
R (% RETAINED ON SIEVE)
36,8
n=60
n=45
n=30
n=5
N=9
n=0
INITIAL SIZE DISTRIBUTION CURVE
HARDGROVE MACHINE COMMINUTION
CURVES FOR n=0, 15, 30, 45 AND 60
TOTAL REVOLUTIONS.



GRAIN SIZE d in μm
R (%RETAINED ON SIEVE)
n=25000
n=10 000
n=5 000
B2
B1
YANCEY GEER AND PRICE
MODEL ABRASIVENESS MECHINE
COMMINUTION CURVES FOR
5 000; 10 000; 25 000 TOTAL
REVOLUTIONS.
INITIAL SIZE
DISTRIBUTION
CURVE
n=0