J. S. Afr. Inst. Min. Metall., vol. 89, no. 1.
Jan. 1989. pp. 13-21.

Observations on the Bond standard grindability test, and a proposal for a standard grindability test for fine materials

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SYNOPSIS

The Bond standard grindability test provides a Work Index that is widely used to estimate the energy required for grinding, but the test cannot be applied to fine materials such as plant tailings and middlings. For such materials, a comparative grinding test must be used in which a reference material from an operating plant is ground in a laboratory mill to determine the 'equivalent' energy consumption per revolution of the laboratory mill. As the Bond grindability test mill and its operating conditions are specified, its equivalent energy consumption per revolution should be a constant, here designated as *B*. Once *B* has been determined, the mill can be used to estimate the grindability of fine materials without the need for reference materials.

A value of *B* can be calculated from any Bond grindability test, and 245 tests that were conducted at Mintek were examined to determine its value. A wide range of values was found, but most of them were grouped around 198×10^{-7} kWh/rev, which is taken as the best estimate of *B* that is available at present. Values of *B* that are not close to this figure are obtained from materials for which the Bond grindability test gives misleading or 'spurious' Work Indexes. These spurious Work Indexes lead to the apparent departure of *B* from its true value.

Some limitations of the Bond grindability test arise from its use of a mill without lifters and of screening, instead of classification, to close the circuit.

SAMEVATTING

Die Bond-standaardmaalbaarheidstoets verskaf 'n 'werkindeks' wat algemeen gebruik word om die energie te beraam wat vir maling nodig is, maar die toets kan nie op fynmateriaal soos aanleguitskot en middelskotprodukte toegepas word nie. Vir sulke materiaal moet daar 'n vergelykende maaltoets uitgevoer word waarin 'n verwysingsmateriaal afkomstig van 'n bedryfsaanleg in 'n laboratoriummeul gemaal word om die 'ekwivalente' energieverbruik per omwenteling van die laboratoriummeul te bepaal. Aangesien die Bond-maalbaarheidstoetsmeul en sy werktoestande omskryf word, behoort sy ekwivalente energieverbruik per omwenteling, hier deur *B* aangedui, konstant te wees. As *B* eers bepaal is, kan die meul gebruik word om die maalbaarheid van fynmateriaal te beraam sonder dat verdere verwysingsmateriale nodig is.

'n Waarde van *B* kan aan die hand van enige Bond-maalbaarheidstoets bereken word en 245 toetse wat by Mintek uitgevoer is, is nagegaan om die waarskynlikste waarde van *B* te bepaal. Daar is 'n groot verskeidenheid waardes gevind, maar die meeste daarvan was om 198×10^{-7} kWh/r gegroepeer wat geneem is as die beste raming van *B* wat op die oomblik beskikbaar is. Waardes van *B* wat nie naby hierdie syfer is nie, word verkry van materiaal waarvoor die Bond-maalbaarheidstoets misleidende of 'dwalende' werkindekse gee. Hierdie dwalende werkindekse lei tot die skynbare afwyking van *B* van sy konstante waarde.

Sommige tekortkominge van die Bond-maalbaarheidstoets spruit voort uit sy gebruik van 'n meul sonder ligter en sifting, in plaas van klassifikasie, om die kring te sluit.

Introduction

The work described here began with a search for a grindability test that could be applied to fine materials such as tailings and middlings. It first led to a proposal for such a test, and then to an examination of the results of Bond standard grindability tests that had been conducted at the Council for Mineral Technology (Mintek) over a long period. The examination disclosed that the grindability of some materials could not be determined reliably by the Bond test and, of more importance, it distinguished between materials for which the Bond test gave 'true' results and those for which it gave 'spurious' results; when the results described as true are used in the estimation of the energy required for grinding, the estimates are correct, whereas spurious results lead to estimates that are not realized in practice.

The Bond grindability test, the Bond Work Index, and the Bond Comminution Law are closely linked; together they are the most widely used means of estimating the energy required for comminution, and of studying the efficiency of grinding mills.

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 ISSN-0038/223X/3.00 + 0.00. Paper received 25th July, 1988.

The Bond Work Index

The Bond Work Index of a material is defined as the energy needed to reduce one short ton of that material from a notional infinite size to a d_{80} size of 100 μm. It is determined by the Bond grindability test, and is expressed in kilowatt-hours per short ton. It can be expressed in kilowatt-hours per ton (1000 kg) through multiplication by 1,1.

W_i is the conventional symbol for the Bond Work Index; in this paper W_{im} is used to indicate the metric form of the Bond Work Index, i.e. kilowatt-hours per ton (1000 kg).

The Bond Standard Grindability Test

The Bond standard grindability test[1] is a batch-type, dry test in which the circuit is closed by a screen, known as the limiting screen. The mill is 12 inches in length by 12 inches in diameter (305 by 305 mm) with a smooth shell, and is rotated at 70 r/min; it is loaded with balls of specified sizes that have a total mass of 20 125 g. The material to be tested is reduced to minus 6 mesh (3,35 mm) by careful stage crushing. The amount of material used as the charge to the mill is the mass of minus 6 mesh material that occupies 700 ml after being shaken. The material is ground for either an estimated or an arbitrarily chosen number of revolutions, and then screened on the limiting screen. The oversize is returned for regrinding, together with an additional quantity of minus 6 mesh material to make the charge up to its original mass. The number of mill revolutions is adjusted in successive cycles, so that a steady-state circulating load of 250 per cent is achieved. The test gives the Standard Work Index (W_i), which is calculated from the following equation:

$$W_i = \frac{4,45}{P_i^{0,23} \times G^{0,82}\left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}}\right)}, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where P_i is the aperture of the limiting screen (μm),
G is the net mass of screen undersize produced per mill revolution (g),
P is the d_{80} size of the mill product (μm), and
F is the d_{80} size of the mill feed (μm).

The Standard Work Index can be used in the calculation of the energy consumed by wet grinding in a ball mill of 8 ft (2,44 m) diameter operating with a 250 per cent circulating load in a circuit closed by a classifier. Departures from these and other specified conditions of operation are accommodated by correction or 'efficiency' factors that must be applied to the Work Index[2].

The Bond Comminution Law

The Bond Law[1] leads to the expression

$$W = 10\,W_{im}\left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}}\right), \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where W is the energy required to grind 1 t (1000 kg) of material from its initial size F to the product size P.

Conversely, if the value of W is known from plant information, the equation can be used to determine the Work Index for the material concerned. This Work Index is known as the Operating Work Index to distinguish it from the index determined in the laboratory, the Standard Work Index. A comparison of the Operating and Standard Work Indexes can be used to check either the grinding efficiency of a plant mill or the validity of the Standard Work Index, depending on the circumstance.

Grindability of Fine Materials

Material for a Bond grindability test should be coarse enough to allow stage crushing in the preparation of the specified minus 6 mesh (3,35 mm) feed to the test mill. The Bond test cannot therefore be applied to fine materials such as sands and plant middlings, and a comparative grinding test must be resorted to. This grinding test requires a reference material from an operating plant that grinds the material to a known particle size with a known expenditure of energy. Ideally, the reference material, the 'known', and the material whose grindability is required, the 'unknown', should be of the same type or should have similar physical properties. Equal bulk volumes (or equal masses if the two materials have the same density) are ground in a laboratory mill for a varied number of mill revolutions, and size analyses are then done on the products. The number of revolutions needed to grind the known material from plant feed size to plant product size can then be determined. This number of mill revolutions is equivalent to the specific energy consumption of the plant mill, and it leads to the statement that one revolution of the laboratory mill is equivalent to a certain specific energy consumption by the plant mill. This statement can then be applied to the results of the grinding tests on the unknown material, and the specific energy required in practice to grind this unknown material from the original size to any other size can be estimated.

A major difficulty in the use of the comparative grindability method is that of obtaining a suitable reference material and its accompanying plant data. However, if different reference materials are ground under identical conditions in the same laboratory mill, the relationship between the energy consumption of the industrial mill and one revolution of the laboratory mill should be the same. Further, if the laboratory mill and its operating conditions are standardized, there should be no need for additional reference materials once the equivalent energy consumption for one revolution of the laboratory mill has been reliably determined. Because the Bond grindability test mill and its operating conditions are specified and well-known[1], it seems reasonable to adopt them as a standard for the determination of the grindability of materials that are too fine for determination by the standard Bond test.

The equivalent energy per revolution of the Bond test mill, which is designated as B, can be calculated from the results of any standard Bond grindability test, but a value derived from a number of tests would be more reliable.

Calculation of Equivalent Energy per Revolution

The equivalent energy per revolution of the Bond grindability test mill can be calculated from a Bond standard grindability test as follows.

In the Bond test, G is the net mass (in grams) of the undersize material produced per revolution of the Bond grindability test mill. The total amount of undersize material obtained per revolution consists of G and the proportional amount of undersize material present in the minus 6 mesh feed to the mill.

If U is the percentage undersize in the minus 6 mesh feed, the total amount of undersize obtained per revolution is

$$G \times \frac{100}{100 - U}.$$

To obtain 10^6 g (1 t) of undersize would require

$$\frac{10^6 \times (100 - U)}{G \times 100} \text{ revolutions.}$$

If W is the energy required in an operating plant to reduce

10^6 g of material from a feed size F to a product size P, then from equation (2)

$$\frac{10^6 \times (100 - U)}{G \times 100} \text{ revolutions is equivalent to}$$

$$W_{im}\left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}}\right) \text{kWh.}$$

One revolution of the mill is, therefore, equivalent to

$$\frac{10\ W_{im}\left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}}\right) \times G \times 100}{10^6 \times (100 - U)} \text{ kWh.}$$

When W_{im} from (1) has been substituted, it is concluded that the energy consumption per revolution is

$$B = \frac{4{,}9 \times 10^{-3} \times G^{0,18}}{P_1^{0,23}\ (100 - U)} \text{ kWh.}$$

Evaluation of B

Values of B were determined from the results of 272 Bond grindability tests that had been conducted at Mintek between 1975 and 1985. Because the results of replicate tests were averaged and tests on materials significantly finer than the stipulated minus 6 mesh (3,35 mm) were excluded, the number of items available for examination was reduced to 248. The items were arranged in 34 groups, each representative of a particular type of material.

The two largest groups were those dealing with samples from the Witwatersrand gold mines and the copper–lead–zinc ores at Aggeneys in the north-western Cape Province, which is now the site of the operations of the Black Mountain Mine. The Witwatersrand gold ores are noted for their relative uniformity of composition. However, the samples from Aggeneys varied greatly in their proportions of copper, lead, and zinc sulphides, pyrite, and magnetite, and therefore represent a wide range of compositions. Overall, the data examined can be regarded as representative of a wide range of materials.

The test results, and the values of B relating to the 248 items, are recorded in full in a document at Mintek. Table I presents only the tests and data to which reference is made in the text of this paper.

The Mintek Bond Grindability Tests

Although the main purpose of the examination of the grindability test results is to provide information on the value of B, it is of interest to draw attention to some features of the Bond test that were revealed by the examination.

Variations in the Work Index

By definition, the Work Index for a particular material should be constant, i.e. it should not vary with changes in the apertures of the limiting screen. However, variations in the Work Index are frequent. For most materials, the Work Index increases as the grind becomes finer, but the opposite does sometimes occur.

An example of increasing Work Indexes is provided by gold-ore sample G819 (Table I, items 6 to 13), for which the Work Index of 13,7 kWh/t for a limiting screen of 813 μm increased fairly regularly to 20,2 kWh/t for a limiting screen of 54 μm. The very rapid increase in the Work Index for a sample of ferrochromium (Table I, items 204 to 206) is noteworthy: the Work Index of 14,5 kWh/t for a limiting screen of 106 μm increased to 22,8 kWh/t for a limiting screen of 63 μm.

The uranium ore from the Karoo (items 162 to 164) and dolomite (items 227 to 229) had Work Indexes that decreased as the grind became finer.

Slip of the Grinding Load

Items 232 to 234 in Table I refer to tests on material described as anode scrap, which contained a considerable proportion of carbon, possibly graphite. In the course of the grindability tests, it became evident that the grinding load was slipping on the smooth shell of the mill. As a result, the grinding times increased with successive cycles, and it was not possible to reach a steady-state condition. The Work Indexes shown in Table I were calculated for the conditions that existed when the tests were discontinued, and are clearly not true Work Indexes.

Comparative grinding tests on the anode scrap, in which a mill with lifters was used, demonstrated that the difficulties described above may not have occurred, or would have been greatly diminished, if the Bond test mill had been provided with lifters. A Witwatersrand gold ore was used as the reference material, and a Work Index of 14 kWh/t (for the anode scrap) was calculated from the results.

It is not surprising that the grinding of a graphite-like material in a mill without lifters should cause the load to slip, and that this should lead to both a high Work Index and a low value of B. Further, it is possible that the high Work Indexes (above 20 kWh/t) found for a coal (Table I, items 183 and 184) may be due to the slip of the grinding load, and not to a genuine 'hardness' of the coal. It is also possible that a moderate amount of slipping occurs in most Bond grindability tests, a possibility that is supported by the actual measurement of slip reported in experimental work on a mill with smooth liners[3].

Presence of Coarse Mica

The effect on the Bond grindability test of the presence of coarse mica—phlogophite in the particular sample tested—was demonstrated by tests on an apatite ore (Table I, items 247 and 248). In the standard test using a 300 μm limiting screen, the proportion of mica in the screen oversize increased in successive cycles, and a steady state was reached only after 17 cycles. A Work Index of 18,8 kWh/t was calculated. This value was considerably higher than was expected for a plant operation in which the circuit is closed by a classifier. Classification would direct fairly large, thin flakes of mica into the overflow, whereas the limiting screen used in the Bond test returned them to the mill for regrinding. This effect of the screen was demonstrated by a repetition of the test, but with the addition of air classification (by winnowing) of the screen oversize. The air classification removed the

TABLE I

BOND GRINDABILITY TESTS PERFORMED AT MINTEK*

P_l = Limiting screen aperture (μm)
U = Undersize, % of feed smaller than limiting screen aperture
P = Product size as 80% passing size (μm)
G = Net undersize per revolution
W_{im} = Work Index, kWh/t
B = Equivalent energy per revolution (kWh/rev) $\times 10^{-7}$

Item no.	Sample no.	P_l	U	P	G	W_{im}	B
Witwatersrand Gold Ores							
4	G404	300	21,3	237	2,47	13,9	197
6	G819	813	35,2	638	5,17	13,7	218
7	G819	540	26,6	438	3,58	14,4	198
8	G819	300	11,6	254	2,75	14,6	192
9	G819	208	11,4	187	2,21	14,2	187
10	G819	140	10,3	125	1,51	16,0	189
11	G819	108	7,6	91	1,17	17,3	186
12	G819	76	6,7	64	0,93	18,3	191
13	G819	54	4,4	41	0,66	20,2	190
25	J9	106	11,1	82	1,25	15,5	196
Barberton Gold Ore							
47	J689	106	9,7	78	1,25	15,2	193
Antimony Ore							
54	H133	208	14,8	178	2,06	14,4	192
Nickel Ore							
63	H72	208	17,8	170	1,60	17,1	190
Platinum Ore (Merensky Reef)							
67	G253	208	19,4	142	1,85	13,9	199
Copper-Lead-Zinc Ores							
69	G678	410	33,5	312	4,26	10,4	240
80	G909	108	11,1	90	1,60	13,2	204
96	G980	108	9,0	90	1,37	15,1	194
108	H201	140	19,4	118	2,63	10,3	232
Dolomitic Zinc Ore							
121	J687	300	23,6	236	2,17	16,0	199
Dolerite							
135	G664	540	22,8	390	1,43	27,9	159
136	613/2	297	9,1	208	0,92	28,1	143
Limestone							
145	G520	208	23,3	145	4,21	7,0	242
Fluorspar Ores							
152	J47	150	21,4	130	3,92	7,7	252
153	J47	106	17,0	85	2,66	8,7	241
154	J47	75	14,6	63	2,01	9,8	241
Karoo Uranium Ore							
162	H679	540	27,5	395	1,98	21,5	180
163	H679	297	22,0	216	1,63	18,4	185
164	H679	212	19,4	166	1,57	17,1	192
Matte (Copper-Nickel)							
173	H1004	425	25,1	330	4,48	10,4	213
174	H1004	150	11,7	128	1,60	15,6	191
175	H1004	85	9,0	61	0,30	44,2	156
Coal							
183	G699	540	12,8	455	2,46	20,2	155
184	G699	140	6,3	124	0,95	23,4	158
Chromite							
192	G863	140	11,5	126	1,86	19,3	199
197	H140	140	21,1	128	3,32	8,9	248
Ferrochromium							
204	J769	106	10,1	92	1,50	14,5	201
205	J769	75	6,0	67	0,91	19,5	190
206	J769	63	5,1	54	0,67	22,8	185
Ferrosilicon							
210	F841	150	4,3	125	0,48	40,9	142
Iron Ore							
213	G245	150	5,9	117	1,08	19,9	167
214	G245	75	3,2	60	0,68	22,8	175
215	G241	600	24,1	428	2,72	18,1	178
216	G242	600	21,5	422	1,76	25,4	159
217	G243	600	26,9	396	4,32	11,6	200
218	G245	300	11,9	265	1,83	19,5	167
Lithium Ore (Petalite)							
224	J885	230	20,1	195	1,78	17,6	195
Dolomite							
227	G.D.	550	28,6	462	2,69	19,7	192
228	G.D.	212	16,7	168	1,90	15,0	193
229	G.D.	150	14,3	116	1,73	13,7	199
Anode Scrap†							
232	J788	150	27,9	123	0,27	68	170
233	J788	150	27,9	104	0,32	53	175
234	J788b	212	30,5	163	0,11	153	135
Shale							
238	J781	150	22,3	109	2,38	10,3	233
Phosphate Ore with Phlogopite							
247	H17	300	20,1	247	1,89	18,8	186
248‡	H17	300	20,1‡	253‡	3,52‡	11,5‡	208‡

* This table has been abridged from a table that is available at Mintek; it contains only data to which reference is made in the text. 'Item no.' refers to the items in the complete table.

† Tests terminated before steady-state was reached
‡ Screening followed by winnowing

fairly large, thin flakes of mica, which were added to the screen undersize. As a result of this modified procedure, a constant circulating load was reached in seven cycles, and a Work Index of 11,5 kWh/t was found. Not only was the Work Index reduced to a more realistic figure by the modified procedure, but the number of cycles required was greatly reduced.

Presence of a Minor Hard Constituent

In the grindability tests on a copper-nickel matte (Table I, items 173 to 175), the Work Index increased from 10,4 to 15,6 kWh/t as the apertures of the limiting screening were reduced from 425 to 150 μm. The Work Index then increased abruptly to 44,2 kWh/t, and no fewer than 44 cycles were needed to attain a constant circulating load when an 85 μm limiting screen was used. The explanation for these observations was the presence in the matte of a small proportion of fairly tough, possibly metallic, particles. These particles were apparently small enough to pass through the screens used in the preceding tests, but there were enough metallic particles larger than 85 μm to accumulate in the circulating load when the finest limiting screen was used. There is little doubt that the removal of the metallic particles from the circulating load, either in each cycle or at longer intervals, would have reduced the Work Index and the number of cycles needed to reach a constant circulating load.

The Values of *B* from Bond Standard Grindability Tests

The 248 values of B calculated from the results of the Bond grindability tests are expressed in units of (kWh/rev) $\times$ 10^{-7}. The values ranged from 138 to 491, which is a disconcertingly large range for a value that is expected to be constant.

The energy consumption per revolution of the Bond mill—except for some possible unusual conditions of operation—is constant. Bond says[4], 'One revolution of the mill represents a constant work input' and the 'scale-up' of that energy consumption for application to a defined industrial mill should also be constant; that is, the equivalent energy consumption per revolution of the Bond mill, B, should be constant. Fig. 1 shows the actual distribution of the values of B. In the construction of this figure, the values of B were divided into 14 classes.

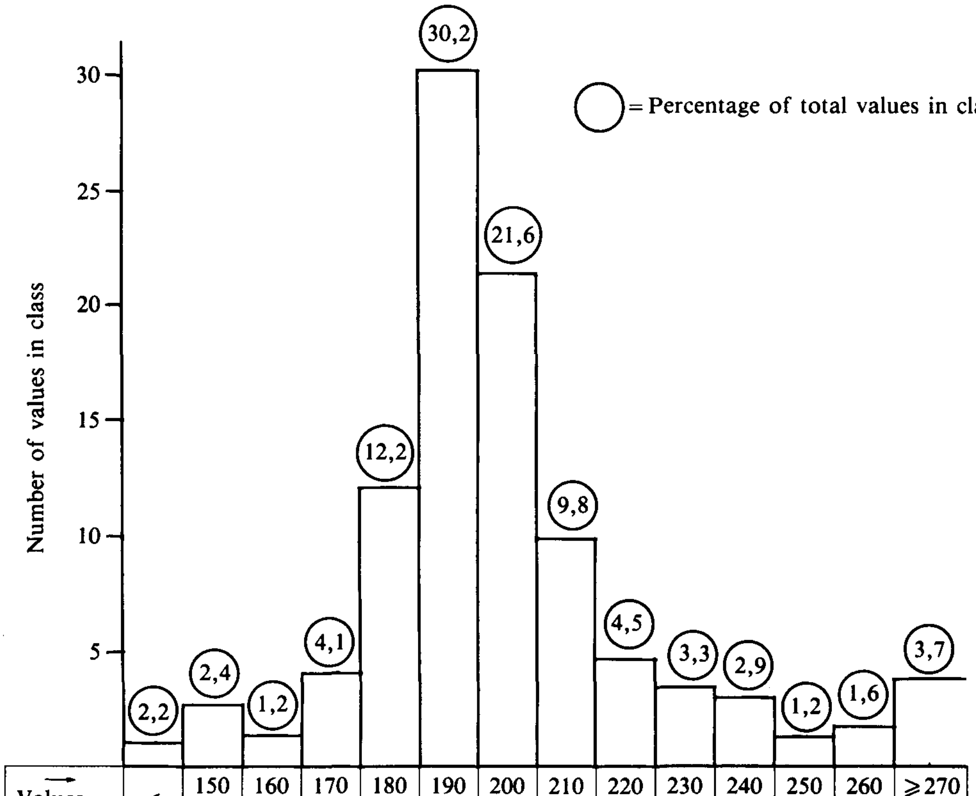
Fig. 1 shows a conspicuous concentration of values in the modal class number 6, and in the adjoining classes, numbers 5, 7, and 8. Class number 6 contains 30,2 per cent of the values, while the four classes 5 to 8 contain 73,8 per cent of the total values. The average value of B in these four classes is 198,4, which is a value that falls within the modal class, and is probably close to the true value of B. A value of 198,4 (or one close to it) would be readily acceptable as the true value if explanations could be offered for those values that are far removed from it. Those values are referred to here as 'spurious' values.

Explanations for Spurious Values of B

The value of B is calculated from the equation

$$B = \frac{4,9 \times 10^{-3} \times G^{0,18}}{P_1^{0,23}\,(100 - U)}.$$

A constant value of B depends on the relationship between the three variables G, P_1, and U, and there is no immediately evident reason why they should have a constant relationship. Additional information on the dependence of B on the relationship of G, P_1, and U was sought from a comparison of grindability tests that gave low, intermediate, and high values of B. Tables II, III, and IV show the relevant information.



Values of B →	< 150	150 to 159	160 to 169	170 to 179	180 to 189	190 to 199	200 to 209	210 to 219	220 to 229	230 to 239	240 to 249	250 to 259	260 to 269	⩾270
Class number	1	2	3	4	5	6	7	8	9	10	11	12	13	14

Note: Values of B are kW·h/revolution $\times$ 10^{-7}

Fig. 1—Distribution of values of *B*, which are given in kWh/rev × 10^{-7}

TABLE II
GRINDABILITY TESTS WITH LOW VALUES OF B
(CLASSES 1, 2, AND 3 IN FIG. 1)

Item no.	Material	B	W_{im}	P_1	U
183	Coal	155	20,2	540	12,8
184	Coal	158	23,4	140	1,3
210	Ferrosilicon	142	40,9	150	4,3
135	Dolerite	159	27,4	540	22,8
136	Dolerite	143	28,1	297	9,1
241	Calcined flint clay	155	22,3	212	4,1
172	Slag	167	20,3	140	3,2
213	Iron ore	167	19,9	150	5,9
216	Iron ore	159	25,4	600	21,5
218	Iron ore	167	19,5	300	11,9
Average		157	24,7		

TABLE III
GRINDABILITY TESTS WITH NORMAL VALUES OF B
(CLASS 6 IN FIG. 1)

Item no.	Material	B	W_{im}	P_1	U
7	Witwatersrand gold ore	198	14,4	540	26,6
4	Witwatersrand gold ore	197	13,9	300	21,3
25	Witwatersrand gold ore	196	15,5	106	11,1
47	Barberton gold ore	193	15,2	106	9,7
54	Antimony ore	192	14,4	208	14,8
63	Nickel ore	190	17,1	208	17,8
67	Platinum ore (Merensky Reef)	199	13,9	208	19,4
96	Copper-lead ore	194	15,1	108	9,0
80	Zinc ore	199	16,2	76	8,0
121	Dolomite-zinc ore	199	16,0	300	23,6
140	Manganese ore	197	17,4	106	12,9
174	Copper-nickel matte	191	15,6	150	11,7
192	Chromite	199	19,3	140	11,5
200	Chromite (UG-2 Reef)	199	16,4	105	11,8
205	Ferrochromium	190	19,5	75	6,0
221	Synthetic magnetite	193	16,5	75	4,3
224	Lithium ore	195	17,6	230	20,1
228	Dolomite	193	15,0	212	16,7
Average		195	16,1		

Note: Only 18 test results of the 75 in Class 6 are shown above

Because U and P_1 are interdependent, their relationship is shown in Fig. 2 and the slopes of the best-fit straight lines for the three sets of data were calculated.

The information provided by Tables II, III, IV, and Fig. 2 is summarized in Table V, which shows that

(i) low values of B arise from materials that have a high Work Index, produce little fines, and have a steep particle-size distribution, and

(ii) high values of B arise from materials that have a low Work Index, produce much fines, and have a flat particle-size distribution.

It appears from the above that intermediate (or normal) values of B, i.e. close to 198 (kWh/rev) $\times 10^{-7}$, are confined to materials with intermediate Work Indexes and intermediate particle-size distributions. However, it

TABLE IV
GRINDABILITY TESTS WITH HIGH VALUES OF B
(CLASSES 10 AND 11 IN FIG. 1)

Item no.	Material	B	W_{im}	P_1	U
238	Shale	233	10,3	150	22,3
245	–	235	11,7	150	23,1
180	Pyroxenite	238	14,5	560	38,8
197	Chromite	248	8,9	140	21,1
219	Copper-zinc-pyrite	239	10,0	300	29,1
145	Limestone	242	7,0	208	23,3
153	Fluorspar ore	241	8,7	106	17,0
154	Fluorspar ore	241	9,8	75	14,6
159	Fluorspar ore	237	8,1	212	22,2
160	Fluorspar ore	232	9,0	106	15,5
161	Fluorspar ore	235	9,9	75	12,8
182	Foskorite	241	11,9	540	36,9
108	Copper-lead-zinc ore	232	10,3	140	19,4
69	Copper-lead-zinc ore	240	10,4	410	33,5
Average		238	10,0		

TABLE V
FEATURES OF LOW, INTERMEDIATE, AND HIGH VALUES OF B
INDICATED BY TABLES II TO IV AND FIG. 2

Values of B	Low	Intermediate	High
Class nos. in Fig. 1	1, 2, 3	6	10, 11
Range of B	< 170	190 – 199	230 – 249
Average B	157	195	238
Range of Work Index (W_{im})	19,5 – 40,9	13,9 – 19,5	7,0 – 14,5
Average	24,7	16,1	10,0
Undersize in feed, U (%)			
Average U for P_1 = 212 μm	7,3	17,7	25,5
Slope of particle-size distribution curve*	1,14	0,54	0,48

* Calculated for log per cent undersize at log limiting-screen aperture

is difficult to see why these characteristics of the material being ground should affect the energy calculated for one revolution of the test mill.

Consideration must therefore be given to the possibility that the spurious values found for B are connected to the method of calculation for B. The standard Work Index was used for the calculation of B, and it follows that an inaccurate (or spurious) Work Index will lead to an inaccurate (or spurious) value for B. (For the present purpose, the possibility of experimental error in carrying out the Bond grindability test is disregarded.) An inaccurate or spurious Standard Work Index is one that differs from the Operating Work Index that can be calculated from plant data. The following information shows that occasional spurious Work Indexes are not abnormal and should be expected.

(1) Austin *et al.*[5] say, 'The Bond method is based on the mean empirical fit of data from a number of mills and materials run under normal conditions, and there will be a range of error for any specific mill and material and set of operating conditions'. The standard Work Index will therefore be true for many plant operations,

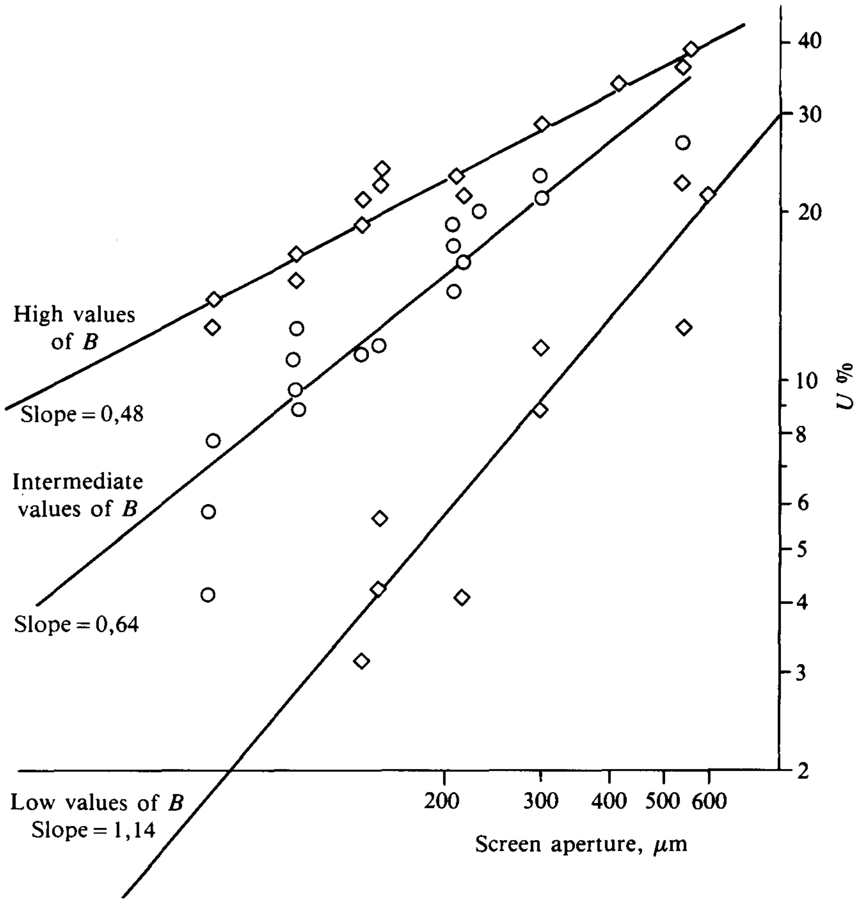


Fig. 2—Values of U for the apertures (P_1) of various limiting screens

but not for all.

(2) The Bond Work Index is true only for materials that have a particular or 'normal' particle-size distribution.

Bond[6] says, 'Variations in the slope of the product size distribution from the normal value greatly affect the new surface area produced and have the square root of this effect upon the energy input required'.

Viswanathan[7] says, 'it is shown that Bond's law is valid only for a particular product size distribution'.

Holmes[8] says 'The Third Theory [that of Bond] is based on the behaviour of an average material'.

It is concluded that the equivalent energy per revolution of the Bond grindability test mill is a constant close to 198 kWh/rev $\times 10^{-7}$, and that calculated values of B not close to this value arise from materials for which the Bond grindability test gives misleading or spurious Work Indexes.

Information on the Value of B from Other Sources

Are the values of B that have been reported here peculiar to the methods used and the materials encountered at Mintek, or are they universal, i.e. obtainable by other workers and other materials? Some evidence is provided by grindability tests published by Bond[4]. These tests deal with 15 materials that had been selected from among the large number tested by the Allis–Chalmers Company only because they had been tested at no fewer than four limiting screen apertures, and their selection was therefore unbiased. The grindability test results for a limiting screen of 65 mesh (probably 212 µm) are shown in Table VI, which includes the values of B calculated from the results. Although there are only 15 values of B, they were classified as was done in Fig. 1 for the results obtained at Mintek. A reasonably close similarity to the distribution of values for the tests at Mintek is apparent. The average value of B determined from the results indicated in Table VI is 208 kWh/rev $\times 10^{-7}$, which is sufficiently close to the Mintek figure of 198 kWh/rev $\times 10^{-7}$ to justify the acceptance of the latter figure for the present purpose of the grindability test for fine materials.

The Grindability Test for Fine Materials

The proposed grindability test for fine materials indicates the specific energy needed to grind the material concerned from its original size to any specified size or sizes. Depending on the method of grinding to be used in the projected plant operation, the test can be conducted by simulated open-circuit or simulated closed-circuit grinding. As small ratios of reduction are frequently adequate for the regrinding of tailings and middlings, open-circuit grinding is often used in practice, and the description of a grindability test that follows is based on open-circuit grinding. However, it should be noted that a dry open-circuit grinding test should not be used when the amount of fines generated in the course of the test is enough to cause inefficient grinding.

The operating conditions that are specified for the Bond test with regard to the mill dimensions, mill speed, and ball load, also apply to the grindability test for fine materials. There may be some uncertainty with regard to the mass of material to be ground, but no serious error

TABLE VI

VALUE OF B (THE EQUIVALENT ENERGY PER REVOLUTION OF THE BOND TEST MILL) FROM PUBLISHED DATA[4]

Results for grind to minus 65 mesh (212 μm)

Sample no.	W_{im}	U % minus 65 mesh	B kWh × 10^{-7}/rev	Class into which B falls (as in Fig. 1)
1	16,3	21,7	199	6
2	11,8	21,0	214	8
3	12,0	31,4	248	11
4	13,0	18,5	205	7
5	11,8	18,4	208	7
6	16,4	12,1	174	4
7	17,8	17,8	186	5
8	12,5	21,4	213	8
9	16,9	22,6	205	7
10	17,3	15,0	186	5
11	11,7	20,8	215	8
12	13,8	19,1	200	7
13	21,8	13,6	167	3
14	13,6	11,0	183	5
15	14,5	17,8	196	6

Note: The values of B in the present work were calculated from the data in Bond's paper[4]

Classification of results (as in Fig. 1)

B class	3	4	5	6	7	8	11
Average B	167	174	185	197	204	214	248
No. of values	1	1	1	3	2	4	3
U average	13,6	12,1	14,6	19,8	19,7	21,1	31,4
W_{im} average	21,8	16,4	16,2	15,4	13,9	12,0	12,0
Average B for classes 5, 6, 7, and 8 = 208							

would be introduced if a mass equivalent to a packed bulk volume of 700 ml is used. However, it is preferable to determine the mass from the relative density of the material by a formula based on observations of the mass of material used in various Bond grindability tests:

$$\text{Mass (g)} = \frac{1300 \times \text{relative density}}{2,75}$$

$$= 473 \times \text{relative density.}$$

Calculation of Energy Required for Grinding

The energy needed to grind to x per cent minus 75 μm by open-circuit grinding is found as follows.

Several charges, each of the determined mass (m), in grams, are ground for several different numbers of revolution (r_1, r_2 . . .). From particle-size analyses of the ground products, the percentages of material smaller than 75 μm produced by r_1, r_2, . . . revolutions are found, and the number of revolutions needed to produce x per cent material smaller than 75 μm is estimated. If that number is N,

then m g of the desired product are obtained in N revolutions, and

10^6 g of the desired product would be obtained in $N/m \times 10^6$ revolutions.

Each mill revolution is equivalent to an energy input of 198×10^{-7} kWh. Therefore, the energy required to reduce 10^6 g to the desired size is

$$= \frac{198 \times 10^{-7} \times N \times 10^6}{m} \text{kWh}$$

$$= \frac{19,8 \times N}{m} \text{kWh.}$$

The specific energy thus found applies to open-circuit, wet grinding in a mill 8 ft (2,44 m) in diameter. For other conditions, the correction factors normally applied to calculations involved the Bond Work Index can be used.

If the energy for grinding in a closed circuit is required, the grindability test should be carried out by simulated closed-circuit grinding with a limiting screen to close the circuit, as is done in the Bond grindability test. Alternatively, but less reliably, the Bond open-circuit correction factors[2] can be applied to the results of an open-circuit grindability test.

The Validity of the Grindability Test for Fine Materials

The validity of the grindability test for fine materials can be demonstrated only by a comparison of plant data for the grinding of fine materials with the estimates of energy requirements indicated by the grindability tests. However, at the time when the work described here was done, only one source of suitable material and reliable plant data was available. To supplement that source, the grindability test was applied to the feed to the secondary mills of plants where two stages of grinding were employed, and where the primary mill was in open-circuit. The tests were conducted by open-circuit batch grinding, and the results were adapted to closed-circuit grinding by the use of correction factors[2]. The plant data and the results of the grindability tests are shown in Table VII.

TABLE VII

COMPARISON OF PLANT DATA WITH RESULTS OF THE GRINDABILITY TEST

Materials and origin	kWh/t Plant	kWh/t Grindability test for fine material
Gold ore, East Driefontein	14,4	14,8
Gold ore, Libanon	10,8	11,3
Gold ore, Western Deep Levels, VCR Reef	14,7	13,8
Gold ore, Western Deep Levels, Carbon Leader	17,6	16,4
Fluorspar, Chemspar	4,3	3,3
Copper-lead-zinc ore, Black Mountain	12,8	11,1
Copper-zinc ore, Prieska	13,6	12,8
Sand tailing, Crown Mines	9,3	9,3

The comparisons of energy consumptions are considered satisfactory in view of the several possible sources of error that exist, such as the accuracy of the samples and the plant data, the reliability of the correction factors, and the effect of pebble-mill, instead of ball-mill, grinding on some of the plants. Additional comparative data would be needed to establish the validity of the proposed test with greater certainty.