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A PROPOSED TEST FOR THE DETERMINATION OF THE GRINDABILITY OF FINE MATERIALS

by

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SYNOPSIS

The grindability of ores is generally determined by the Bond standard grindability test. However, this test is not applicable to fine materials such as sands; the grindability of fine materials must therefore be determined by a comparative grinding method, for which a reference material of known grindability is required. Suitable reference materials are not easily obtained, and a grindability test that does not depend on reference materials is needed. This report proposes such a test and records the results of some tests on the validity of the proposed method.

The proposed grindability test uses the Bond standard test mill and a quantity called the 'equivalent energy per minute', which is the energy per minute that would be used by the mill if it were scaled up to a wet-grinding industrial mill of 2,44 m (8 ft) diameter. The value of this quantity, denoted by E, was calculated from the results of Bond standard grindability tests on various materials, and an average value of 1425×10^{-6} kW·h/min was determined. It is suggested that values far removed from this figure indicate that the ores concerned do not conform to the Bond Law of Comminution.

The proposed grindability test was applied to seven samples of ore from industrial secondary grinding mills and to one sample of sand, and good agreement was found between the energy consumption calculated in the laboratory tests and those reported for the operating plants. The energy consumption calculated from the results of the Bond standard grindability test agreed fairly well with the plant data for the secondary grinding circuits, but the correlation for the primary grinding circuit was erratic.

SAMEVATTING

Die maalbaarheid van ertse word gewoonlik deur Bond se standaardmaalbaarheidstoets bepaal. Hierdie toets is egter nie op fyn materiaal soos sand van toepassing nie; die maalbaarheid van fyn materiaal moet dus deur 'n vergelykende maalmetode bepaal word waarvoor daar 'n verwysingsmateriaal met 'n bekende maalbaarheid nodig is. Geskikte verwysingsmateriale is nie maklik bekombaar nie en daar is 'n maalbaarheidstoets nodig wat nie van verwysingsmateriale afhanklik is nie. Hierdie verslag stel so 'n toets voor, en gee die resultate van sommige toetse om die geldigheid van die voorgestelde metode te bepaal, aan.

Die voorgestelde maalbaarheidstoets gebruik die Bond-standaardtoetsmeul en 'n grootheid wat die 'ekwivalente energie per minuut' genoem word wat die energie per minuut is wat die meul sal gebruik as dit volgens skaal vergroot sou word tot 'n industriële natmaal-meul met 'n diameter van 2,44 m (8 voet). Die waarde van hierdie grootheid, wat deur E aangedui word, is bereken aan die hand van die resultate van Bond-standaardmaalbaarheidstoetse met verskillende materiale en daar is 'n gemiddelde waarde van 1425×10^{-6} kW·h/min vasgestel. Daar word aan die hand gedoen dat waardes wat ver van hierdie syfer verwyder is, toon dat die betrokke ertse nie aan Bond se verpoeieringswet voldoen nie.

Die voorgestelde maalbaarheidstoets is toegepas op sewe ertsmonsters afkomstig van industriële sekondêre maalmeule en een sandmonster en daar was 'n goeie ooreenkoms tussen die energieverbruik wat in die laboratoriumtoetse bereken is en dié wat vir bedryfsaanlegginge gerapporteer is. Die energieverbruik wat aan die hand van die resultate van die Bond-standaardmaalbaarheidstoets bereken is, stem redelik goed ooreen met die aanlegdata vir die sekondêre maalkringe maar vir die primêre maalkring was die korrelasie wisselvallig.

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1. INTRODUCTION

The 'grindability' of a material indicates the energy required to reduce the material from one particular size to another. It can be expressed in different ways, the best known being the Bond[1] Standard Work Index (Wi), which purports to be the amount of energy required to reduce 1 t of material from infinite size to a d_{80} size of 100 μm. The Bond Standard Work Index is a well-established indicator of grindability and, in conjunction with the Bond Law of Comminution, is widely used in the estimation of the energy required for many crushing and grinding operations.

The Bond Work Index is determined by a standardized procedure in which the material is crushed in stages to finer than 6 mesh (3,35 mm), and ground under specified conditions in a laboratory ball mill, the Bond test mill. As the Bond grindability test starts with the reduction of the material to finer than 3,35 mm, it is applicable to materials that are initially fairly coarse but not to materials so fine that the specified products smaller than 3,35 mm cannot be prepared from them. For such materials, among which are sand-dump residues, calcines, and middling products from concentration processes, one must resort to a comparative grindability test in which the rate of grinding of the material to be tested (the unknown material), is compared with the rate of grinding of a material of known grindability (the comparative or reference material). The reference material should be similar to the unknown material in its physical properties, including its particle size, and should be derived from an industrial operation for which the energy used for grinding is known. Unfortunately, it is generally difficult for dependable reference samples to be obtained. This report describes a procedure for the estimation of the grindability of fine materials that is not dependent on a reference sample.

2. PRINCIPLES OF THE PROPOSED GRINDABILITY TEST FOR FINE MATERIALS

In a conventional comparative grinding test, the reference material and the unknown material are ground in a laboratory batch ball mill, and the times required for each material to be ground to the desired product size are determined. This information, together with that on the energy required for the grinding of the reference material, is then manipulated so that the energy required for the grinding of the unknown material can be estimated.

As part of the above procedure, the 'equivalent energy consumption per minute' (referred to in this report as *E*) of the laboratory test mill is determined indirectly, this quantity being the energy per minute that the test mill would use if it were the industrial mill that provided the reference sample. If the conditions for the laboratory grinding test are standardized, the mill will have the same value of equivalent energy for any material ground in it, provided that the industrial mills supplying the reference materials have the same efficiency. Standardized grinding conditions are part of the Bond standard grindability test, and the results of the Bond test are related to the energy consumption of a stipulated industrial grinding operation, namely one in which wet grinding is done in a ball mill of 2,44 m (8 ft) diameter. It is therefore convenient for one to adopt, with only a few necessary alterations, the conditions of the Bond standard test as the standard for a grindability test for fine materials; it then remains only for the value of *E* to be determined for the Bond test mill.

It should be noted that the objective in a grindability test for fine materials is not the determination of the Bond Work Index, because the relevance of the Index to materials such as sand-dump residues and plant middling products has not been established, and the use of the Index might lead to incorrect estimates; instead, the proposed test allows direct estimation of the energy required for the grinding of a given material to a specified size.

In preliminary work at the Council for Mineral Technology (Mintek) it was shown that several techniques can be used for the determination of *E*, but that considered to be the most practicable is based directly on the results of a Bond standard grindability test. A value for *E* can be calculated from the results of any Bond test, as is shown in the Appendix. Table I gives the values of *E* calculated from the results of 66 of the large number of tests done at Mintek over a considerable length of time; histograms of the distribution of the values are shown in Figure 1.

It can be seen that there is a marked concentration of values between 1300×10^{-6} and 1550×10^{-6} kW·h/min. This 'core' of values is flanked by two isolated low values and a thin 'string' of high values. The distribution shown could be taken as a continuous distribution skewed away from the high values, but it is considered preferable for the values in the core to be regarded as normal and for the others to be regarded as abnormal or errant values because *E* should have a constant value, apart from variations that result from experimental errors. Explanations for the errant values have not yet been established, but the following appear plausible.

TABLE 1

Estimation of E, *the equivalent energy consumption per minute, from the results of Bond standard grindability tests*

Mintek sample no.	Description or source	Feed d_{80} size µm	Limiting screen µm	Product d_{80} size µm	G (net undersize produced per revolution) g	U (undersize in feed) %	Bond Work Index kW·h/t	E (kW·h/min) × 10^{-6}
G819	St Helena Gold Mine	2690	54	41	0,66	4,4	21,0	1390
		2690	76	63	0,90	6,7	19,4	1420
		2690	108	91	1,17	7,6	18,1	1370
		2690	140	125	1,52	9,3	16,8	1360
		2690	208	187	2,21	11,4	15,0	1430
		2690	300	253	2,75	17,6	14,1	1420
H826	Black Reef ore (Blyvooruitzicht)	2700	75	65	0,10	8,5	18,2	1420
		2700	150	134	1,73	13,8	15,5	1490
		2700	212	181	2,30	16,1	14,0	1470
		2700	300	241	2,70	19,2	13,8	1425
H679	Karoo prospect	2570	212	166	1,57	19,4	18,1	1460
		2570	297	216	1,63	22,0	19,5	1410
		2570	540	395	1,98	27,5	22,9	1390
64378	Cape uranium ore	2470	105	88	1,69	11,9	13,2	1480
		2470	150	128	2,33	17,1	11,5	1530
		2470	297	220	3,45	26,3	10,7	1720
H133	Antimony ore (Gothic Mine)	2500	208	178	2,06	14,8	15,2	1450
H137	Chromite ore (Pandora Mining Company)	2240	140	130	2,89	27,0	10,9	1990
H55	Chromite ore (Zimbabwe)	2330	540	397	3,54	35,7	14,8	1690
H135	Antimony ore	2320	208	174	1,94	18,8	15,9	1450
OD613/2	Dolerite	2800	297	200	0,92	9,1	29,9	1090
OD613/1	Carbonatite	2900	297	237	3,99	16,0	9,7	1470
H434	Fluorspar ore (Chemspar)	1870	208	177	4,26	29,8	8,9	1980
H700	Bentonite (crude)	2670	53	16	0,83	5,2	10,3	1440
–	Limestone	2140	300	257	5,29	15,6	10,6	1930
–	Manganese ore	1620	106	76	1,12	5,5	17,4	1370
J179	Manganese ore	1870	106	82	1,13	12,9	18,3	1370
J180	Manganese ore	2490	106	82	1,03	5,1	18,9	1300
J181	Manganese ore	2470	106	80	1,18	6,5	16,7	1370
J182	Manganese ore	2620	106	78	1,31	7,2	15,1	1360
J47	Fluorspar ore (Zeerust)	2100	150	130	3,92	21,4	8,1	1860
		2100	106	85	2,66	17,0	9,1	1770
		2100	75	63	2,01	14,6	10,2	1800
H43	Synthetic magnetite	2520	75	63,5	1,10	4,3	17,3	1410
		2520	54	47	0,8	3,1	20,2	1420
		2520	45	41	0,70	2,7	22,0	1400
H72	Nickel ore	2520	297	222	1,72	20,2	19,1	1360
		2590	208	170	1,60	17,8	18,1	1410
		2590	140	113	1,28	14,9	18,3	1430
EM122	Uranium ore	2300	150	125	1,57	15,3	16,4	1490
		2300	106	85	1,22	13,4	17,6	1500
		2300	75	66	1,07	11,5	17,6	1520
J234	Dolomite (Glen Douglas)	2350	540	462	2,69	28,6	21,4	1390
		2350	212	168	1,90	16,7	15,8	1390
		2350	150	118	1,76	14,3	14,4	1460
J128	Calcined flint clay	2370	212	184	1,26	4,1	23,5	1150
G678	Black Mountain ore	2350	76	61	1,03	10,2	17,2	1480
			140	127	2,05	17,4	13,7	1610
			440	312	4,26	33,5	11,7	1890
G980	Black Mountain ore	2570	74	68	1,02	6,3	18,4	1440
			85	78	1,18	8,3	17,2	1440
			108	91	1,37	9,0	16,2	1450
G874	Black Mountain ore	2520	76	66	1,08	6,8	17,3	1440
		2520	85	80	1,33	8,2	15,9	1480
		2520	108	89	1,53	11,9	14,4	1510
		2520	140	128	2,21	11,6	12,2	1480
J161	Black Mountain ore	2380	106	92			15,3	1570
J434	Black Mountain ore	2170	90	77	1,25	14,6	16,9	1550
J290	East Driefontein Gold Mine	2080	106	89,5	1,10	16,2	18,5	1432
J365	Libanon Gold Mine	2500	106	73	1,02	7,1	17,8	1329
J392	Western Deep Levels VRC circuit	2490	90	76	0,93	9,8	20,4	1398
J388	Western Deep Levels Carbon Leader circuit	2380	90	78	1,00	8,7	19,7	1400
J420	Fluorspar (Chemspar)	1540	106	81	2,40	15,5	9,6	1700
J537	Copper–zinc–pyrite ore (Prieska)	2300	106	81	1,25	12,6	16,2	1463
J741	Merensky Reef ore (Western Platinum)	2070	106	81	0,99	9,6	19,9	1356
J769	Ferrochromium	2200	63	55	0,67	5,1	24,2	1353

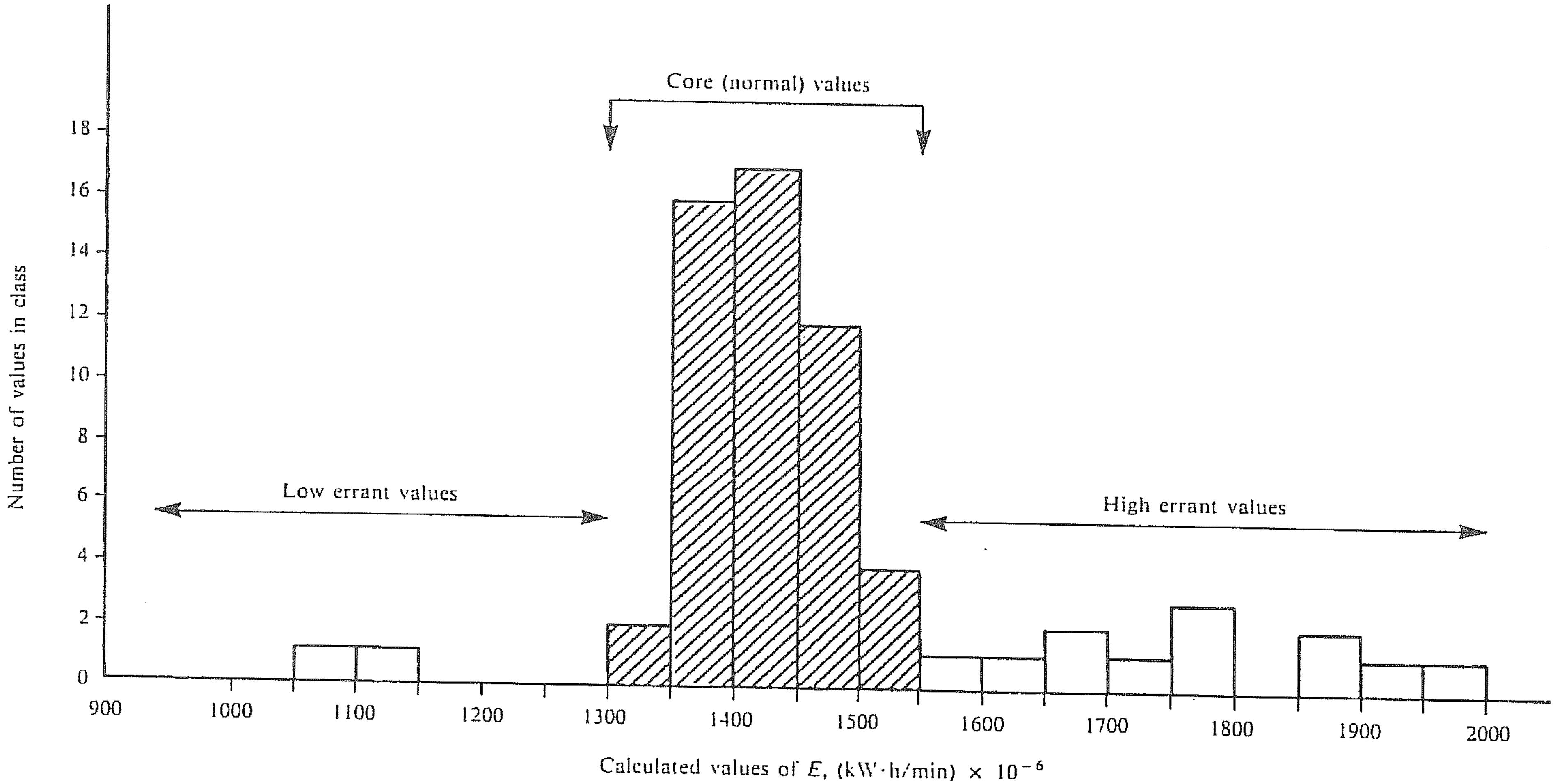

FIGURE 1. Distribution of values of E calculated from results of Bond standard grindability tests

The two low values of E were obtained in tests on sample J128, a calcined flint clay, and sample OD613/2, a dolerite. These two samples were extremely hard, and it is possible that the standard ball charge used in the Bond test is not suited to the grinding of such hard materials. The Bond Work Indices obtained were therefore higher than they should have been, and not in conformity with the energy that would be needed in practice for the grinding of the two materials concerned. (It is well known that the size of the grinding balls used must be increased for hard and for coarse materials.)

The high values for E were obtained for the materials listed in Table 2.

TABLE 2

Materials for which high values of E *were obtained*

Mintek sample no.	Description or origin	Bond Work Index kW·h/t	E (kW·h/min) × 10^{-6}
H55	Chromite (Zimbabwe)	14,9	1690
H137	Chromite (Pandora)	10,9	1990
G678	Black Mountain ore	13,7	1610
	Black Mountain ore	11,7	1890
J161	Black Mountain ore	15,3	1570
J434	Black Mountain ore	16,9	1550
J747	Fluorspar (Chemspar)	8,1	1860
H434	Fluorspar (Chemspar)	8,9	1980
J747	Fluorspar (Chemspar)	9,1	1770
J420	Fluorspar (Chemspar)	9,6	1700
J747	Fluorspar (Chemspar)	10,2	1800
Limestone	Limestone	10,6	1930

The high errant values of E appear to be associated to some extent with softer ores and, more markedly, with specific types of ore, notably fluorspars from the western Transvaal, some chromite ores, and some of the ores from the concentrator at the Black Mountain Mine. These errant values of E might indicate that the Bond Law of Comminution does not apply to these materials. In illustration, the Bond Law equates the energy used for comminution to an inverse function of the product size raised to the power 0,5, and the power index for different materials has been found[1] to vary between 0,2 and 1,4.

If the errant values of E are in fact associated with materials whose comminution behaviour departs from the Bond Law, they would serve as an indication that a correction factor should be introduced when the Bond Work Index is used in the estimation of the energy required for grinding. (Correction factors are a normal concomitant of the application of the Bond Work Index[2].)

Although explanations for the errant values of E have not yet been established, it was decided that only the values in the core of the distribution should be used, and an average value of 1425×10^{-6} kW·h/min was calculated. This value of E converts dry grinding in the Bond test mill to wet grinding in a mill of 2,44 m (8 ft) diameter. The correction factors used in the application of the Bond Law can also be used in calculations involving mills of other diameters, allowances for dry grinding, and variations in the circulating load.

3. DESCRIPTION OF THE PROPOSED GRINDABILITY TEST FOR FINE MATERIALS

3.1. Open-circuit Grinding

The procedure is illustrated by the following example.

For the estimation of the energy required for the grinding of material from a sand dump to z per cent finer than 75 μm in a wet open-circuit ball mill, the laboratory grindability test is done in the Bond standard grindability test mill with its specified ball load and at its specified rotational speed. The charge for the Bond grindability test is defined as 700 ml of the material reduced to finer than 3,35 mm but, for fine materials, the mass (m) of the charge for the proposed grindability test is determined from the relative density (r.d.) of the material as follows:

$$\text{Charge} = \frac{1300 \times \text{r.d.}}{2{,}7}\ \text{grams}$$

$$= 480 \times \text{r.d.} = m\ \text{grams.}$$

(A typical mass observed in Bond standard grindability tests on material of relative density 2,7 is 1300 g.)

Portions of the sample submitted for the grindability test, each of mass m, are ground in the Bond mill for various times, e.g. 3, 5, 10, and 15 minutes. As an exact mill speed of 70 r/min cannot be ensured, it is advisable for the grinding times to be estimated from the number of revolutions of the mill. A particle-size analysis is done on each product to give the percentage of material smaller than 75 μm achieved for each grinding time. The grinding time, t minutes, required for the specified size of z per cent passing 75 μm to be attained is then determined from a graph of grinding time against the percentage of material smaller than 75 μm attained.

From the above, it can be calculated that, if

m grams of material is reduced to z per cent passing 75 μm in t minutes,

10^6 g of material is reduced to z per cent passing 75 μm in $\frac{t}{m} \times 10^6$ min.

$$\text{The energy consumed in this time} = \frac{t}{m} \times 10^6 \times E\ \text{kW·h}$$

$$= \frac{t}{m} \times 10^6 \times 1425 \times 10^{-6}\ \text{kW·h/t}$$

$$= \frac{t \times 1425}{m}\ \text{kW·h/t.}$$

3.2. Closed-circuit Grinding

The energy required for closed-circuit grinding can be estimated from the results of laboratory grinding tests using a circulating load, as is done in the normal Bond standard grindability test. In each test, the circuit is closed by a screen. As each test must be continued through several cycles to attain steady-state conditions, the procedure is clearly laborious. However, it is considered that open-circuit grinding tests can be done as described above, and that, for many materials, the estimate of the energy required for open-circuit grinding can be converted to that required for closed-circuit grinding with little loss in accuracy by the introduction of a conversion factor. Values for the conversion factor have been published[3], the factor 0,9 being recommended when the product size is 70 per cent finer than 75 μm.

Although it was considered that there is a need for an independent estimate of the conversion factor, it was decided that the figure of 0,9 would be accepted in the present investigation, even when the product size was not 70 per cent passing 75 μm because, in most instances, the resulting error would be small.

4. THE VALIDITY OF THE PROPOSED GRINDABILITY TEST FOR FINE MATERIALS

For an assessment of the validity of the proposed grindability test for fine materials, samples of materials from operating plants were obtained, together with information from the plants on the energy used in the grinding of these materials. In one instance, samples of the feed to a ball mill treating material from a sand cyanidation residue were obtained; in all other instances, the samples were the feed and product of a primary mill, and the product of the secondary grinding circuit. Although the laboratory grindability tests were aimed primarily at the estimation of the energy used by the secondary mills, the additional data were used in an assessment of the correlation between estimates based on the results of the Bond standard grindability test and plant data. The plant data, the results of the Bond standard grindability tests on the primary mill feeds, and the results of the grinding tests on the primary mill products are shown in Table 3.

The particle size of the plant products shown in Table 3 was determined on all the samples provided by the various plants except those provided by the two Western Deep Level plants, for which the samples of the final products were exceptionally fine; the sizes recorded in the table for those samples are the figures quoted for the plant operations at the time. It should also be noted that the pebbles added to pebble mills are included in the total tonnage milled, and that the estimates of energy consumption recorded in the table do not include corrections that might be made for differences in circulating loads and mill diameters because in most instances, such corrections would be relatively small.

The information in Table 3 that relates to the secondary grinding operations is summarized in Table 4.

TABLE 3

Energy required for grinding: comparison of plant data, estimates based on the Bond Work Index, and the results of the proposed grindability test

Source of samples	East Driefontein	Libanon	Western Deep Levels VCR Section	Western Deep Levels Carbon Leader Section	Chemspar fluorspar concentrator	Black Mountain concentrator (Cu, Pb, Zn)	Prieska concentrator (Cu, Zn)	Rand Mines sand project
Mintek sample no.	J290, J291, J292	J365, J366, J367	J392, J393, J394	J388, J389, J390	J420, J421, J417	J434, J435, J436	J537, J538, J539	J600
Grinding circuit	Rod mill and pebble mill	Ball mill and pebble mill	Ball mill and pebble mill	Ball mill and pebble mill	Rod mill and ball mill	Rod mill and ball mill	Rod mill and pebble mill	Open-circuit ball mill (12 ft dia.)
Plant products								
Primary mill feed, d_{80} size, μm	12 000	11 600	10 500	11 000	10 000	10 400	30 500	6,8 (mill feed)
Primary mill product, % <75 μm	17	28,5	26	22,5	26,6	14,0	17,5	
Secondary mill: final product d_{80} size, μm	1 200	545	1 020	1 000	1 000	570	2 060	
Secondary mill: final product % <75 μm	71	70	70	79	56,6	72,8	73,9	45 (mill product)
Secondary mill: final product d_{80} size, μm	90	102	102	80	140	93	88	
Plant energy consumption, kW·h/t								
Primary mill	3,5	7,2	6,2	5,4	4,1	2,8	2,9	
Secondary mill	14,4	10,8	11,0	14,1	4,3	12,8	13,6	9,3
Bond standard grindability test								
Feed size, d_{80} size, μm	2 080	2 500	2 490	2 380	2 160	2 170	2 300	
Product size, d_{80} size, μm	90	73	76	78	81	77	81,5	
Work Index, kW·h/t	18,5	17,8	20,4	19,7	9,55	14,6	16,2	
Proposed grinding test (to simulate secondary grinding)								
Mass of charge, g	1 350	1 232	1 308	1 280	1 356	2 019	1 662	1 207
Grinding time to produce final product, min	16	11,2	11,75	15	3,4	18,3	17,5	8,8
Calculated energy consumption kW·h/t	14,6	11,6	11,5	15,0	3,6	11,6	13,5	10,35
Energy consumption calculated from Bond Work Index, kW·h/t								
Primary mill	3,66	5,96	4,39	4,35	2,06	4,7	2,6	
Secondary mill	14,15	10,06	13,81	15,80	5,05	9,0	13,7	

E = t(min) x 1425

TABLE 4

Energy consumption in secondary mills, (kW·h/t)—summarized results

Source of samples	Plant data	Calculated from proposed grindability test for fine materials	Calculated from Bond Work Index
East Driefontein Gold Mine	14,4	14,6	14,15
Libanon Gold Mine	10,8	11,6	10,0
Western Deep Levels Gold Mine, VCR Section	11,0	11,5	13,8
Western Deep Levels Gold Mine, Carbon Leader Section	14,1	15,0	15,8
Chemspar fluorspar concentrator	4,3	3,6	5,05
Black Mountain: copper–lead–zinc concentrator	12,8	11,6	9,0
Prieska: copper–zinc concentrator	13,6	13,5	13,7
Rand Mines sand project	9,3	10,4	–

In view of the difficulties one has in obtaining reliable samples and operational data from plants, the correlation between the energy consumption on the plants and the estimates based on the results of the proposed grindability test for fine materials is considered to be very satisfactory. Also worthy of note is the generally good agreement between the plant data and the estimates based on the results of the Bond test. This agreement is possibly not as close as that between the plant data and the results of the proposed grindability test, but the amount of information presented is not sufficient for a firm conclusion to be drawn.

5. CONCLUSIONS AND RECOMMENDATIONS

The correlation between the data from operating plants and estimates based on the results of the proposed grindability test are surprisingly good in view of the numerous possibilities for error. The continued use of the test is therefore justified. However, for the development of full confidence in the test, a considerable amount of additional work is needed, as follows.

(i) More comparisons between plant data and estimates based on the results of the proposed grindability test should be made.

(ii) The correction factors for the conversion of estimates for open-circuit grinding to estimates for closed-circuit grinding (and *vice versa*) should be determined.

(iii) Explanations for the errant values of E should be sought.

(iv) The relationship between wet grinding and dry grinding and the possible limitations on dry-grinding tests should be investigated.

Further experimental work in connection with the value of E could contribute considerably to the correct application of the Bond standard grindability test and to the establishment of a test procedure for the grindability of fine materials that could be accepted as a standard test.

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APPENDIX

THE CALCULATION OF *E*, THE EQUIVALENT ENERGY CONSUMPTION PER MINUTE, FROM THE RESULTS OF A BOND STANDARD GRINDABILITY TEST

1. DATA

Material for test	Witwatersrand gold ore, sample G819
Nature of test	Bond standard grindability test with 75 μm limiting screen
Feed d_{80} size (F)	2690 μm
Product d_{80} size (P)	63 μm
Net undersize produced per revolution (G)	0,90 g
Undersize in feed (U)	6,7 per cent
Bond Work Index (Wi) determined	19,4 kW·h/t.

2. CALCULATION

G, the net undersize produced per revolution, is converted to gross grams of undersize produced per minute (GGM):

$$\text{GGM} = \frac{G \times 70 \times 100}{100 - U} = 67{,}5;$$

that is, in the Bond test mill GGM grams of product are produced per minute. Therefore, 10^6 grams (1 t) of product are produced in $\frac{10^6}{\text{GGM}}$ minutes. But, from the Work Index determined, the energy required for the reduction of the material from size F to size P in an industrial ball mill is

$$W = 10\ \text{Wi}\left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}}\right)$$

$$= 10 \times 19{,}4 \times \left(\frac{1}{\sqrt{63}} - \frac{1}{\sqrt{2640}}\right)$$

$$= 20{,}7\ \text{kW·h/t}.$$

Therefore $\frac{10^6}{\text{GGM}}$ minutes of grinding in the Bond test mill $\equiv$ 20,7 kW·h, or

1 minute of grinding in the Bond test mill $\equiv 20{,}7 \times 10^{-6} \times \text{GGM}$,

i.e. $E = 1400 \times 10^{-6}$ kW·h/min (for this example);

or, in general terms,

$$E = \frac{70\,000 \times G \times \text{Wi} \times \left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}}\right) \times 10^{-6}}{100 - U}\ \text{kW·h/min}.$$

An alternative expression is obtained as follows. For the calculation of the Work Index from the Bond standard grindability test,

$$\text{Wi} = \frac{4{,}45 \times 1{,}1}{P^{0{,}22} \times G^{0{,}82}\left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}}\right)}.$$

Therefore

$$E = \frac{70\,000 \times G \times 4{,}9 \times \left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}}\right) \times 10^{-6}}{(100 - U) \times P^{0{,}22} \times G^{0{,}82}\left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}}\right)}$$

$$= \frac{70\,000 \times 4{,}9 \times G^{0{,}18} \times 10^{-6}}{(100 - U) \times P^{0{,}22}}$$

$$= \frac{343\,000 \times G^{0{,}18} \times 10^{-6}}{(100 - U) \times P^{0{,}22}} \text{ kW} \cdot \text{h/min.}$$