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Indicators of grindability and grinding efficiency

by J. Levin*

SYNOPSIS

Bond's Standard Work Index (SWi) indicates the grindability of an ore, and his Operating Work Index (OWi) indicates the performance of a grinding mill or circuit. The comparison of the two indices offers a measure of the efficiency of the grinding operation. Mill (or circuit) performance, particularly on the Witwatersrand, is often indicated by the index kilowatt-hours per tonne of minus 75 μm material produced (kWh/t minus 75 μm or OE_{75}). The paper shows that a standard kWh/t minus 75 μm index (SE_{75}) can be obtained from the standard Bond grindability test (which provides the SWi), and asks whether the two E_{75} indices can be used in the various ways in which the two Work Indices are used. For the answer, the paper presents averaged values for the standard grindability indices of the gold ores of the Witwatersrand, averaged values for the performance of grinding mills operating on those ores, and the results of laboratory grinding tests on a composite of several Witwatersrand ores.

The particle-size indicator for the calculation of the Wi indices, the d_{80} size, is constant in its relation to the largest particles present, whereas the percentage minus 75 μm, the indicator of size for the E_{75} index, varies with the degree of grinding in its relation to the size of the largest particles. Because of this difference, the standard Work Index increases as the grind becomes finer, whereas the standard kWh/t minus 75 μm value decreases. The Wi and E_{75} indices nevertheless serve similar purposes when applied to moderately fine grinding—finer than 70 per cent minus 75 μm.

Open-circuit laboratory grinding tests revealed three stages in the grinding process, and credible values for the open-circuit Work Index were obtained only from the second stage. The conversion of the open-circuit Work Indices to the equivalent of closed-circuit indices by the application of Bond's open-circuit inefficiency factor (a constant for grinds indicated by the d_{80} size) was of limited success; however, the development of a conversion factor related to particle-size should not be difficult.

Initially difficulty was experienced in the calculation of the OE_{75} indices from the results of the laboratory tests, but it was eventually considered that a constant value of the index derived from the results would be close to the true open-circuit index. The open-circuit grinding test could therefore be a convenient method for the detection of differences in the grindability of ores.

SAMEVATTING

Bond se Standaardwerkindeks (SWi) dui die maalbaarheid van 'n erts aan, en sy Bedryfswerkindeks (OWi) die werkverrigting van 'n meul of 'n maalkring. Die vergelyking van die twee indekse bied 'n maatstaf van die doeltreffendheid van die maalbewerking. Meul-(of kring-)werkverrigting word dikwels, veral aan die Witwatersrand, aangedui deur die indeks kilowatt-uur per ton materiaal kleiner as 75 μm geproduseer (kWh/t minus 75 μm of OE_{75}). Die referaat toon dat 'n standaard kWh/t minus 75 μm-indeks (SE_{75}) aan die hand van Bond se standaardmaalbaarheidstoets (wat die SWi gee) bepaal kan word, en vra of die twee E_{75}-indekse soos die twee werkindekse op verskillende maniere gebruik kan word. As antwoord gee die referaat gemiddelde waardes vir die standaardmaalbaarheidsindekse van die goudertse van die Witwatersrand, gemiddelde waardes vir die werkverrigting van meule wat daardie ertse bewerk en die resultate van laboratoriummaaltoetse met 'n saamgestelde monster van verskeie Witwatersrandse ertse.

Die partikelgrootteaanwyser vir die berekening van die Wi-indekse, die d_{80}-grootte, is konstant wat betref sy verhouding tot die grootste aanwesige partikels, terwyl die persentasie kleiner as 75 μm, die grootteaanwyser vir die E_{75}-indeks, wat sy verhouding tot die grootte van die grootste partikels betref, wissel volgens die maalgraad. Vanweë hierdie verskil neem die standaardwerkindeks toe namate daar fyner gemaal word, terwyl die standaard kWh/t minus 75 μm-waarde afneem. Die Wi- en E_{75}-indeks dien nietemin dieselfde doel wanneer dit op matig fyn maling—fyner as 70 persent kleiner as 75 μm—toegepas word.

Oopkringlaboratoriummaaltoetse het drie stadiums in die maalproses getoon en geloofwaardige waardes vir die oopkringwerkindeks is slegs van die tweede stadium verkry. Die omrekening van die oopkringwerkindekse na die ekwivalent van toekringindekse deur die toepassing van Bond se oopkringondoeltreffendheidsfaktor ('n maalkonstante wat deur die d_{80}-grootte aangedui word) was in 'n beperkte mate geslaagd; die ontwikkeling van 'n omrekeningsfaktor wat met die partikelgrootte verband hou, behoort egter nie moeilik te wees nie.

Daar is aanvanklik probleme ondervind met die berekening van die OE_{75}-indekse aan die hand van die laboratoriumtoetse, maar daar is uiteindelik besluit dat 'n konstante waarde van die indeks wat van die resultate verkry is, na aan die ware oopkringmaaltoets sal wees, en dus 'n gerieflike metode vir die opsporing van verskille in die maalbaarheid van ertse kan wees.

GRINDABILITY AND MILL-CIRCUIT EFFICIENCY

The efficiency of a grinding mill or a grinding circuit is an elusive concept, and there is no generally accepted method for its determination. A method that can be resorted to is based on the use of the two Bond Work Indices: the Standard Work Index (SWi) and the Operating Work Index (OWi). The SWi, which is determined in the laboratory, is a measure of the grindability, or combined hardness and toughness, of the material to be ground. The OWi is a measure calculated from plant operating data, and depends both on the grindability of the material and the efficiency of the grinding mill (or grinding circuit). A comparison of the two indices provides a measure of the efficiency of the grinding mill (or circuit) and the value of SWi/OWi x 100 can be taken as its percentage efficiency.

Where the SWi and OWi are equal, the performance of the mill is equal to the average performance of the mills observed by Bond when he developed his standard

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grindability test. Instances where the OWi is less than the SWi, i.e. where the mill efficiency exceeds 100 per cent, are therefore not precluded.

Many operators, notably those engaged in treating the gold ores of the Witwatersrand, make use of the index kilowatt-hours per tonne of minus 75 µm material produced (OE_{75}) in comparing the performance of mills treating the same or similar ores and in designing new mills. Like the OWi, the OE_{75} is a function of both the efficiency of a mill and the grindability of the material. An estimate of the efficiency of a mill can be obtained from a comparison of the OE_{75} with the grindability of the material concerned as determined in a standard laboratory test that would provide a standard measure of kWh/t of minus 75 µm material produced (SE_{75}). The percentage efficiency of a mill can then be expressed by $Se_{75}/OE_{75} \times 100$. So far, no standard test for the determination of the SE_{75} has been devised, but all the data needed for its calculation are provided by the Bond standard grindability test. The calculation makes use of the information obtained previously[1] that the 'equivalent' energy consumption per revolution of the Bond grindability test mill is 198×10^{-7} kWh. (Equivalent energy consumption is the energy per tonne of product that would be used in a mill of diameter 2,44 m grinding wet with a circulating load of 250 per cent. An example of the calculation is shown in Table I.

The Bond standard grindability test is well known and widely used, and it therefore seems reasonable for it also to be used in the determination of the standard index SE_{75}.

With the availability of a method for the determination of the SE_{75}, it may be possible to use the SE_{75} and OE_{75} indices in the same way as the two Bond work indices are used, and it becomes of interest to ask whether the E_{75} indices provide the same information as the Bond indices; whether one type of index is more accurate or more useful than the other; whether there are limitations to the E_{75} indices similar to those to the Bond Wi indices. Information on these questions is presented here from work done on Witwatersrand gold ores. However, the principles relating to the use of the Wi and E_{75} indices should be generally applicable, i.e. applicable also to other ores and to product sizes other than the percentage of minus 75 µm material.

The information presented here comprises

(a) values for the SWi and SE_{75} from Bond standard grindability tests

(b) values for the OWi and OE_{75} from a survey of milling practice on the Witwatersrand[2]

(c) laboratory batch closed-circuit and open-circuit grinding tests.

Table I

Calculation of the SE_{75} index from a Bond standard grindability test

Source of data: Bond grindability test on an ore from Blyvooruitzicht

Limiting screen aperture		150 µm
Feed:	% −150 µm	13,8 (U)
	% −75 µm	8,0 (F_{75})
Product:	% −75 µm	47,7 (P_{75})
Net undersize per revolution		1,73g (G)

Calculation:

$$\text{Total undersize per revolution} = \frac{1,73 \times 100}{100 - 13,8}$$

$$= 2,01$$

Revolutions required to produce 1 t of undersize = $2,01 \times 10^6$

Equivalent energy consumption of the test mill = 198×10^{-7} kWh per revolution

$$\text{Equivalent energy to obtain 1 t of undersize} = 10^6 \times \frac{198 \times 10^{-7}}{2,01}$$

$$= 9,89 \text{ kWh}$$

9,89 kWh increases the percentage −75 µm from 8,0 to 47,8, i.e. it produces 0,478 − 0,080 = 0,398 t of −75 µm material.

$$\text{To produce 1 t of −75 µm material would require } \frac{9,89}{0,398} = 24,8 \text{ kWh},$$

$$\text{i.e. } SE_{75} = \frac{19,8 \times (100 - U)}{G\,(P_{75} - F_{75})} \text{ kWht/t of minus 75 µm produced.}$$

WORK INDICES FROM BOND STANDARD GRINDABILITY TESTS

The Bond grindability tests done at Mintek in the period between 1975 and 1985[1] included a considerable number on Witwatersrand gold ores. Grindabilities were expressed as Standard Work Indices, and the data obtained have since been used in the calculation of the SE_{75}.

Table II

Variation of SWi and SE_{75} with the aperture of the limiting screen (averages of data from standard grindability tests)

Limiting screen aperture, µm	d_{80}, µm	SWi kWh/t	−75 µm material, %	SE_{75}
300	243	13,4	28,3	27,8
212	178	14,5	35,3	26,6
150	126	16,0	50,5	24,8
106	84	16,6	73,4	23,1
75	62	18,1	–	–

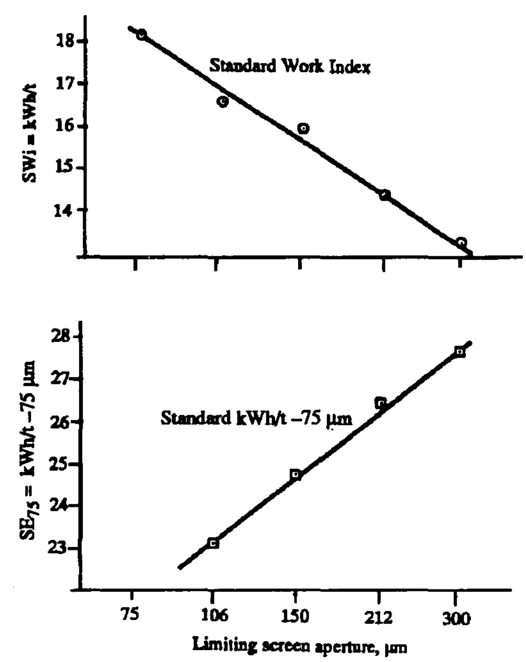

Figure 1—Variation of standard grindability indices with the aperture of the limiting screen

The averages of the results of tests with limiting screens of various apertures are shown in Table II and illustrated in Figure 1. Both indices vary with the degree of grinding employed but, whereas the SWi increases as the grind becomes finer, the SE_{75} decreases. If the increase is interpreted as indicating that the ore becomes 'harder' as the particle size decreases, it would be wrong to conclude that the E_{75} index shows an opposite effect. The explanation for the apparent anomaly is that the two indices are based on single but very different parameters (d_{80} size and percentage minus 75 µm) to indicate the 'size' of the products of grinding. The difference is illustrated in Figure 2, which shows a typical curve for the particle-size distribution resulting from grinding in a circuit closed by a screen.

It is seen that the d_{80} size is always close to, but less than, the aperture of the limiting screen, which is also the size of the largest particles in the product. However, the point indicating the percentage of minus 75 µm material varies in relation to the aperture of the limiting screen and the d_{80} size indicator: it is close to the d_{80} size indicator for a fine limiting screen (e.g. 106 µm), and the percentage of minus 75 µm material is then large. As the aperture of the limiting screen increases, the indicator of the percentage minus 75 µm moves downward along the curve. For a screen aperture of 300 µm, for example, the percentage minus 75 µm indicator is far removed from the d_{80} size indicator, and this leads to a small value for the percentage minus 75 µm, and a consequent high value for the E_{75} index.

The Wi and E_{75} indices evidently give somewhat different information. The Wi index relates to the energy required to reduce the size of the largest particles in the feed, whereas the E_{75} index relates to the energy needed to increase the minus 75 µm material, i.e. the amount of fines, and it gives no direct information on the grindability of the possibly large proportion of coarse material that may be present in the feed to the grinding operation and in the product. For coarse grinding, such as the primary grind in a two-stage circuit, the size and amount of large particles in the product are the main concern, and the Work Index is then directly relevant to any calculations that may be required; on the other hand, the significance of the E_{75} is uncertain. It is only for fine grinding, where the final product contains a large proportion of minus 75 µm material that the SE_{75} value is significant. In general, the limiting screen for a standard grindability test should be selected to give an undersize product that is fairly close to the particle size expected in the plant operation concerned; the results of tests that give products far removed from those desired in the plant operation may be misleading.

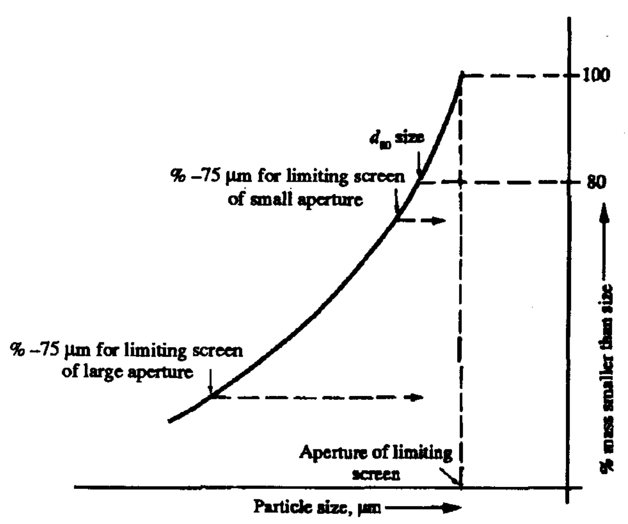

Figure 2—Varying relationship between d_{80} size and % -75 µm in standard grindability tests

OPERATING INDICES FROM PLANT DATA

Powell[2] carried out a survey of the grinding mills and grinding circuits used in the grinding of Witwatersrand gold ores. The information on 53 grinding circuits was analysed to give averages that provided an overall picture of the types of mills and circuits in use, their performance, and the wear of liners and grinding media.

The primary purpose of the survey was an examination of the wear of liners and grinding media, but the information obtained on the performance of the mills and grinding circuits also bears on the subject of this paper, particularly on the questions of whether the E_{75} index determined from plant data serves the same purpose as the Operating Bond Work Index, and whether the information in the survey can be used in comparisons of the efficiencies of several grinding circuits, or in evaluations of efficiencies in relation to standard indices determined in the laboratory.

Of the various types of grinding circuits dealt with, only three provided sufficient examples of application to justify the calculation of averages. These three circuits accounted for 81 per cent of the individual circuits featuring in Powell's report, and they are the only ones that are considered here. The circuits are as follows:

(1) primary grinding in open-circuit rod mills with secondary grinding in closed-circuit pebble mills (referred to as Circuit 1)

(2) primary grinding in closed-circuit ball mills with secondary grinding in closed-circuit pebble mills (referred to as Circuit 2)

(3) single-stage grinding of run-of-mine ore or, because balls were added to assist the grinding in nearly all instances, semi-autogenous (SAG) grinding (referred to as Circuit 3).

The extensive information obtained on the performance of the mills and circuits is summarized and presented as averages in Table III.

It can be seen that, for the two circuits that employ two stages of grinding, the primary grind accounts for a relatively small proportion of the total energy consumption (17 and 31 per cent for Circuits 1 and 2 respectively). The overall performance is therefore determined largely by the performance of the secondary mills, i.e. the pebble mills.

Because the ores used in the three circuits were similar, the OWi and OE_{75} values indicate the relative efficiency of each circuit. The two indices agree in ranking Circuit 1 as the most efficient and Circuit 3 as the least efficient, and also show that the efficiencies of Circuits 1 and 2 are fairly close to each other.

The efficiencies of the three circuits can also be assessed by the evaluation of the performance of each circuit against the SWi and SE_{75} indices. Table II shows that the average

Table III

Performance of Witwatersrand grinding circuits (after Powell[2])—average values calculated from data in the work cited

	Circuit 1			Circuit 2			Circuit 3
	Rod mill primary, pebble mill secondary			Ball mill primary, pebble mill secondary			Semi-autogenous grinding
	Rod mill	Pebble mill	Overall	Ball mill	Pebble mill	Overall	
% –75 μm Feed	2,7	16,8	2,7	3,3	30,6	3,3	2,4
Product	16,8	72,7	72,7	30,6	74,9	74,9	74,8
kWh/t	3,5	15,4	18,4	6,8	13,4	19,8	23,6
kWh/t –75 μm (OE)	25,2	27,8	26,2	25,8	30,3	27,6	32,5
d_{80} μm Feed	12 700	945	12 700	10 200	366	10 200	111 000
Product	945	89	89	366	87	87	90
Reduction ratio*	13,4	10,6	143	27,8	4,2	117	1 233
Operating work index (OWi) kWh/t	16,2	21,3	19,2	15,3	26,5	20,3	22,4
% of total energy used in primary grind			17			31	

$$\text{* Reduction ratio} = \frac{d_{80} \text{ of feed}}{d_{80} \text{ of product}}$$

Note: The OWi and OE_{75} indices were not corrected for variations in mill diameters or circulating loads because it was considered unlikely that the corrections would affect the indices significantly

Table IV

Efficiencies of the three types of circuit

Circuit	Efficiency, %	
	SE_{75}/OE_{75} x 100	SWi/OWi x 100
1. Rod and pebble mills	88	87
2. Ball and pebble mills	84	82
3. Single-stage SAG mills	71	74

SWi for Witwatersrand ores at a limiting screen of 106 μm is 16,6 kWh/t, and the corresponding SE_{75} index is 23,1. The undersize from a 106 μm screen is close to the average size of the final products shown in Table III; the average grindability figures obtained from Table II can therefore be used as standards for comparison with the operating indices from plant operations. The absolute (non-relative) efficiencies for the three circuits are therefore calculated as shown in Table IV.

Table IV shows that the estimates of the efficiencies of the three circuits by use of Work Indices and of the SE_{75} and OE_{75} indices are similar. Furthermore, the efficiencies are ranked in the same order as was obtained by the foregoing comparative method. This information supports the possibility that, for the application described, the E_{75} index could serve the same purposes as the Bond Work Index.

BATCH GRINDING TESTS

The tests described here were part of a related investigation into aspects of the Bond grindability test. They were done by dry-grinding in a Bond grindability test mill under conditions that conform to the Bond test as regards the grinding medium, mill speed, feed quantity, and feed particle size. Grindability indices were calculated from the results by use of the equivalent energy consumption per revolution of the test mill (198 x 10^{-7} kWh).

The tests were carried out on a composite sample of several Witwatersrand gold ores (Sample K51), and comprised two closed-circuit tests with various circulating loads and a test simulating open-circuit grinding. The grindability indices calculated from the results of the closed-circuit tests are designated operating closed-circuit Work Indices, CWi(cc), and operating closed-circuit E_{75} indices, OE_{75}(cc), to distinguish them from standard indices. The indices from the open-circuit test are indicated by Wi(oc) and E_{75}(cc).

Tests Simulating Closed-circuit Grinding

Table V(a) shows the results of tests with a limiting screen of 106 μm and various circulating loads. The effects of increasing the circulating loads were as could be expected: as the circulating loads increased, both the Wi and the E_{75} decreased. At the same time, the products became coarser, as indicated by the higher values of the d_{80} and the lower values of the percentage minus 75 μm.

Table V(b) shows the results for a similar test with a 300 μm limiting screen. The results, compared with those of Table V(a), indicate the expected decreases in the kWh/t and CWi(cc) values, and increases in the OE_{75}(cc) values. What may, however, at first glance appear to be anomalous is the increase in the E_{75} figures as the circulating load increased. The explanation for this is connected with the higher values that are obtained from limiting screens of larger aperture, as has been discussed previously.

Tests Simulating Open-circuit Grinding

The results of particle-size analyses on the ground products after various revolutions of the mill are shown in Table VI and in Figures 3 and 4. Figure 3 deals with the data relating to the estimation of the Work Index. In Figure 3A, the particle size of the products is expressed as

Table V

Closed-circuit grinding tests with variation of the circulating load

Feed material: Sample K51: 7,4% –75 μm

d_{80} = 1900 μm

Mill charge: 1336 g

Circulating load, %	Revolutions per cycle	Product g/cycle	Product % –75 μm	Product d_{80} μm	kWh/t product	OWI (cc)	OE_{75} (cc)
			(a) Limiting screen: 106 μm				
47	850	966	80,2	76	17,4	19,0	23,9
123	500	626	76,2	80	15,8	17,7	23,0
226	320	421	74,2	82	15,0	17,1	22,5
*250			74,0	82		17,0	22,4
			(b) Limiting screen: 300 μm				
54	330	1011	32,3	225	6,46	14,7	25,9
95	230	769	29,3	240	5,92	14,2	27,0
282	100	371	26,7	250	5,34	13,3	27,7
*250			27,2	248		13,2	27,5

* Estimated

Table VI

Batch grinding tests simulating open-circuit grinding

Material: Composite of Witwatersrand gold ores: Mintek sample K51

Mass of charge: 1336 g

Mill revolutions	Equivalent kWh/t*	d_{80} μm	$\frac{1}{\sqrt{d_{80}}}$	OWi kWh/t	–75 μm Determined	–75 μm Adjusted†	OE_{75}, kWh/t –75 μm Determined	OE_{75}, kWh/t –75 μm Adjusted†
0	–	1900	0,0229	–	7,4	7,4		
200	2,96	1000	0,0316	34,0	19,2	19,4	25,1	24,6
300	4,44	605	0,0407	25,0	24,7	25,4	25,7	24,6
400	5,92	389	0,0507	21,3				
500	7,40	271	0,0607	19,6				
600	8,89	200	0,0707	15,6	42,3	43,5	25,5	24,6
900	13,32	116	0,0925	19,1	60,5	61,6	24,9	24,6
1100	16,28	87	0,1072	19,3	73,6	73,6	24,6	24,6
1300	19,24	74	0,1162	20,6	80,6		26,1	
1400	20,72	70	0,1195	21,5	83,2		27,3	
1700	25,16	60	0,1291	23,7	91,7		29,7	

* One revolution of the mill = 0,0148 kWh/t

† Adjusted on the basis of 100 revolutions of the mill increasing the % –75 μm material by 6,02%. The values for 400 and 500 revolutions were obtained by interpolation (Figure 3A)

$1/\sqrt{d_{80}}$, this being the size indicator used by Bond in the calculation of the Work Index.

Open-circuit Operating Work Indices were calculated from the data of Table VI and are illustrated in Figure 3B, which shows that there are three stages in the grinding process. In the first stage, the Work Index descends very sharply from a very high, not clearly indicated, value to a minimum that marks the end of the first stage. The first stage is one of rapid change, for reasons that can be surmised but are not immediately evident; no use can therefore be made of the grindability indices calculated from that stage. In the second stage, the Work Index increases regularly, after which, in the third stage, the Work Indices increase sharply, probably because of increasing agglomeration of the fines. The second stage extends from roughly 600 to 1100 revolutions of the mill, and the Work Indices shown for that stage are probably close to those that can be expected in plant-scale open-circuit grinding. Their possible application to closed-circuit grinding is discussed later.

Figure 4 illustrates the data relating to the E_{75} index. In Figure 4A, mill revolutions (or energy inputs) are related to the percentage of minus 75 μm material in the ground products. The two straight lines suggest constant but different relationships; the flatter slope of the line for grinds of more than about 1100 revolutions indicates a reduced rate of grinding, which could be due to increasing agglomeration of the material being ground.

Figure 4B relates mill revolutions and the E_{75} values calculated from actual size analyses. Of the three intersecting straight lines shown, the one for mill revolutions of more than about 1100 indicates rapidly increasing values of the index, which conforms to the reduced rate of grinding suggested above. The other two lines present an unexpected saw-tooth profile which, as will be explained below, is probably not real but due to small experimental errors.

Repetitions of the test gave somewhat different values for the E_{75} indices and different saw-tooth profiles; these

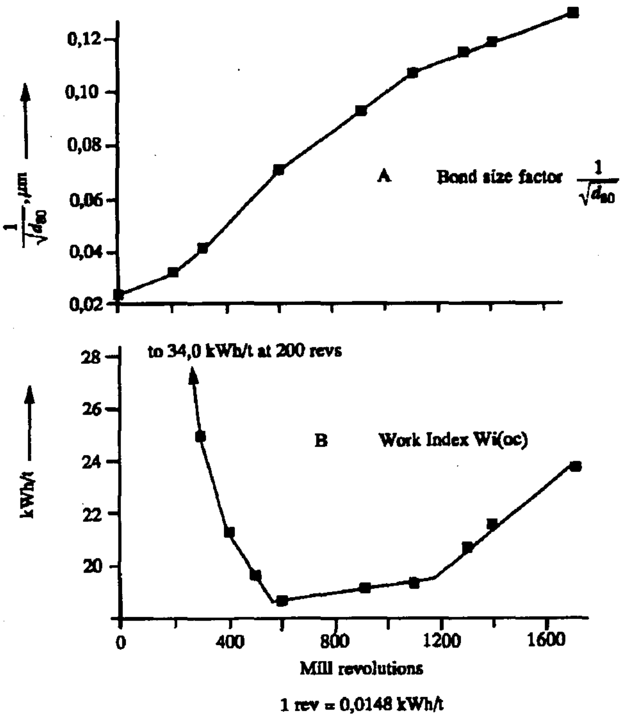

Figure 3—Batch open-circuit test results relating to the Work Index

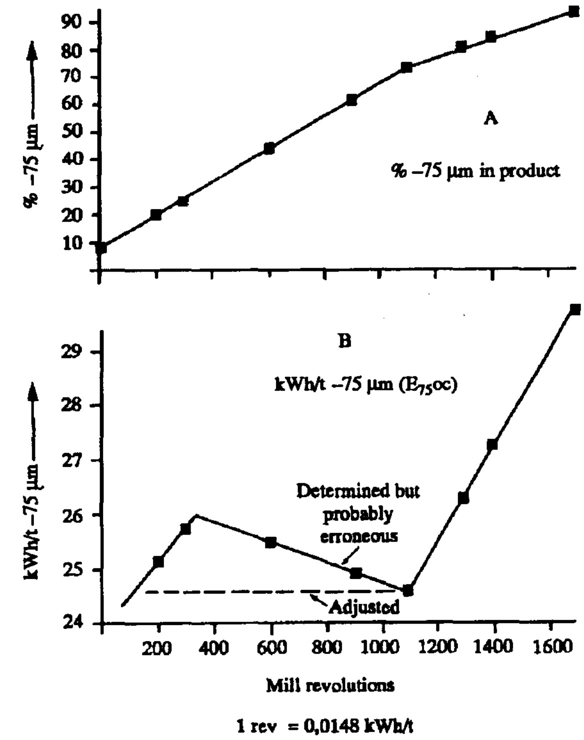

Figure 4—Batch open-circuit test results relating to kWh/t -75 µm

differences are attributed to small errors in the determination of the percentage minus 75 µm material in the ground products. Small errors in the early stages of grinding lead to significant errors in the calculated E_{75} index, and it is difficult to avoid small errors in the sampling and sieve-analysis operations, in which relatively small amounts of minus 75 µm material must be estimated in the coarse products. The percentages of minus 75 µm material in the ground products can be rationalized by calculations based on the straight-line relationship between mill revolutions and the percentage of minus 75 µm material shown in Figure 4A. It was found that 1100 revolutions increased the percentage of minus 75 µm material by 67,2, i.e. each 100 revolutions increase the minus 75 µm material by 6,11 per cent. The percentages of minus 75 µm calculated on this basis are referred to as the adjusted figures and are included in Table VI, together with the determined figures. It is seen that the maximum difference between an adjusted and a determined E_{75}(oc) value is 1,1, or only 4,3 per cent of the determined figure.

The adjusted E_{75}(oc) figures are considered to be closer to the correct ones, and they lead to the tentative conclusion that the open-circuit E_{75} index obtained during the batch grinding test is a constant equal to 24,6 for all grinds up to the beginning of agglomeration.

Standard Grindability Indices from the Open-circuit Laboratory Test

The Bond standard grindability test is cumbersome and expensive, and attempts are made intermittently to derive the standard Work Index from open-circuit tests or to find ways of shortening the standard procedure. Especially noteworthy in this regard is the use of computer simulation in the determination of the Work Index from the results of a single cycle of the Bond test[3].

The correlation of data from closed-circuit and open-circuit tests is difficult and restricted in its range of application. Among the difficulties are the differing shapes of the particle-size distribution curves produced by the two types of grinding, and the conventional use of a single indicator of size—the d_{80} value or the percentage smaller than 75 µm—to characterize the whole distribution. Because the grinding for the grindability tests is dry, the useful results are confined to degrees of grinding at which the efficiency of grinding is not noticeably affected by agglomeration of the material. Agglomeration is of little consequence in the Bond standard grindability test, which is a closed-circuit test; however, in open-circuit grinding, agglomeration imposes a limit on the fineness of grind that provides usable information. The limit varies with the characteristics of the material being ground but, for the ores considered here, it is in the vicinity of 1100 revolutions of the test mill, which corresponds to a product with a d_{80} size of about 87 µm or containing about 80 per cent minus 75 µm. Figure 3B shows that there is also a limit on the coarse grinding side, in the vicinity of 600 revolutions of the test mill, below which the Work Index changes rapidly. It appears therefore that usable grindability data can be obtained only in the range roughly between 600 and 1100 revolutions of the test mill.

A relationship between energy consumption in closed-circuit and open-circuit grinding could be established empirically for a particular ore, as was done by Bond in his provision of 'inefficiency' factors[4], which are presumably average figures for the ores that he dealt with. These factors are reproduced in Table VII. Although their applicability to the ores of the Witwatersrand has still to be tested, it is of interest to apply them to the open-circuit grinding test recorded in Table VI.

Table VII
Bond's open-circuit and closed-circuit relationship

Product-size control Reference % passing	Inefficiency factor
50	1,035
60	1,05
70	1,10
80	1,20
90	1,40
92	1,46
95	1,57
98	1,70

For the estimation of Work Indices, the relevant indicator of size is the 80 per cent passing that size, for which the inefficiency factor is 1,2. The application of this factor is shown in Table VIII.

Table VIII
Application of the inefficiency factor

Open-circuit grindability test			Derived closed-circuit Work Index kWh/t*
Mill revolutions	d_{80} µm	Wi(oc) kWh/t	
600	200	18,6	15,6
900	116	19,1	15,9
1100	87	19,3	16,1

* Derived by division of the open-circuit Work Index by 1,2

An initial assessment of the validity of the derived closed-circuit Work Indices can be made by comparison with the standard Work Indices obtained by the conventional Bond grindability test. This is shown in Figure 5, which represents graphically both the average standard Work Indices recorded in Table II and the closed-circuit Work Indices derived from the open-circuit tests.

Despite the paucity of the data, it is evident that the variation of the Work Index with the degree of grinding (or the d_{80} size of the product) is greater for the standard than for the derived indices. A constant inefficiency factor cannot therefore be applied to a range of product sizes but, with data of the type shown in Figure 5, a size-dependent inefficiency factor could easily be developed. However, it is of interest to note that the standard and derived Work Indices coincide for a d_{80} product size of 100 µm, and that the difference between the two indices is small for product sizes between, say, 90 and 130 µm.

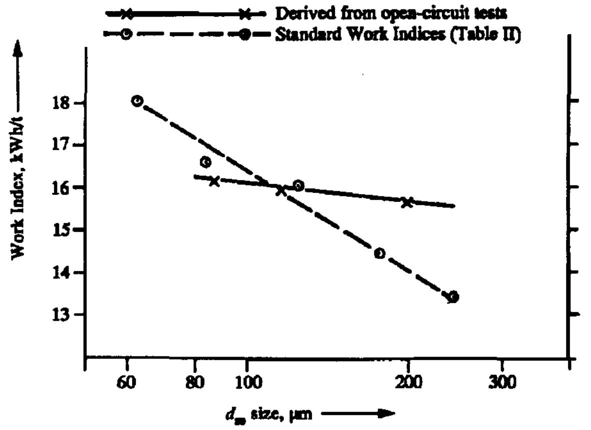

Figure 5—Standard Work Indices compared with closed-circuit indices derived from open-circuit Work Indices

With regard to the possible use of the open-circuit test to predict the index, it is of interest to note that the constant value of 24,6 kWh/t of minus 75 µm deduced from the open-circuit test does not depart greatly from the data presented in Table II.

SUMMARY AND CONCLUSIONS

(1) The Bond standard grindability test can be used in the determination of the standard kWh/t minus 75 µm index (SE_{75}), as well as the standard Work Index (SWi).

(2) For Witwatersrand gold ores, both standard grindability indices vary with the degree of grinding (or the aperture of the limiting screen) employed. The SWi decreases, but the SE_{75} increases, as the aperture of the limiting screen increases.

(3) The fundamental difference between the two indices is that the Work Index is based on the d_{80} size, which is always fairly close to the size of the largest particles, whereas the E_{75} index is based on the percentage of minus 75 µm material, which is a roving parameter that may be close to or far from the size of the largest particles.
The SWi deals directly with the energy required to reduce the size of the large particles in the feed, whereas the SE_{75} relates to the energy required to increase the percentage of minus 75 µm material (the fines) with no direct concern for the possibly large amount of coarse particles in the feed and product. The SE_{75} index serves the same purpose as the SWi only when the product contains a large proportion of minus 75 µm material, say more than 65 per cent. In coarse-grinding tests, the use of an index other than SE_{75} (e.g. SE_{150}) may be advantageous.

(4) In laboratory tests in a circuit closed with a 106 µm screen (which gave products containing more than 74 per cent minus material), increasing grinding efficiencies with increasing circulating loads were indicated equally by Wi and the E_{75} indices.
In similar tests using a limiting screen of 300 µm aperture, which gave products containing less than 33 per cent minus 75 µm material, increasing efficiencies with increasing circulating loads were indicated by the Wi indices but not by the E_{75} indices.

(5) Three stages in the grinding process were observed in laboratory open-circuit grinding tests. Credible values of the open-circuit Work Index were obtained only in the second stage, which encompassed the range from about 600 to 1100 revolutions of the mill. No clear demarcation between the first and second stages of the grinding process was provided by the open-circuit E_{75} values. Erratic E_{75} values were obtained in calculations from the experimentally determined values for percentage minus 75 µm, and it was believed that more consistent and reliable values would result from an assumption that the increases in the percentages of minus 75 µm material are proportional to the energy consumption (or the revolutions of the test mill). The assumption led to a constant value for the open-circuit

E_{75} indices from the beginning of grinding to the beginning of the third stage.

(6) Bond inefficiency factors purport to convert energy consumptions in open-circuit grinding to the equivalent of closed-circuit grinding. A test on their application to the laboratory open-circuit grinding test gave what appear to be correct values for d_{80} product sizes in the neighbourhood of 110 µm but, for a more general application, inefficiency factors that are a function of the product size are necessary and could easily be developed.

ACKNOWLEDGEMENTS

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BOOK Review *continued*

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use being made of current/potential curves. The effects of various process parameters, other ionic species, etc., on recovery efficiency are described. The fundamentals of electrowinning are stated very briefly as a prelude to a description of the reaction chemistry of electrowinning, which is much more detailed.

Surface Chemical Methods

A review of the principles of surface chemistry, i.e. electrical double layer, PZC, hydrophobicity, etc., is given as a prelude to the froth flotation of gold-bearing and gangue minerals, the amalgamation of native gold, and agglomeration flotation. The basic theory and the discussion of the structure and action of surface-active reagents provide a clear explanation of the flotation phenomenon related to gold recovery. Brief reference is made to flash flotation, column flotation, and air-sparged hydrocyclones.

Refining

Classical unit processes such as acid leaching, roasting, smelting, and retorting for the production of bullion are described, good use being made of phase diagrams, atomic-structure diagrams, etc. Interesting data are presented for the refining of electrolytic bullion.

Effluent Treatment

This topic is treated thoroughly. Firstly, the types of waste and effluent-control parameters are described, and then a discussion is given of the recovery of reagents and metals (direct solution recycle, AVR process, ion exchange, and activated-carbon and electrolytic processes) and detoxification (dilution, removal, or conversion to less toxic forms). The complex 'cyanide cycle' is highlighted dramatically in diagrammatic form, and the mechanisms involved in the destruction or degradation of cyanide are detailed. Of special interest is the biological oxidation of cyanide as practised at Homestake since 1984.

INDUSTRIAL APPLICATIONS

This chapter is a particular strength of this book. It is well-researched, and the worldwide distribution of process technology as given here is enhanced by the liberal and imaginative use of diagrams, maps, and tables. There follows an exhaustive description of no fewer than 30 industrial process flowsheets, including locations, startup dates, mineralogical factors, process statistics, process descriptions, and the main features in each case. This is an invaluable source of practical reference, covering every possible type of gold-bearing ore.

GENERAL

The great value of this new text on gold extraction lies in the concise presentation of basic theory, and its skilful application to all stages of the gold-extraction process as practised worldwide. The technology is presented comprehensively, has been well researched, and remains uncluttered by unnecessarily lengthy descriptions, detailed drawings of equipment, manufacturers' specifications, etc. (Other excellent texts are available that address these more practical details.)

Diagrams and tables are used in an imaginative way to replace excessive description.

These factors, together with the comprehensive process flowsheets, reference lists, and a usable index, combine to give a highly informative, wide-ranging treatise on the chemistry of gold extraction.