A full-scale centrifugal mill*

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SYNOPSIS

As part of its programme to develop methods for concentrating minerals underground, the Chamber of Mines of South Africa in conjunction with Lurgi evolved and tested a 1 MW centrifugal mill.

The machine is capable, in the autogenous mode, of grinding more than 25 t/h of minus 75 plus 44 mm hard quartzite to a minus 3 mm product containing over 50 per cent minus 75 μm material, and as a ball mill of grinding more than 60 t/h of minus 19 mm quartzite to a minus 3 mm product containing over 35 per cent minus 75 μm material. Extrapolation of computer models of the process suggests that these limits can be comfortably exceeded. Long-term continuous testing is in hand, aimed at proving that this 1 m in diameter by 1 m long mill is in every respect the equivalent of a conventional 4 m by 6 m ball mill.

SAMEVATTING

Die Kamer van Mynwese van Suid-Afrika het, as deel van sy program om metodes vir die ondergrondse konsentrasie van minerale te ontwikkel, in samewerking met Lurgi 'n sentrifugale meul van 1 MW ontwikkel en getoets.

Die masjien kan op 'n outogene wyse meer as 25 t/h harde kwartsiet met 'n grootte van tussen 75 en 44 mm maal tot 'n produk kleiner as 3 mm wat meer as 50 persent materiaal kleiner as 75 μm bevat en as 'n balmeule kan dit meer as 60 t/h kwartsiet kleiner as 19 mm maal tot 'n produk kleiner as 3 mm wat meer as 35 persent materiaal kleiner as 75 μm bevat. Ekstrapolering van rekenaarmodelle van die proses dui daarop dat hierdie perke maklik oorskry kan word. Daar is ononderbroke langtermyntoetsing onderhande wat daarop gemik is om te bewys dat hierdie meul met 'n diameter van 1 m en 1 m lank in alle opsigte gelyk staan met 'n konvensionele balmeule van 4 m by 6 m.

Introduction

The concept of centrifugal milling is old[1]. In this concept, the forces in the charge inside the mill are increased by operation of the mill in a centripetal instead of in a gravitation field. Comminution is more rapid, and the size of machine needed for a given milling duty is therefore reduced. A smaller machine would cost less to build and install, and maintenance would be simpler.

In this paper, an outline is given of a detailed study of the centrifugal milling concept. This study gave rise to a cooperative development programme between the Chamber of Mines of South Africa and Lurgi. The outcome of this programme is a 1000 kW machine, which has been tested satisfactorily on a South African gold mine.

Theoretical

The motion of a planetary or centrifugal mill, or a vibration mill with a circular vibration, is shown in Fig. 1. If an external observer sees the mill rotating about its own axis with a frequency N_1 and the mill axis rotating about the centre of gyration with a frequency N, with N positive when it is in the same direction (clockwise or counter-clockwise) as N_1, then it can be shown[2] that the mill is critical if

$$N_1/N = \pm\sqrt{G/D} = r_c. \qquad (1)$$

For other values of the ratio $N_1/N = r$, the per cent critical is $|100\ r/r_c|$.

The power drawn by the mill can similarly be shown to be proportional to

$$D^3\ L\ G\ N^3\ (1 - r)\ \sin\phi, \qquad (2)$$

where L = tube length, and

ϕ = angle between centre-of-mass of charge the centre of the mill and the centrifugal vector.

Small-scale Confirmation of Theory

High-speed photographic studies of plastic models from 100 to 1000 mm in diameter have confirmed the validity of equation (1). Similarly, for values of r between $\pm\sqrt{G/D}$, equation (2) has been shown to be valid over a side range of values of N, D, L, and G. However, at small values of G/D the power is less than that predicted by equation (2). Photographic studies show that the charge is unstable and out of phase with

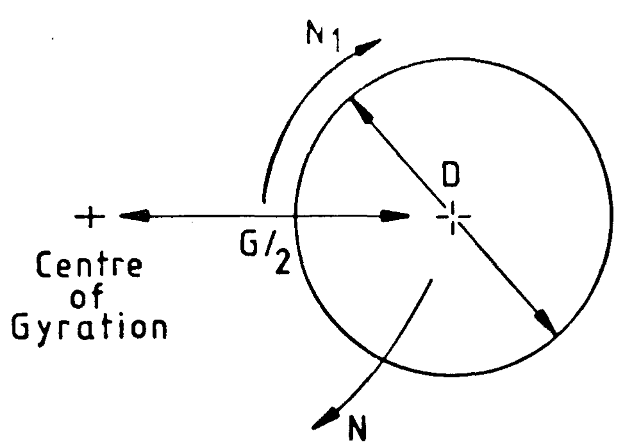

Fig. 1—Nomenclature for the analysis of the motion of a centrifugal mill

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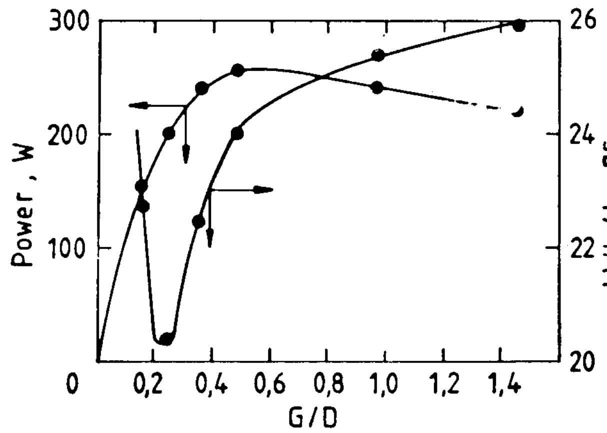

Fig. 2—Variation of power and milling efficiency as a function of the ratio G/D for a batch mill of 100 mm diameter operating at constant speed and filling

the mill and the centrifuge for values of $G/D < 0{,}2$. Efficient milling is possible in this regime only if the filling of the mill is increased.

An important regime was identified where $N_1 = 0$, i.e. the mill was not rotated as its axis was gyrated about the centre of gyration. The centrifuge could then be run at any speed without the charge going critical, and the power drawn by the mill varied with the cube of the speed as required by equation (2). A practical advantage of this type of drive is that feeders and discharge arrangements have a constant orientation. Similarly, a regime in the region of G/D between 0,25 and 0,5 was identified as being promising, as Fig. 2 indicates. While the milling efficiency appeared to improve as G/D was reduced in this range, the power drawn by the mill, and thus the productivity, dropped by a larger proportion.

Model studies also showed that it was desirable to have lifters inside the mill. With lifters, the charge tumbled in a manner similar to that in a conventional mill. Without lifters, the charge slipped on the mill wall and then cataracted, leaving a 'hole' in the charge when the filling was < 50 per cent.

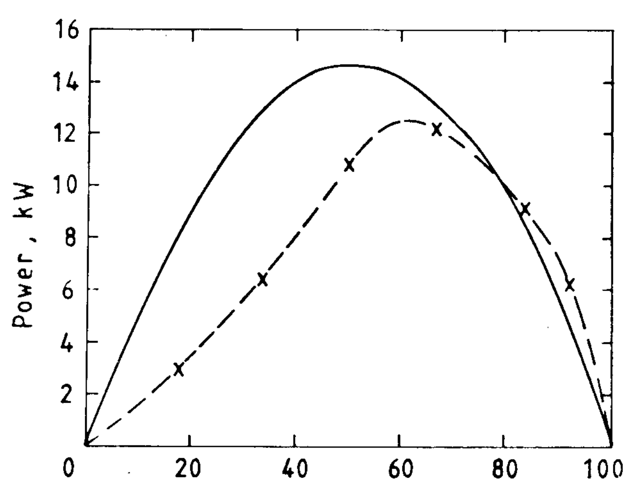

Fig. 3—Variation of power with filling for a batch mill of 100 mm diameter at G/D = 0,4 and constant speed

It was also shown that the charge lagged behind the centrifugal vector in a complex manner. Fig. 3 compares the actual power drawn by a small mill with the power calculated on a basis that the centre of mass lagged by exactly 90° ($\sin \phi = 1$).

Small Continuous Machines

A variety of continuous machines based upon the above principles were developed for test[3, 4]. These studies confirmed all the findings of the small-scale batch studies, and led to the decision to 'freeze' the design at values of $r = 0$ and $G/D = 0{,}3$ to $0{,}5$. A further continuous machine was therefore designed particularly so that the feed and discharge arrangements could be evaluated. This machine comprised a mill tube 200 mm in diameter and 300 mm long, mounted in the centre of a triangular plate. At each corner of the plate there was a bearing carrying a counter-balanced crankshaft of 40 mm throw. The crankshafts were carried on bearings in a triangular frame. One crankshaft was driven by a 30 kW motor. The machine is shown in Fig. 4.

A variety of feeders was tested. It proved to be essential to introduce feed at the centre of the mill tube. The method of doing this comprises a vertical chute with its axis to one side of the axis of the mill. At its lower end the chute develops into a spiral, which forces material into the centre of the mill.

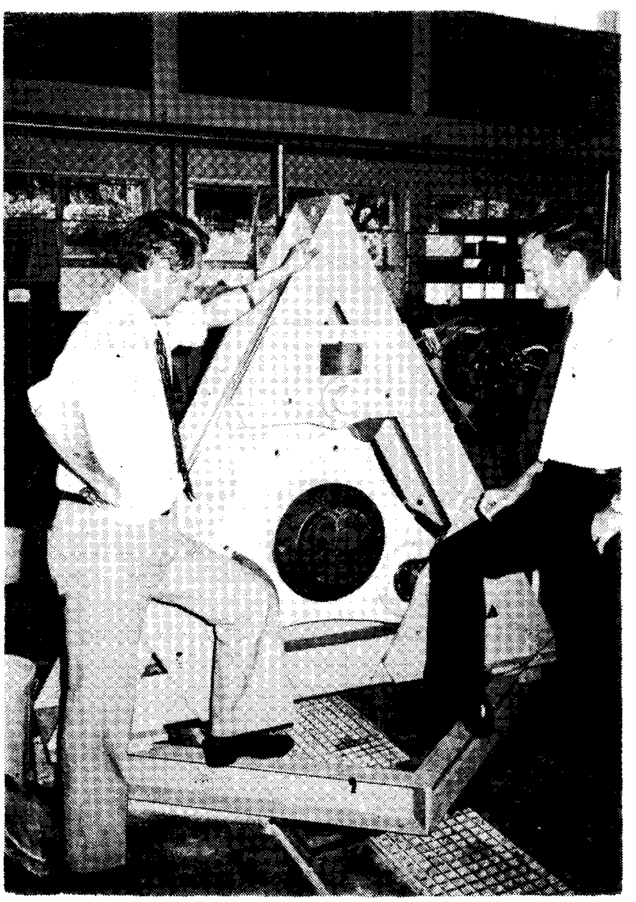

Fig. 4—The 200 mm diameter 30 kW mill before the spiral feeder was installed. In the centre the mill tube is mounted in a triangular plate with bearings and crankshafts at each corner. The whole is carried in the triangular frame

Several discharge arrangements were tried. It proved beneficial for the diameter of discharge to be larger than the diameter of the circle of gyration. If a screen was fitted, it was desirable for the plane of the screen to be parallel to the axis of the mill rather than normal to the axis.

The variation of throughput with operating parameters was studied. It was found that the mill choked suddenly and repeatably as the feed rate was increased. As the mill choked, the level in the mill increased, the power dropped (as Fig. 3 indicates), and the grinding media were carried to the discharge end of the mill.

Fig. 5 shows the effect of changes in the ball size on the maximum throughput of the 30 kW mill, and Fig. 6 shows the effect of changes in the mill speed. In this latter case, the throughput varies nearly as the cube of the speed; that is, in the same relationship as the mill power varies with speed.

From these studies it was concluded that larger, continuous machines could be designed from first principles, and could operate in a predictable manner. Accordingly, the Chamber of Mines and Lurgi entered into an agreement for the design and testing of larger machines.

Design of Full-scale Prototype

It was apparent that the larger forces operating in a centrifugal mill might permit autogenous milling with a smaller feed than in conventional mills. Preliminary tests indicated that minus 75 mm material would self-grind efficiently in the centrifugal mill. A feeder with a minimum dimension at least three times the diameter of the feed, i.e. about 225 mm, would be needed for this material. The minimum diameter of mill tube to suit such a feeder was about 1 m.

Milling had been found to be efficient up to power densities of about 500 kW per ton of balls. A mill 1 m in diameter and about 1 m long would require 2 t of balls, thus requiring an installed power of about 1 MW for ball milling.

Within these constraints the machine shown in Figs. 7 and 8 was evolved. This machine has the following features:

(1) a 1 MW drive at a speed variable by about 20 per cent either side of the design speed of 230 r/min;

(2) two eccentric shafts with a 200 mm throw mounted either side of the mill, and driven synchronously by coupled gearboxes, with a drive train incorporating a torque tube fitted to one of the gearboxes and a brake fitted to the other;

(3) a U-frame assembly supported by roller bearings on the eccentric shafts to carry the mill;

(4) a 1,0 m diameter by 1,2 m long mill tube fixed in the U-frame by 6 hydraulically-tensioned bolts, which can be released for the tube to be rapidly removed for relining;

(5) counterweights fixed to the eccentric shafts to balance the mass of the mill; and

(6) feed and discharge arrangements as described previously.

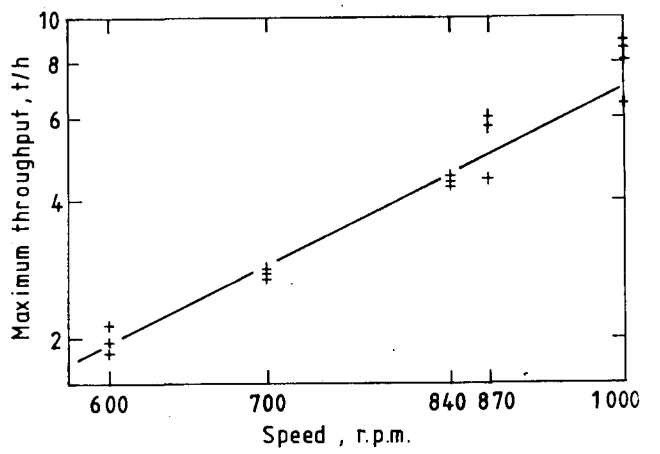

Fig. 6—Variation of throughput with mill speed for the 200 mm mill

The mill was erected for test in the reduction works at Western Deep Levels Gold Mine, near Carletonville, Transvaal. The circuit for the feed and discharge has a number of interesting features:

(a) the feed is drawn from two bins containing, respectively, minus 75 plus 44 mm pebbles and minus 19 mm fines, which can be mixed in any desired proportion;

(b) the minus 12 mm discharge of the mill passes over a 1,5 m by 3 m vibrating screen fitted with 3 mm square wedge-wire mesh;

(c) the plus 3 mm product is returned to the feed;

(d) the minus 3 mm product passes to a small, agitated sump;

(e) a flow meter, a variable-speed pump, and a feedback loop from a density gauge to water injection to the sump give a constant flowrate to a 760 mm cyclone;

(f) splitters on both the overflow and the underflow streams from the cyclone to recycle material to the sump ensure adequate solids for a constant feed to the cyclone; and

(g) the balance of the overflow is delivered as product to the mine, and the balance of the underflow is returned to the mill.

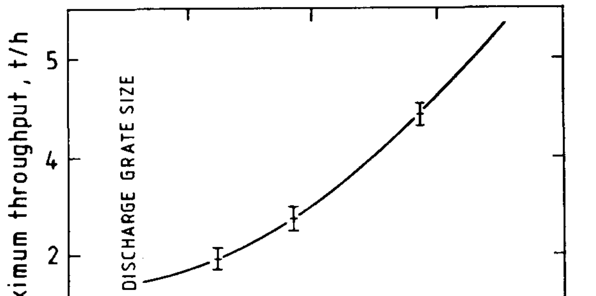

Fig. 5—Variation of throughput with ball size in the 200 mm diameter continuous mill

Operational Findings

By January 1982, the mill had operated for well over 1000 hours. This running time was broken down into three phases.

In the first phase, the mill was run empty for 7,5 × 10^6 cycles at 230 r/min so that the fatigue behaviour and bearing performance could be checked. There were no signs of stress, and mechanical problems were minor, such as the cracking of one roller in a roller bearing as a result of incorrect metallurgical treatment.

In the second phase, the mill was run autogenously on feeds of both pure pebbles and mixed pebbles–fines, with the circuit closed initially by the 3 mm vibrating screen and then also by the hydrocyclone. The results are given in Tables I to III. At the end of this phase the mill was again stripped for examination. The only significant

TABLE I

AUTOGENOUS MILLING TESTS WITH PEBBLE FEED AND CIRCUIT CLOSED BY 3 mm SCREEN

Speed r/min	Pebbles t/h	Screen oversize t/h	Net power kW	Product grading % −75 μm
210	13,1	—	298	65
	14,2	—	316	67
	15,2	—	334	65
	16,8	—	383	72
230	14,3	0,3	356	46
	16,4	0,4	384	50
	18,6	0,2	422	51
	20,5	0,6	441	53
	22,3	3,7	457	51
	24,8	6,2	512	55
	23,8	3,5	458	50
	25,7	3,9	478	51
	21,4 (0.2)*	3,9 (0,8)	441 (8)	52 (1)

* Mean and standard deviation for 6 similar runs.

TABLE II

AUTOGENOUS MILLING TESTS WITH MIXED FEED AND CIRCUIT CLOSED BY 3 mm SCREEN

Speed r/min	Pebbles t/h	Fines t/h	Screen oversize t/h	Net power kW	Product grading % −75 μm
210	9,5	6,2	1,7	278	55
	9,9	7,8	2,2	296	44
	9,9	10,3	6,8	327	49
	9,4	12,2	9,2	358	48
	12,8	3,8	—	315	55
	13,1	6,0	6,6	352	57

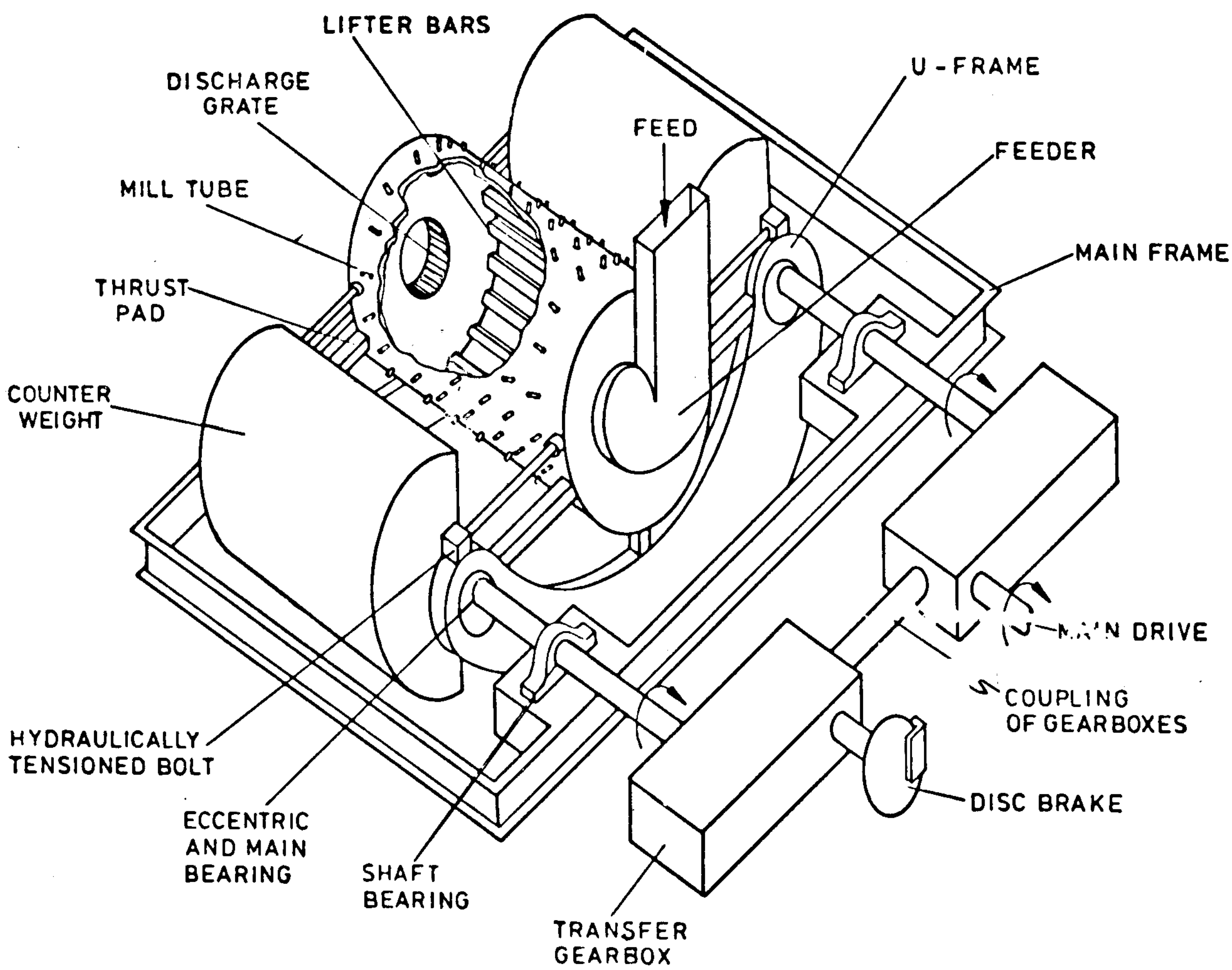

Fig. 7—A diagrammatic view of the 1 MW centrifugal mill with 1 m diameter mill tube

TABLE III

AUTOGENOUS MILLING TESTS WITH PEBBLE FEED AND CIRCUIT CLOSED BY HYDROCYCLONE

Speed r/min	Pebble feed t/h	Screen oversize t/h	Underflow recycle t/h	Net power kW	Product grading %−75μm
230	8,4	2,9	60,3	370	69
	9,7	4,0	46,7	410	57

finding was abrasive wear of the oil seals on the main bearings due to dirt penetration of a labyrinth. The seals were rebuilt and the lubrication changed to grease.

In the third phase, the mill was operated as a ball mill with fines feed and, again, the circuit was closed initially by the 3 mm screen and then also by the hydrocyclone. The results are given in Tables IV and V. In addition, a study was made of the variation of power with mill speed and fractional volumetric filling with balls. The results are given in Fig. 9.

In this phase of the study, the liner wear was initially very high (with a life of less than 20 hours) because of shattering of the Nihard IV lifter bars. As a temporary measure, the bars were replaced by mild steel with rubber face-plates between them. These gave lifetimes of about 50 hours, which is plainly not satisfactory but must be viewed as a stop-gap until manganese-steel liners are procured.

Discussion of Results

The results of the autogenous pebble-milling tests given in Table I were unexpected, in that a change of speed from 210 to 230 r/min gave a decrease rather than an increase in the fineness of the product at similar throughputs. An explanation was sought by modelling studies, following conventional ideas[5] on autogenous milling, in which breakage is presumed to follow three different mechanisms:

(i) impact breakage, in which large pieces of rock are shattered,

(ii) abrasive breakage, caused by relative motion between particles of similar sizes, and

(iii) attrition breakage, in which fine particles are crushed between coarser particles.

A computer model was developed that included not only these types of breakage, but also allowed for the effects of pulp hold-up in the mill and the cushioning effect of excessive pulp. The model indicated that the effect of an increase in speed could be interpreted as a change in the parameters of the breakagefunc tion for the pebbles. Abrasive breakage is characterized by a breakage function with a high proportion of fines. Impact breakage

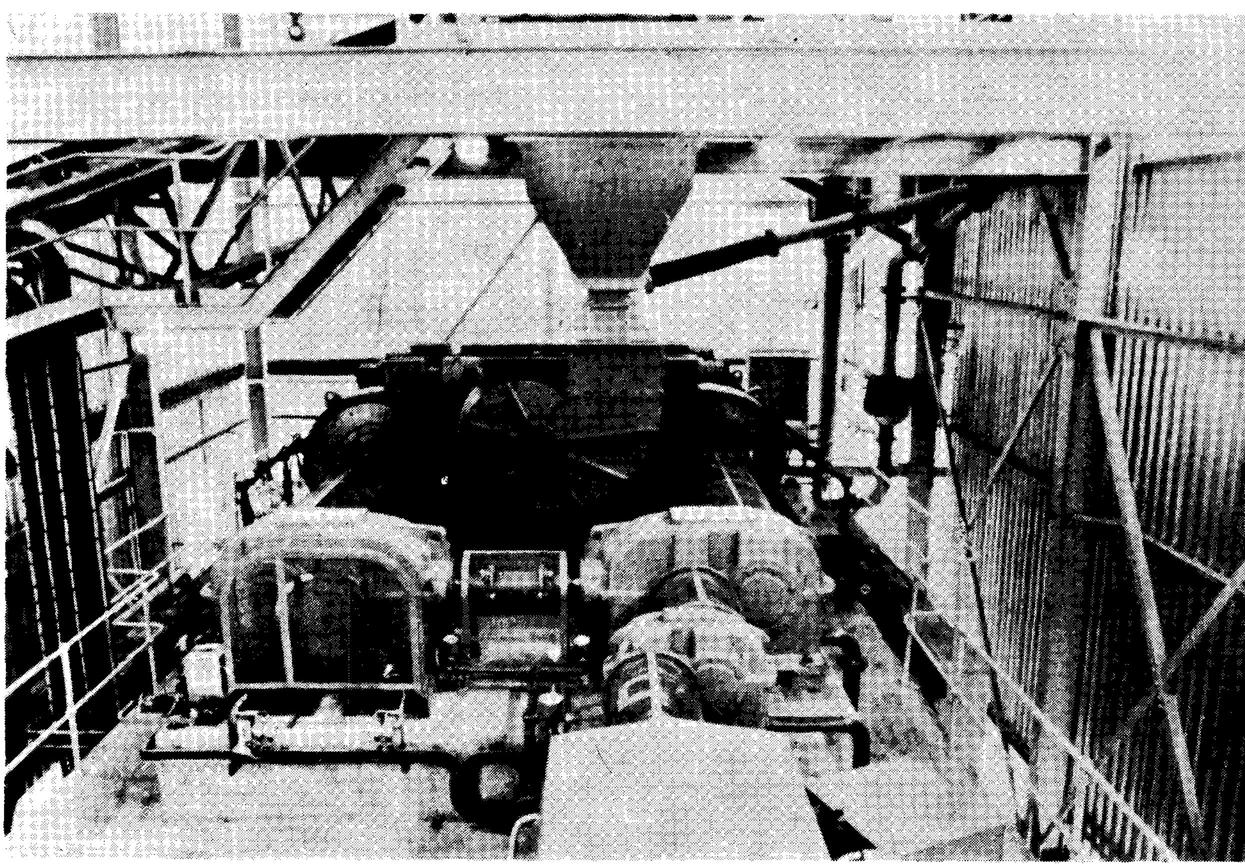

Fig. 8—Photograph of the full-scale prototype showing (foreground) variable-speed hydraulic gearbox; coupled transfer gearboxes with disc brake on left-hand box; in centre feed chute and spiral feeder; on either side of and slightly below spiral feeder, the eccentric shaft and main bearings in the U-frame; and the hydraulically tensioned bolts to hold the mill tube at the top of the mill frame

TABLE IV

BALL-MILLING TESTS WITH FINES FEED AND CIRCUIT CLOSED BY 3 mm SCREEN

Speed r/min	Ball size mm	Fractional ball filling	Feed t/h	Screen oversize t/h	Net power kW	Product grading %−75 μm
215	25	0,5	54,0	5,2	931	38
170	32	0,3	21,2	4,2	259	26
170	32	0,3	21,2	4,6	269	30
170	32	0,3	18,7	5,3	259	37
170	32	0,4	26,2	3,8	350	33

TABLE V

BALL-MILLING TESTS WITH FINES FEED AND CIRCUIT CLOSED BY HYDROCYCLONE, USING 32 mm BALLS

Speed r/min	Fractional ball filling	Feed t/h	Screen oversize t/h	Cyclone recycle t/h	Net power kW	Product grading % −74 μm
215	0,5	37,8	8,8	59,4	879	52
215	0,5	38,4	13,5	58,7	849	51
215	0,5	23,7	2,4	62,0	869	81
215	0,5	28,7	6,4	66,0	839	73
215	0,5	33,7	7,7	93,7	833	68
225	0,5	33,1	6,4	90,4	986	64

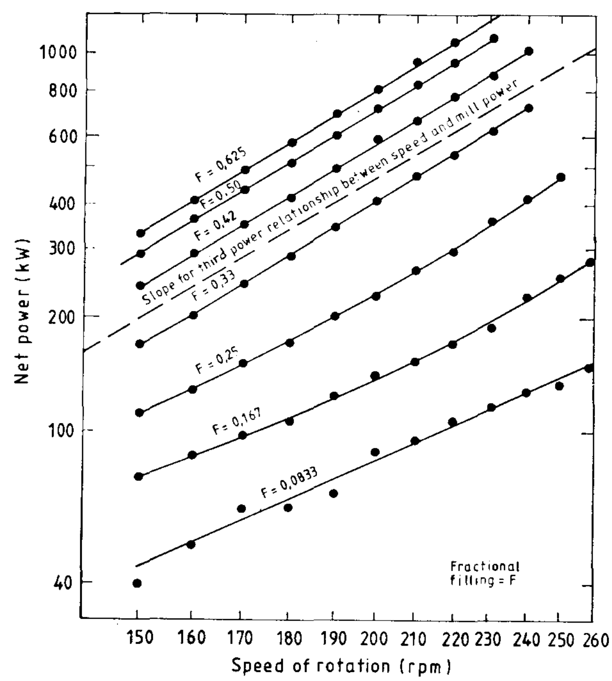

Fig. 9—Variation of power drawn by the mill with ball filling and mill speed (no feed was used except water for cooling)

is characterized by a breakage function with a lower proportion of fines. Figs. 10 and 11 show the degree of correlation between the model and the experimental results. In all cases, the model parameters were identical. The excellent agreement between model and experiment gives some confidence in the physical significance of the mechanisms postulated by the model.

The same model parameters were used to satisfactorily describe the tests shown in Tables II and III. The low through-puts and poor grinding efficiencies given in Table III are particularly interesting. These findings were interpreted as the consequence of a correlation between pebble breakage rates and pulp hold-up. Thus the increase of the circulating load with a hydrocyclone resulted in an increase in the hold-up of pulp, which decreased the breakage rate of the pebbles. The pulp can be described loosely as having a cushioning effect on the interaction between the pebbles. Since the pebbles cannot leave the mill without first breaking to the mesh size of the discharge screen, there was a tendency for the mill to choke with pebbles. Stable operation of the circuit was possible only by a reduction of the pebble feed rates to about 9 t/h. It was clear from examinations of the mill contents that the breakage rates of the pebbles are particularly sensitive to fractional hold-ups of pulp greater than about 10 per cent.

The finding by Weymont[5] that there must be a balance between the various modes of breakage for autogenous milling to be efficient is entirely borne out by these results.

In the case of the ball-milling tests, the breakage and selection functions were determined in a small (100 mm diameter) batch mill[6], and the resultant functions were used in the interpretation of the results given in Tables IV and V. In addition, the residence-time distribution of the material in the mill was determined by the use of radiotracers[7]. This modelling is still incomplete, but preliminary indications are that a satisfactory model is available, as Fig. 12 shows.

The values of Fig. 9 fully confirm the third power of dependence of mill power on speed for mill fillings of over about 25 per cent. At smaller fillings, it appears that the mill power depends on the second power of the speed. The reason for this is not fully understood. It is also noteworthy that a plot of power versus percentage filling at any given speed shown in Fig. 9 has a curve virtually identical to that shown in Fig. 3 for a small-scale mill.

Table VI shows the effect of mill speed on maximum throughput for the full-scale mill. There are relatively large errors in the determination of this parameter in the full-scale mill, but it is clear that the relationship shown in Fig. 6 is valid on the full-scale mill. Sufficient data have not yet been acquired to confirm the relationship between ball size and throughput found on the small-scale mill. However, there are indications that this relationship is indeed valid.

Summary and Conclusions

The results of tests on a 200 mm diameter, 30 kW

TABLE VI

VARIATION OF MAXIMUM FEED RATE WITH MILL SPEED FOR 50 % FILLING OF 25 BY 25 mm CYLPEBS

Speed r/min	Maximum throughput t/h	Maximum theoretical* throughput, t/h
150	16 ± 5	21
180	27 ± 3	36
215	61 ± 1	61

* On the assumption that third-power dependence on speed (see Fig. 6) normalized to 61 t/h at 215 r/min.

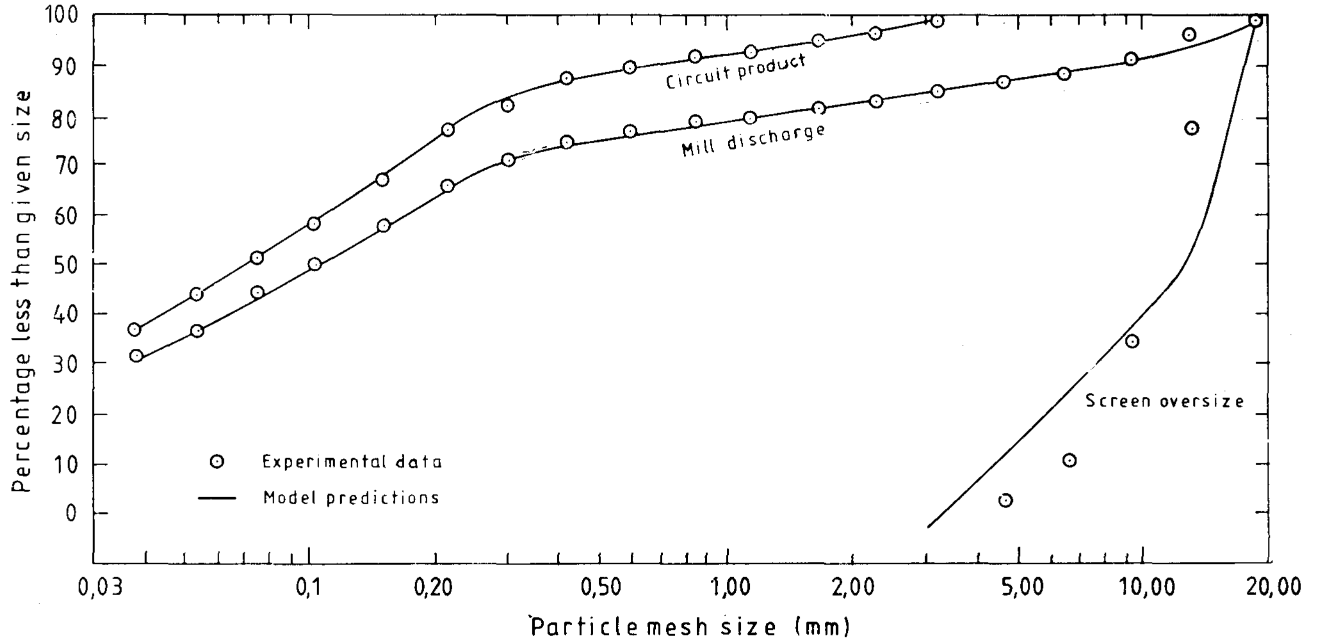

Fig. 10—Comparison of experimental size distributions in various fractions with predictions based on the autogenous-mill model: −75 + 44 mm pebble feed, 21,4 t/h, 230 r/min

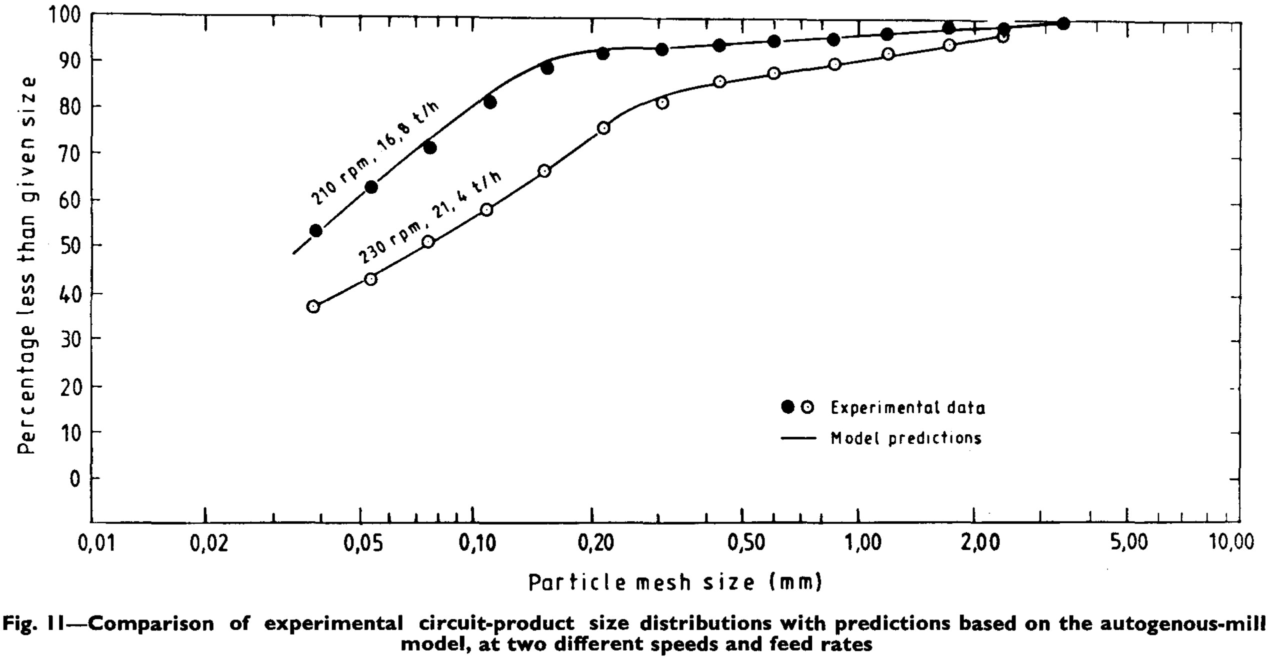

Fig. 11—Comparison of experimental circuit-product size distributions with predictions based on the autogenous-mill model, at two different speeds and feed rates

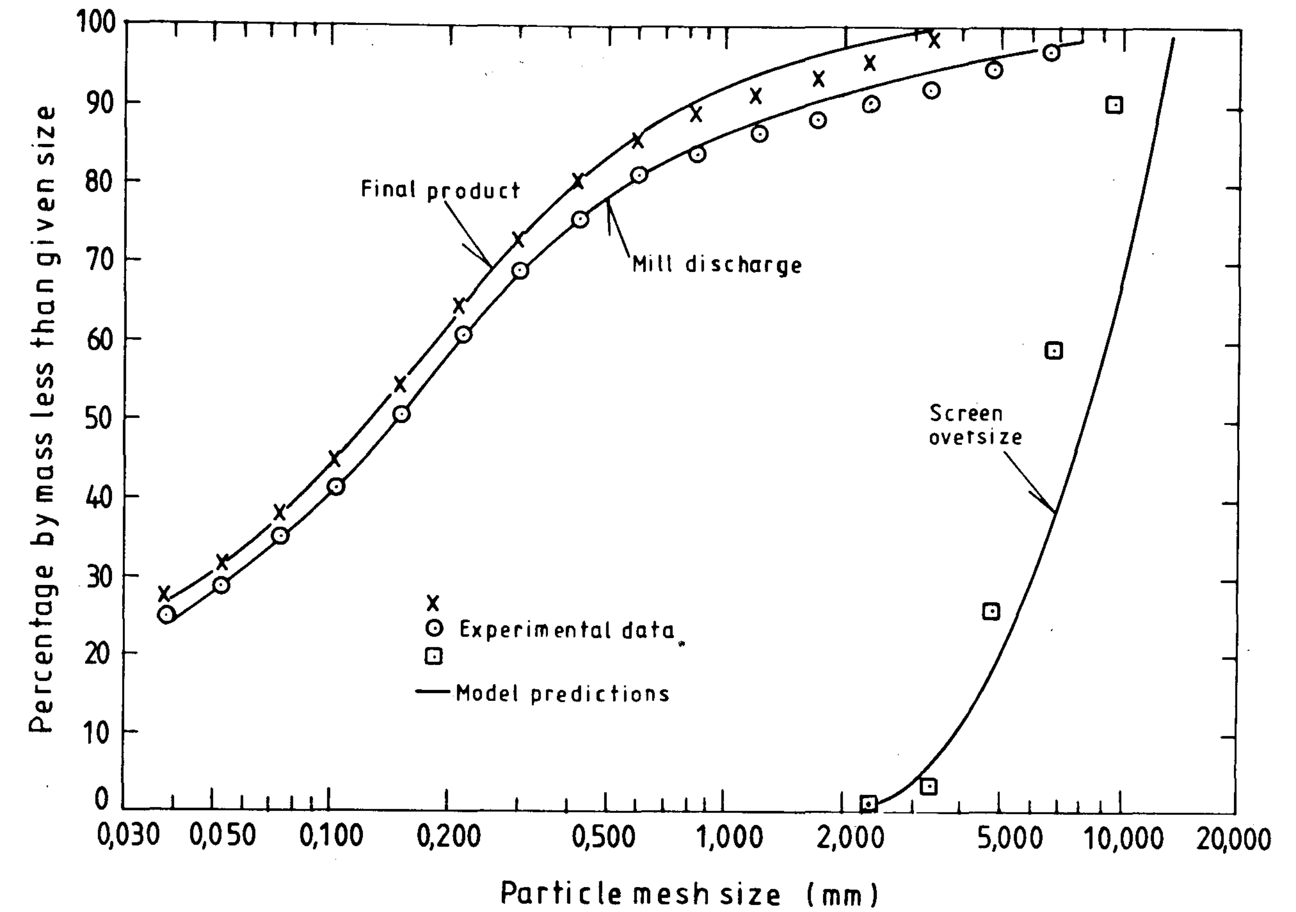

Fig. 12—Comparison of full-scale ball-mill results with model predictions based on studies on a 1000 mm diameter batch mill

centrifugal mill were used in the design of a 1000 mm diameter, 1000 kW machine. Operation of the large mill has confirmed the design criteria in virtually every respect.

Testing is not yet complete, but the mill has proved capable, in an autogenous mode and fed with minus 75 plus 44 μm pebbles, of grinding over 25 t/h to over 50 per cent minus 75 μm. As a ball mill, it has ground minus 19 mm feed at over 60 t/h to over 35 per cent minus 75 μm. In both cases, the results were achieved with the circuit closed only by a 3 mm screen. Modelling studies have explained the results to date, and extrapolations of these models, admittedly risky, indicate that the present maximum performance limits will be comfortably exceeded as greater experience is gained.

The 1000 kW machine has operated extremely well for a one-off design. Recent measurements of stress levels throughout the machine have shown that the stresses are everywhere within design specifications.

At present, work is in progress to establish liner life and ball consumption under long-term stable conditions, and to demonstrate that the down-time for relining is less than 1 per cent. A target liner life of over 300 hours has been set, and both material and design modifications to achieve this are in progress. Simultaneously, process and operating conditions are being varied to demonstrate that this 1 m by 1 m machine is in every respect as productive and efficient as a conventional 4 m by 6 m ball mill.

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