# Developments in centrifugal milling

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**SYNOPSIS**

The theoretical and experimental results of a study of centrifugal mills are reviewed. Means for the scaling up of such mills are suggested, and tests on a prototype mill are described. Despite the high lining wear in the centrifugal machine, which reduces its productive availability, its other advantages suggest that there is merit in pursuing its further development.

**SAMEVATTING**

Die teoretiese en eksperimentele resultate van 'n studie van sentrifugale meule word in oënskou geneem. Metodes vir die vergroting van sodanige meule volgens skaal word aan die hand gedoen en toetse op 'n prototipe meul word beskryf. Ten spyte van die hoë voeringslytasie in die sentrifugale toestel wat sy produktiewe beskikbaarheid vermin-der, dui sy ander voordele daarop dat dit die moeite werd is om met die verdere ontwikkeling daarvan voort te gaan.

## INTRODUCTION

The concept of centrifugal milling has long been known[1], and many types of batch machine have been developed[2]. In addition, work has been carried out on a number of continuous machines using the same concept[3,4], but as yet there have been no successful full-scale industrial applications.

In 1968, work was initiated in the Chamber of Mines of South Africa Research Organisation on the concept, because there seemed to be merit in attempting to reduce the sheer bulk of conventional comminution machines. Calculations indicated that the volume taken up by the machine should be a simple function of the acceleration that was imposed on the grinding charge, and that accelerations of the order of $10^3$ m.s$^{-2}$ (102 g) should be readily attainable in machinery of moderate size operated at rotation speeds well within the range of conventional rotary-drive and bearing systems. Accordingly, a study of centrifugal mills was initiated, and it is the purpose of this paper to review both the theoretical and experimental results of this study.

## THEORY OF CENTRIFUGAL MILLING[5]

The centrifugal mill comprises a grinding tube that is rotated about its own axis, while that axis is in turn rotated about an axis of gyration parallel to the tube axis, in order to impose a centrifugal force upon the tube and its contents. This is indicated in Fig. 1. Plainly, the grinding tube may be rotated about its own axis by a suitable arrangement of gears, of which sun-and-planet or sun-idler-planet arrangements are particularly convenient if the axis of the sun gear is the same as that of gyration, and the axis of the planet gear is the same as that of the mill.

It may be thought that there is a limit to the speed of rotation of such an assembly above which the charge in the grinding tube will centrifuge. It transpires that this limit is set by the gear ratio, not by the speed, as the following argument indicates.

Consider a sun-to-planet gear ratio of $R$, taken to be positive when the direction of rotation about the tube axis and the direction of rotation about the gyration axis are the

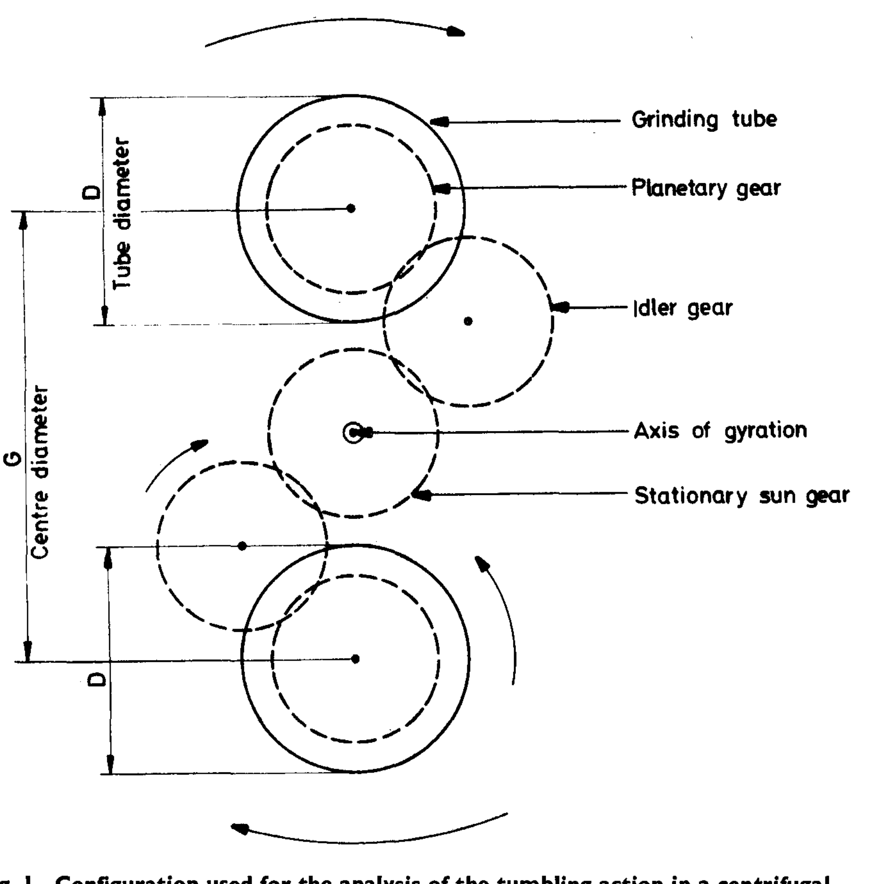


**Fig. 1—Configuration used for the analysis of the tumbling action in a centrifugal mill.**

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same (negative $R$ resulting, for example, when there is an idler gear between the sun and the planet gears). Then, it can be easily shown that, for a frequency of gyration $N$, the frequency of rotation of the mill and tube is $(R+1)N$.

Then, if the force due to gravity is neglected, a small particle on the mill wall will 'centrifuge'; that is, the mill will be operating at the critical speed, when the forces experienced by that particle just tend to keep the particle on the wall. The force due to rotation of the tube about its own axis results from the acceleration $2\pi^2D[(R+1)N]^2$, where $D$ is the diameter of the mill. The force due to gyration of the tube about the central axis similarly results from the acceleration $2\pi^2GN^2$, where $G$ is the diameter of the circle of gyration. The critical speed will be reached when these two accelerations balance, i.e., when

$$2\pi^2D(R+1)^2N^2=2\pi^2GN^2,$$

or when

$$(R+1)^2=G/D.$$

Thus, critical operation of the mill is determined by its configuration, as set by the ratio $G/D$, and by the gear ratio $R$. For a fixed ratio $G/D$, there exists a critical gear ratio $R_c$ given by

$$R_c = -1 \pm \sqrt{G/D},$$

and it will be noted that there are in fact two such ratios. It is also of interest to note that, at $R = -1$, $G/D = 0$ for the above equation to be valid, which implies that there is no mill configuration of finite size that can be operated in a critical state at this gear ratio.

It is also important to note that frequency does not enter into the equation for the critical behaviour of the centrifugal mill. Thus, the mill can be operated at a frequency set only by the limitations on the strength of the materials employed and on the available power.

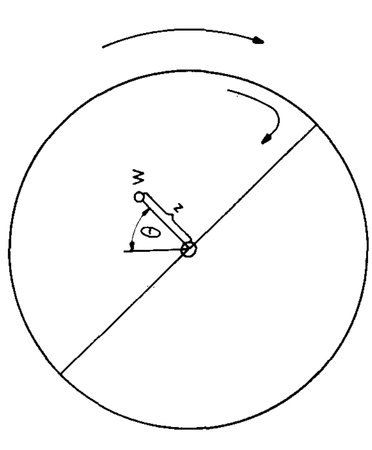

Fig. 2—Couple formed by the displacement of the mill load by friction.

The power drawn by the mill can be estimated approximately as follows. The mill charge can be regarded as being due to a mass $M$ with centre of mass a distance $Z$ from the centre of the mill. Because of frictional forces between the wall of the mill and the mill charge, and because of the rotation of the mill, the centre of the mass will not lie on the line through the axis of gyration and the axis of the mill rotation, but will be displaced by an angle $\theta$ from that line (see Fig. 2). Thus, a couple will be set up that will adsorb power at a rate proportional to $M.\ Z \sin\theta$. In addition, the frequency of rotation of the mill is, as before, $(R+1)N$, and, because the mill charge must follow the main rotary field caused by gyration about the central axis, the mill charge will lag behind the mill, and thus the effective frequency of rotation of the charge will be

$$N - (R+1)N = -NR.$$

Finally, the acceleration impressed upon the mill charge will be close to $2\pi^2GN^2$, and thus the mill power, P, will be given by

$$P \propto M.Z \sin\theta\ (-NR)\ .\ 2\pi^2GN^2.$$

Now, for a given proportional filling of the mill tube, $Z \propto D$. Also, it seems reasonable to assume that $\theta$ will not vary greatly, so that sin $\theta$ will be effectively constant. For a constant level of mill charge, the mass of the charge will be proportional to $D^2L$ and therefore

$$P \propto D^2L.D.\ (-NR)\ .\ (2\pi^2GN^2),$$

$$\text{i.e., } P \propto D.^3L.R.G.N^3.$$

Thus, to a first approximation for a mill of chosen configuration and gear ratio, the power drawn by the mill should be proportional to the cube of the speed of rotation.

It seems reasonable to suggest that scale-up of a centrifugal mill should be based on a constant ratio $G/D$, a constant shape of the mill tube (i.e., constant $L/D$), a constant gear ratio $R$, and a constant acceleration imposed upon the charge (i.e., constant $2\pi^2\ GN^2$). If this is done, then the power drawn by the mill is proportional to $K^{3,5}$, where $K$ is the ratio between a dimension of the small mill and the same dimension of the scaled-up mill. This indicates that very small mills can consume large amounts of power. For instance, if a laboratory-scale mill with a diameter of gyration of 20 cm were found to require 2 kW for efficient milling, a mill with a diameter of gyration of only 60 cm would demand nearly 100 kW when operated under identical conditions, and a 1,44 m mill would demand 1000 kW. Plainly, therefore, it should be possible in principle to design very compact, high-capacity machines by the use of this principle.

## LABORATORY EXPERIMENTATION

The theory of the critical behaviour of the centrifugal mill was checked on a single-tube transparent model in which the effective gear ratio was infinitely variable and in which the ratio $G/D$ could be varied by changes in the mill diameter. The mill was charged with small, varicoloured plastic spheres to approximately 50 per cent by volume. High-speed, colour motion pictures were taken while the mill was in operation and the gear ratio was being varied.

With smooth liners, so much slip could be generated between the charge and the mill wall that it was impossible to determine precisely when the mill became critical. However, when small lifter bars were inserted, slip was prevented and the onset of critical behaviour could then be determined exactly. These studies, which were carried out with $G/D$ ratios of 1,5 and 0,5, and with both positive and negative gear ratios, confirmed the theory of critical behaviour to within the limits of experimental error. Most of this error arose from the determination of the exact value of $R$ at the point where critical behaviour was first observed.

A laboratory-scale mill was constructed for preliminary batch tests. Plate I shows this mill, which has two tubes each of inside dimensions 82,5 mm long and 63,5 mm diameter. These tubes are driven by a sun-and-planet arrangement of gears about a central axis of gyration, and the radius of the circle of gyration is fixed at 76 mm. Drive is via a shunt-wound variable-speed d.c. motor. Accelerations of up to $2 \times 10^3$ m/s$^2$ can be imposed on the tubes, which occur at a speed of rotation of about 26 Hz (1560 rev/min).

Grinding tests were carried out with a feed of minus 2,38 plus 1,19 mm quartzite and steel balls. A number of tests were undertaken to find the optimum conditions of loading, and a charge consisting of 500 g of balls, 125 g of dry feed, and 62,5 g of water, which filled about 70 percent of the mill volume, was found to be optimal. Studies were then carried out on the effects of ball size and speed of rotation. The results are shown in Figs. 3 and 4.

In Fig. 3, the fraction of the charge reduced to minus 74 $\mu$m is shown as a function of ball size for three speeds of rotation. The time of milling was reduced as the speed was increased to ensure identical net energy inputs at each speed, on the assumption that the power varied as the cube of the speed. The results shown indicate clearly that, at each speed, there exists an optimum ball size, and that this optimum size decreases as the speed is increased. This may imply that, at any one speed, as the ball size is reduced the grinding improves because of the increase in the number of impacts, but that at a certain point the force delivered by each impact drops to the point where breakage becomes inefficient, and the rate of comminution accordingly drops off markedly. From Fig. 3, it can be estimated that the optimum ball size varies approximately as (speed)$^{-0,5}$. Thus at the higher speeds, the ball diameter may be reduced markedly without reducing the efficiency of grinding. While this may not be of importance when steel grinding media are used, there may be significant advantage when pebbles are used because the availability of pebbles of adequate size is often limited in conventional milling.

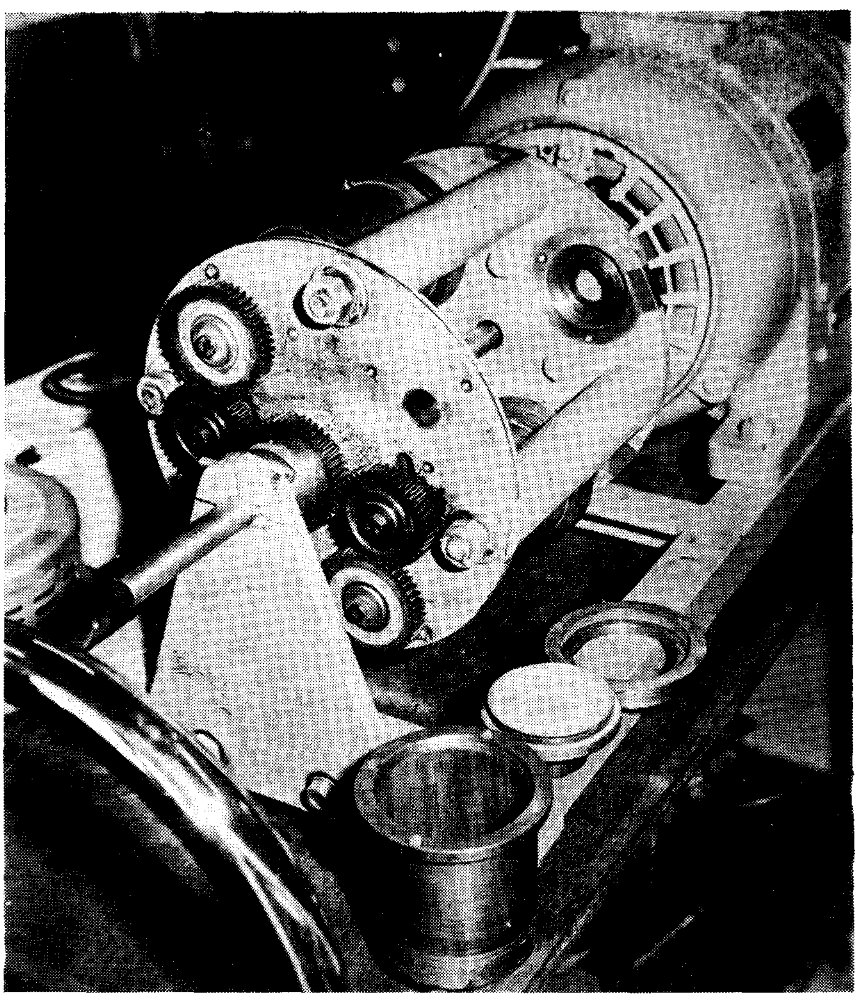

**Plate I—The batch centrifugal mill. Two tubes driven by a sun-idler-planet arrangement of gears are shown installed in the circular frame, which is rotated round the stationary sun gears. A dismantled tube is shown in the foreground.**

The results shown in Fig. 4 indicate the importance of using grinding medium of the correct size to obtain the minimum energy consumption in the grinding of a given feed. They also indicate that, over a limited range of speeds, the grinding mechanism in the centrifugal mill is probably constant, because the net energy used does not vary greatly with speed. It should be noted that the results at 16,6 Hz may be biased because of the difficulties of estimating the power consumption during a 10-second run. The net energy was estimated in these tests by monitoring the armature voltage and current, and subtracting the energy needed to run the mill empty and at the same speed. A small correction was also made for the losses in armature resistance.

It can be noted that, from Fig. 3, at 4,2 Hz for 640 seconds the feed was reduced to approximately 60 per cent minus 74 $\mu$m, at 8,3 Hz for 80 seconds to approximately 60 per cent minus 74 $\mu$m, and at 16,6 Hz for 10 seconds to approximately 55 per cent minus 74 $\mu$m. If the difficulties of experimentation at the fastest speed are borne in mind, it seems reasonable to suggest that these results confirm the cube law of power as a function of speed, because doubling the speed reduces the time taken to produce a product of constant composition by a factor of $2^3$.

## PROTOTYPE TESTING

On the basis of the laboratory results, a continuous centrifugal mill was designed (Fig. 5). The mill has three grinding tubes each of inside dimensions 200 mm diameter and 350 mm length. These tubes are driven by a sun-and-planet gear arrangement giving a value of $R = -1$. The diameter of the circle of gyration is 330 mm, giving a ratio $G/D = 1,65$.

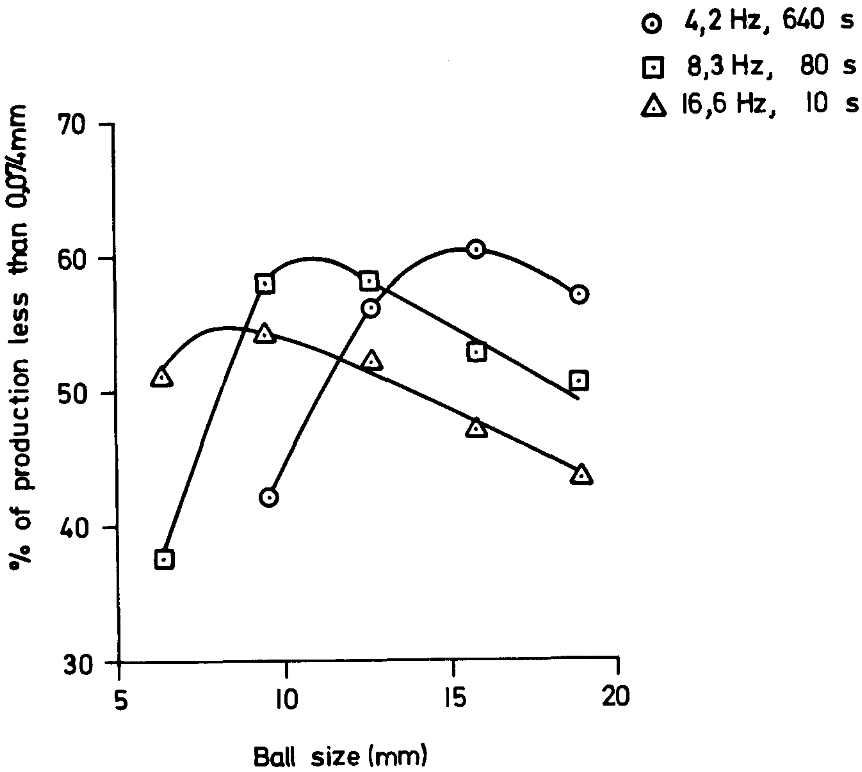


**Fig. 3—The effect of rotation speed and ball size on the milling process.**

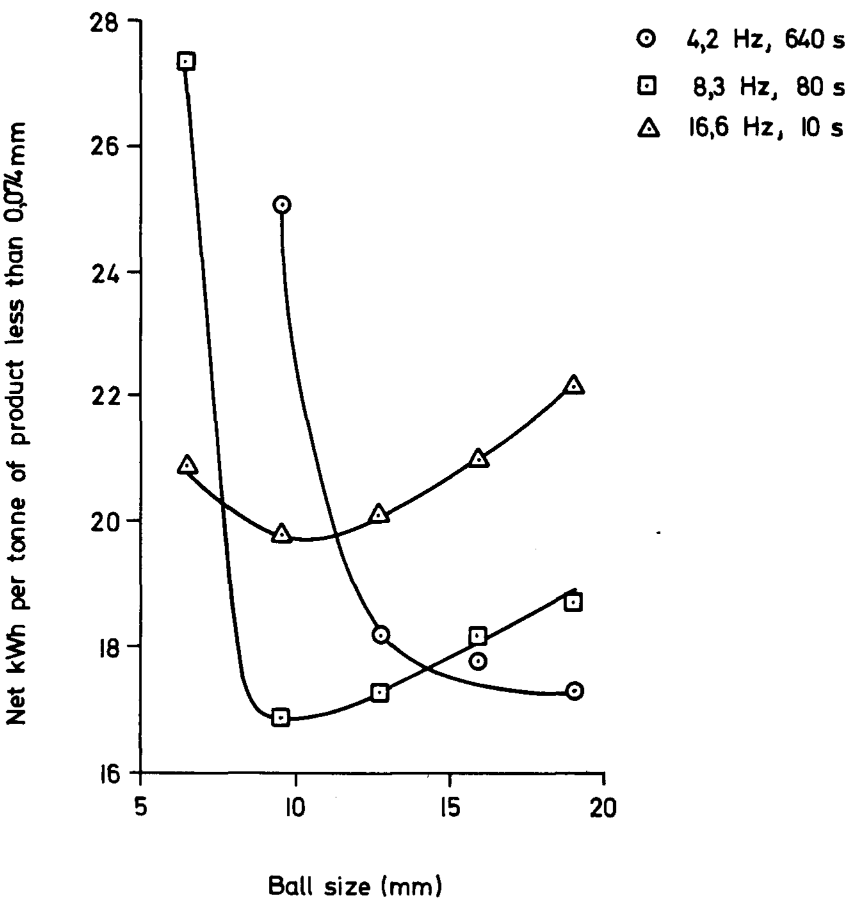


**Fig. 4—The effect of rotation speed and ball size on the net consumption of energy.**

TABLE I

PREDICTED PERFORMANCE OF THE PROTOTYPE MILL

| | | | | | | |
|---|---|---|---|---|---|---|
| Rotation speed, Hz | 3,3 | 5 | 6,7 | 8,3 | 10 | 11,7 |
| Net power, kW | 4,1 | 13,7 | 32,5 | 63,5 | 110 | 174 |
| Centripetal acceleration, 10 $m^2/s^2$ | 0,9 | 2,0 | 3,5 | 5,6 | 8,0 | 11,0 |
| $-74\,\mu m$ material, t/h | 0,15 | 0,50 | 1,28 | 2,3 | 4,0 | 6,4 |

The feed enters a conical rotating hopper having three 30 mm outlets at its base. These outlets discharge into a spiral feeder[6] attached to each grinding tube; this arrangement was chosen because it obviates the need for any seal between the hopper outlets and the grinding tube. The product of the mill is discharged by overflowing down a trunnion and is caught in a slurry tray. A screen may be fitted in each grinding tube as shown. The whole assembly is driven by a hydraulic motor, an arrangement that was used to allow variable-speed operation without great loss in efficiency.

The mill is operated vertically. This does not mean that there is any risk of discharge due to gravity, because, even at the lowest speeds used, the centripetal acceleration is over 90 $m/s^2$, or nine times that due to gravity. The upper level of the charge thus lies effectively vertical during operation.

The predicted performance of the mill is given in Table 1. Tests of the performance were carried out on batches of a crushed quartzite containing 15 per cent by mass of plus 4,76 mm material and 14 per cent of minus 0,074 mm material.

The grinding medium was initially 17,5 mm steel balls, but, during repeated tests on successive batches of feed, the ball charge was worn towards an equilibrium size distribution that varied with the speed at which the tests were carried out. Fig. 6 shows the results of these tests, and it is clear that, as the ball charge was worn towards the equilibrium size distribution, the grinding efficiency increased. This was also indicated by the energy consumption, which was about 40 kW h/t ot minus 74 $\mu$m material with the initial ball charge, but which fell to between 23 kW h/t at 6 Hz and 29 kW h/t at 10 Hz at the end of the test period.

The equilibrium capacity of the mill appears from Fig. 6 to be slightly over 1 t of minus 74 $\mu$m material per hour at 6 Hz, about 2 t/h at 8 Hz, and 4 t/h at 10 Hz. This is in gratifyingly close agreement with the performance predicted from the results of small-scale batch tests.

The mill has been installed on a mine where it is now being operated in closed circuit. Circulating loads of up to 500 per cent can be achieved by the use of one or more 76 mm cyclones in parallel. The mill discharge can contain up to 25 t of solids per hour. Fresh feed is drawn from an ore bin independent of the main mill supply, and is fed to the mill by a belt feeder at rates of up to 12,5 t/h. The feed, which is nominally minus 7 mm, can be diverted into a bin mounted on a weightometer to calibrate the feed rate. Fresh feed can go either direct to the mill or direct to the cyclones. The mill discharge, which contains 60 to 70 per cent moisture, passes through a flow-

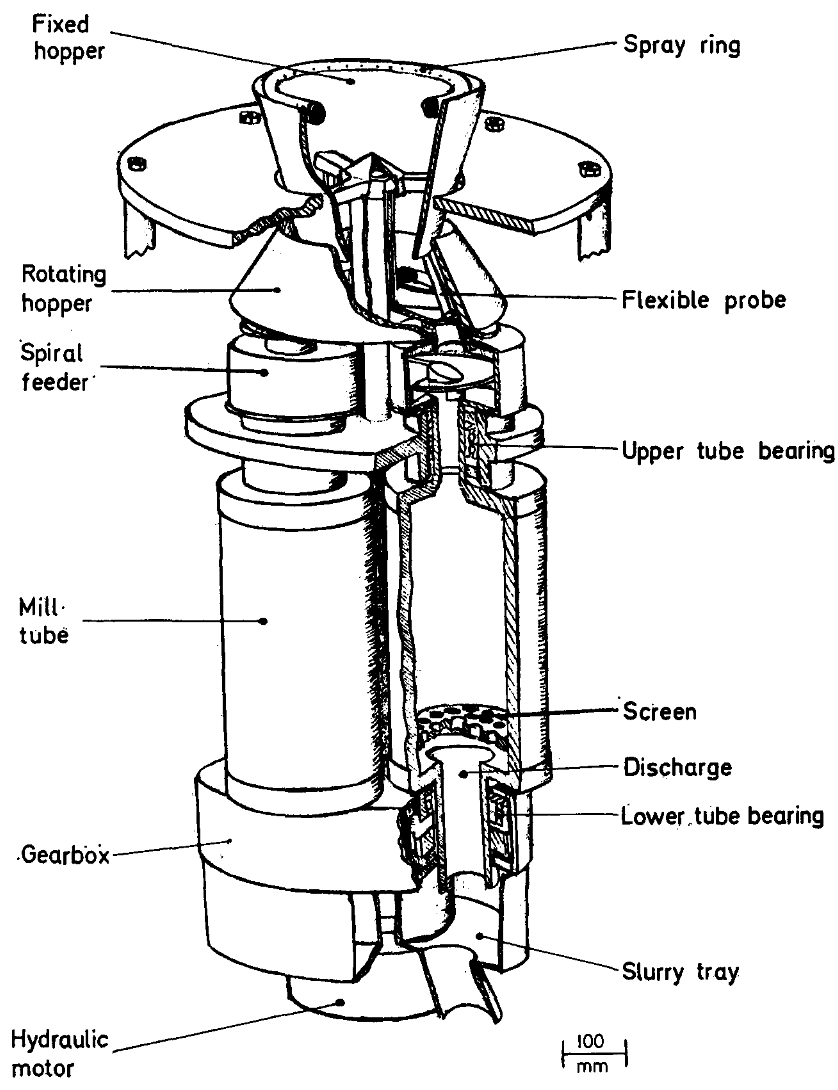


**Fig. 5—Diagram of the three-tube prototype centrifugal mill.**

meter into an agitated sump 1,8 m diameter by 1,8 m high. The sump level is maintained constant by the addition of water. The grinding medium is steel of 16 mm diameter by 19 mm and is fed to the mill by a vibratory feeder. The rate of feed is controlled manually by observation of the power drawn by the mill. Because of the short residence time in the mill (about five seconds), this method of control is very satisfactory, and changes in the feed rate can be detected virtually instantaneously. Any medium that escapes from the mill is caught by permanent magnets installed in the discharge launder.

Much of the work on the mill in its present form has gone into gaining experience and confidence in its use as a continuous production tool. Various features can be summarized as follows.

*Productivity*

It has proved difficult to determine the productivity with any degree of precision, but instrumentation installed recently has indicated a high probability that 2,5 t of minus 75 μm material per hour is exceeded when the cyclone overflow is approximately 70 per cent by mass of minus 75 μm material and the mill is operated at 8,3 Hz.

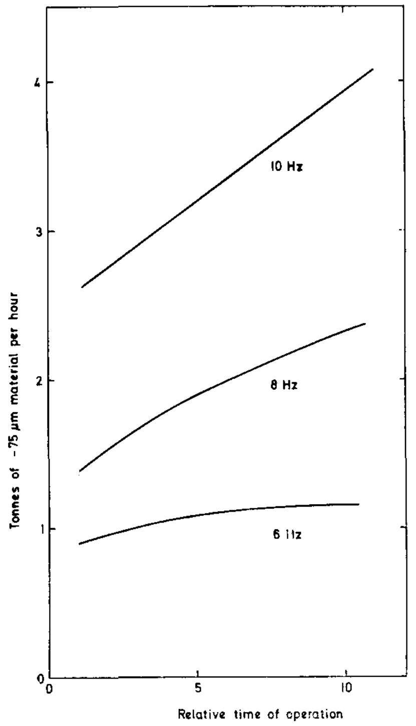


**Fig. 6—The performance of the prototype centrifugal mill in long-term continuous open-circuit operation.**

*Throughput*

When the mill is operated as an overflow mill, throughputs of 25 t of solids per hour have been achieved. Discharge screens to retain the grinding medium have proved to limit the throughput to about 15 t/h at 8,3 Hz operation.

*Energy Consumption*

Because of the difficulties experienced in the precise determination of mill productivity, it has proved difficult also to estimate the power demand. However, the figure of 2,5 t of minus 75 μm material per hour at 8,3 Hz indicates a net energy consumption of about 26 kW h per tonne, which is in good agreement with the energy consumption in conventional milling on the mine at which the work is being undertaken. The net energy in this case includes corrections for the efficiency of the hydraulic-drive system employed on the mill and for the power demand of the pump to feed the cyclones.

*Consumption of Grinding Media*

The steel being used is by no means optimized for wear performance. Accordingly, the estimated consumption of about 4 kg per tonne of minus 75 μm material produced seems reasonable.

*Liner Wear*

Mild-steel liners appear to be worn in the centrifugal mill at approximately 1 kg per tonne of minus 75 μm material produced. Because of the small mass of the wear parts within the mill, this indicates a liner life of only 12 hours at 10 Hz operation, which may seem catastrophic were it not for the fact that the mill tubes can be replaced in about 3 hours with the mill in its present configuration. Rubber liners appear to be more successful, and the mill is currently being operated with a serrated rubber liner. A wear rate of only 0,13 kg per tonne of minus 75 μm material has been indicated in some tests, and there is confidence that this can comfortably be exceeded. The implications of liner wear in the centrifugal mill are discussed more fully below.

*The Wear of Screens and Other Internals*

Discharge screen wear has been very rapid. Cast polyurethane screens lost up to 50 per cent of their thickness (20 mm) in 4 hours of operation at 8,3 Hz, mild-steel screens lost up to 64 per cent of their thickness (12 mm) in 8 hours, and wear-resistant steels lost up to 70 per cent of their thickness (12 mm) in 11 hours, most of this wear occurring at the centre of the screen. As noted above, however, screens have been found to limit the throughput of the mill severely, and, accordingly, the preferred method of operation is without discharge screens, i.e., as an overflow mill. Little grinding medium escapes from the mill whilst it is in operation, and, because of the small size of the medium, it is possible to pump the medium to the cyclones, where it reports to the underflow and is recycled to the mill. Wear of other parts of the mill has been slight. Mild-steel spiral-feeders wore through after the passage of about 1000 t of fresh feed, but rubber liners in this position are showing no apparent wear after the passage of a similar tonnage. The liner end pieces and the discharge trunnion liner, all made of rubber, appear to be behaving satisfactorily.

*Feeding*

No particular difficulty has been experienced in the feeding of ore up to 15 mm in size, but choking was experienced at 22 mm during a test of autogenous grinding. Grinding medium was found to choke the tubes leading from the hopper to the spiral feeders, but these tubes have been enlarged and straightened to overcome this difficulty.

*Discharge*

No difficulty has been experienced with the discharge system.

*Operation*

Startup and shutdown have proved to be relatively simple, although, when the mill is operated vertically and without discharge screens, the contents of the tubes are released on shutdown and during startup this charge must be built up again. In future designs, however, horizontal operation would overcome this difficulty. The mill has operated in reasonable balance provided no chokes have occurred. Some self-balancing is expected because tubes with an excess of charge will draw more power and thus wear the charge more rapidly. In one test, of 124,4 kg fed, the 64,8 kg of grinding medium remaining was found to be distributed among the three tubes as follows: 20,9 21,6 22,3 kg. Any choking rapidly puts the mill out of balance, but stopping the feed and operating at reduced speed usually clears the choke quickly and brings the mill back into balance. During prolonged operation, the oil in the hydraulic-drive system heated up more than was expected, and it has been necessary to install a water cooler to prevent overheating.

*Maintenance*

The maintenance necessary has been mainly the replacement of worn parts as noted above. However, the upper bearings failed when dirt passed through incorrectly installed seals, and examination of the gearbox revealed excessive wear, which was traced to underdesign of the gears. In other respects, the prototype has required no significant maintenance.

Thus, at the present stage, confidence has been generated that the prototype centrifugal mill can be operated continuously and for relatively extended periods. Present work is aimed at a demonstration of the availability of the mill as a production tool, because it is believed that availability is a better measure of liner performance than the period between relinings, particularly as the time taken to reline the mill completely is measured in minutes rather than in days.

## DEVELOPMENTS FROM THE PROTOTYPE

At the present stage, it is believed that an 80 per cent availability can be demonstrated for the prototype mill, and that this is the only parameter in its performance that in any way puts it at a disadvantage in a comparison with conventional mills, which have an availability of about 95 per cent. Two lines of attack are being mounted on this problem. The first has arisen from an assessment of the time taken to change liners on the prototype. Not only is the design of the prototype very cramped, but three tubes must be removed during the liner change. Patently, the time taken to replace the liners could be drastically reduced if there were only a single tube, and if a less compact design were adopted.

Studies have shown that a single tube design is not only practical but that it can offer a number of advantages in addition to reducing the time taken for relining. Plate II shows a working model of such a design, with a large-diameter spiral feeder above, a short grinding tube counterbalanced by a single weight, discharge ports just above the counterbalance arm, and a main driving motor that turns the mill via a two-gear gearbox. The whole assembly, including the main driving motor, is turned by a low-powered subsidiary motor that is merely required to provide the centripetal acceleration. The feeding of this mill is simple, because the spiral feeder can be made so that there is an opening which is stationary at the axis of gyration, and there is thus no need for a rotating hopper as on the multitube mill. The single tube can be removed and replaced extremely rapidly, as required for minimizing the time taken to reline. The drive system is extremely simple and permits very smooth start-up, because the main driving motor effectively draws no power until the subsidiary motor starts and, if the subsidiary motor is of variable speed, the rate of build-up of power demand by the main motor can be controlled by the rate at which the subsidiary motor is brought up to speed. In addition, with a mill of large diameter relative to the amplitude of gyration (i.e., with a small $G/D$ ratio), a machine of a throughput equal to that of a multitube machine can be designed, which occupies no greater volume.

A prototype based on this principle has been designed and is being built for the testing of new liner systems. It is expected that this machine will make it possible to demonstrate that availabilities of over 90 per cent are feasible without any further improvements in liner performance.

The second line of attack on the problem of improving the availability of the centrifugal mill is in the direction of new liner systems. Because the area of the mill is so small relative to its throughput, comparatively exotic materials can be considered for the liner. Compounds such as boron carbide and tungsten carbide have been studied, and, while they do indeed show promise of increasing the availability of the mill, they do not appear to do so to an extent that would nullify their high cost. A more promising solution appears to lie in the direction of pneumatic rubber liners[7].

This development is based on the fact that a minimum thickness of solid rubber is required to resist wear during impact. Thicknesses of solid rubber less than this minimum have insufficient energy absorption to resist impact and therefore wear rapidly. However, a thin layer of rubber backed by a fluid has an energy absorption at least as good as a thick layer of solid rubber, even when the total thickness of the pneumatic system is less than that of the solid rubber. In addition, of course, abrasive wear can take place in the mill, but again there is reason to suppose that the pneumatic system is superior to solid rubber, because the rubber in the pneumatic system can more readily be placed in compression within the mill, in which condition rubber is far more resistant to abrasive wear than it is when unstressed or in tension. This development is being pursued in association with an international rubber company that is to manufacture liners for test in the single-tube prototype.

## THE FUTURE FOR THE CENTRIFUGAL MILL

From what has been said in the previous sections, it is obvious that the centrifugal mill is at present by no means a fully developed machine. However, there are most cogent reasons for believing that development should continue, and it is the purpose of this section to briefly review those reasons.

Firstly, there is every prospect that the centrifugal mill will offer the conventional mill strong competition in normal fine-grinding applications. The centrifugal mill should cost not more than 15 per cent of the cost of a conventional mill of equal capacity, and should be able to be installed for far less than a conventional mill. It should be far

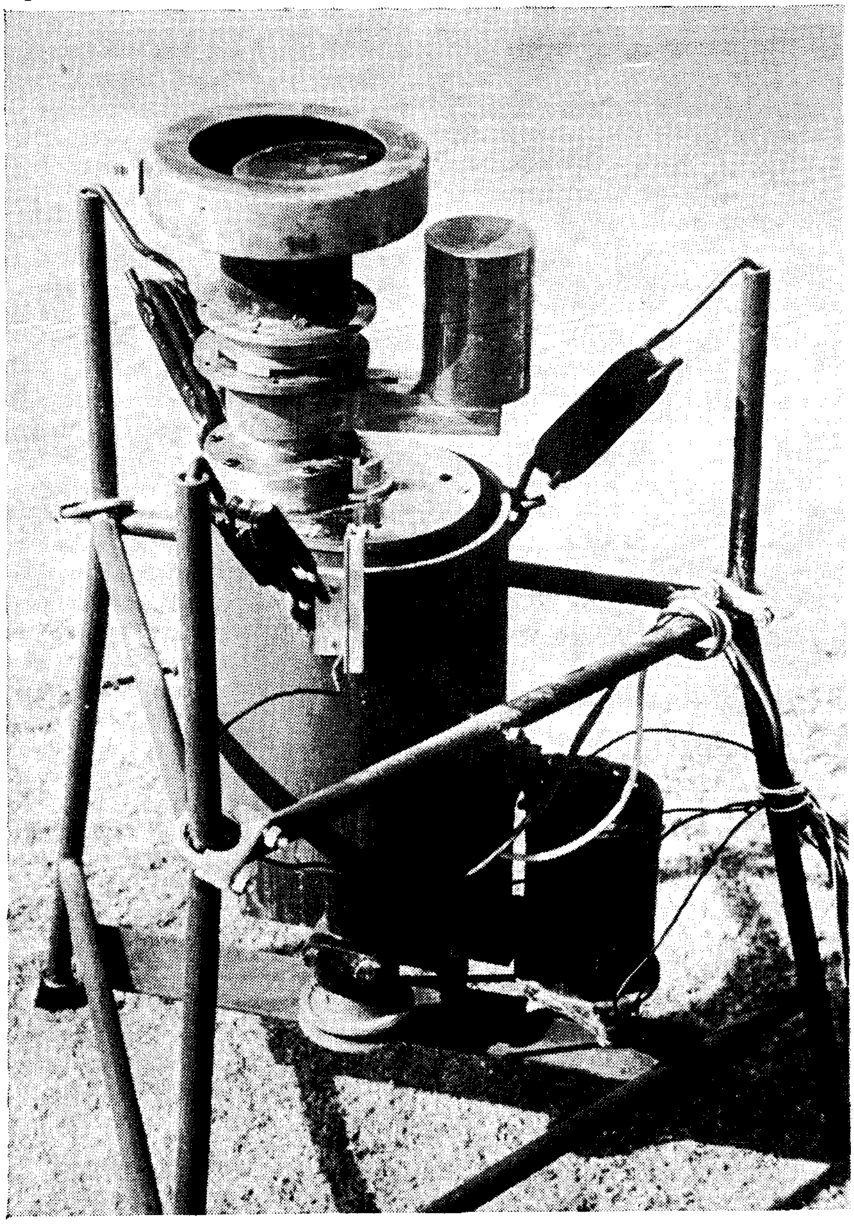

**Plate II—A working model of a single-tube continuous mill. A description of the components is given in the text.**

easier to drive, because the power must be transmitted at relatively high rotational speeds, and drive shafts and gears can thus be reduced in size. As described earlier, smooth start-up can be expected without the need for expensive switchgear or clutches. Control of the milling operation may be simplified because of the rapid response to changes in the inputs. There may be new possibilities for autogenous or pebble milling because of the freedom from limitations on the availability of pebbles of adequate size. The chief disadvantage may be the need for more frequent maintenance, but this may be offset by a reduction in the size of the inventory of wear parts.

Secondly, there is a possibility that the centrifugal mill can be used in an unconventional role in the system for the recovery of metals from ores. Some possible applications in open-pit operations were reviewed previously[8], when it was shown that a system comprising a mobile crushing and centrifugal milling plant within the pit, and hydraulic hoisting of the milled ore from the pit, could offer significant economies. There is merit in the consideration of such a step in some detail, because the conventional means of transporting ore from an open-pit mine can involve costs as high as 40 per cent of the total cost of winning the metal. A hydraulic-hoisting system would offer advantages over the conveyor systems already used because of greater flexibility and lower capital cost.

The possible implications of a similar rock-transportation system in underground mines have also been reviewed[9]. In that study, it was found that, in deep-level mines, there might be great merit in making more general use of incline shafts for the transport of men and materials, and milling of the ore followed by hydraulic hoisting. If underground milling were to be practised, it would be necessary to use very small mills, i.e., either a multiplicity of small conventional mills or a relatively few centrifugal mills.

There would also be great merit in performing some metallurgical treatment underground on the milled ore in order to concentrate the metal values and generate a waste suitable for hydraulic backfill. The implications of such a step are considerable, and require far more assessment than has thus far been possible. However, it can safely be said that it would offer the following:

(1) a marked reduction in the tonnage to be hoisted, and consequent release of hoisting capacity for other purposes;
(2) an improvement in strata control, which might make practical an increase in the amount of ore that could be mined at great depths;
(3) a reduction in the quantity of materials needed for support, and a consequent reduction in the fire hazard; and
(4) a means of mining a series of reefs that are too closely spaced to be mined by present methods.

A constraint on the use of milling equipment underground would be the additional heat load on the ventilation system. This effect might, however, be minimized by appropriate siting of the equipment, and by the reduction in heat pick-up from worked-out areas once they were filled.

At present, the study is being directed at means for the concentration of gold and other minerals into a concentrate that is 20 to 40 per cent by mass of the feed and that contains more than 95 per cent of the gold in the feed. A possible 5 per cent loss of gold may appear very high at present gold prices, but it should be remembered that, below certain depths, it is currently being found necessary to leave up to 20 per cent of the reef *in situ* for support purposes. In addition, if lower tonnages are fed to existing reduction works, an increase in their efficiency may be expected, which would lead to a recovery of some of that 'lost' gold.

## CONCLUSIONS

In this paper, the theory of centrifugal milling has been presented briefly and it has been demonstrated that the theory is obeyed in practice. Means for the scaling up of centrifugal mills have been suggested, and a test of those means has indicated that the results of small-scale batch tests can be applied to the design of large continuous machines that will give predictable performance.

Tests of a prototype machine have indicated that continuous centrifugal mills are powerful, compact machines on a practical scale, and that they can be operated for long periods without difficulty. Liner wear, however, reduces the productive availability of these mills, and, while there are a number of possible solutions to this problem (such as increasing the number of machines for a given duty, or reducing the number of grinding tubes), it has not been demonstrated that centrifugal mills can match the availability of conventional mills, the best expected availability being about 90 per cent.

New liner systems may offer a means for improving the availability of centrifugal mills, and pneumatic liners have particular promise for achieving this end.

The advantages of the centrifugal mill over the conventional mill have been outlined. These advantages are such as to suggest that there is great merit in pursuing the further development of the mill. In particular, the availability of centrifugal mills would permit an integration of milling and rock transport in mines. In both open-pit and underground mines, this integration offers considerable financial advantages. In addition, it is possible to consider simple metallurgical procedures to reduce the tonnage of ore to be transported to surface, and this holds promise of permitting a new method of mining to be developed for the South African gold-mining industry.

## ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance of many individuals, particularly the staff of Durban Roodepoort Deep, Limited, and Messrs G. R. Jennery, R. Neilson, D. G. Sheppard, and P. Willows. In addition, they acknowledge the permission granted by the Chamber of Mines of South Africa to publish this paper.

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