J. S. Afr. Inst. Min. Metall., vol. 88, no. 2.
Feb. 1988. pp. 49-57.

The effects of mill speed and filling on the behaviour of the load in a rotary grinding mill*

by K.S. LIDDELL† and M.H. MOYS‡

SYNOPSIS

The dynamics of the ball load within a wet-grinding mill are examined, using measurements of torque and load position. The test equipment provided an accurate torque measurement, and the toe and shoulder positions of the load were measured by the use of a conductivity probe mounted in the mill shell.

Both the variables tested—mill filling and rotational speed—influence the position of the load, and hence the torque, and have interactive effects on both the torque and the load position. An increase in mill speed and filling causes the torque to increase to a maximum value, after which further increases in speed or filling cause the torque to decrease. The position of the load toe is influenced only by the filling up to speeds of approximately 80 per cent of critical, whereas the speed and filling both cause the load shoulder to rise as their magnitudes are increased.

The power drawn by the mill is predicted by the use of published equations, and these values are compared with the measured power draw.

SAMEVATTING

Die dinamika van die ballading in 'n natmaalmeul word ondersoek met gebruik van metings van die draaimoment en die posisie van die lading. Die toetstoerusting het 'n akkurate draaimomentmeting gegee en die voet- en skouerposisie van die lading is gemeet met gebruik van 'n geleivermoësonde wat in die romp van die meul gemonteer is.

Albei die veranderlikes wat getoets is—meulvulling en draaispoed—beïnvloed die posisie van die lading, en dus die draaimoment, en oefen 'n wisselwerking uit op sowel die draaimoment as die posisie van die lading. 'n Toename in die meulspoed en vulling laat die draaimoment tot 'n maksimum waarde styg, waarna verdere toenames in die spoed en vulling die draaimoment laat afneem. Die posisie van die lading se voet word net tot by snelhede van ongeveer 80 persent van die kritieke waarde deur die vulling beïnvloed, terwyl sowel die spoed as die vulling die lading se skouer laat styg namate hulle vergroot word.

Die krag wat die meul sal trek, word met behulp van gepubliseerde vergelykings voorspel, en hierdie waardes word vergelyk met die gemete krag wat getrek is.

Introduction

The grinding process is reasonably well understood, and can be analysed using the 'selection' and 'breakage' functions. These functions have been the subject of a considerable amount of investigation, and there are numerous publications relating to them. Grinding mills have been designed with some degree of confidence for many years, but very little practical information is available that describes the motion of the grinding load inside a mill, and the influence of variables such as rotational speed, mill filling, and the characteristics of the pulp have on that motion. The motion and the position of the load have the major influence on the power drawn by a mill.

A number of equations have been derived that predict the power drawn by a mill from the geometry of the load, but these are not based on direct observations of what occurs inside a mill, and are over-simplifications. In 1945, A.F. Taggart stated that the net power of a grinding mill cannot be determined analytically because of a general ignorance of the internal dynamics of the tumbling load. In 1985, C.C. Harris commented that, in the 40 years since 1945, few attempts had been made to dispel this ignorance, and that Taggart's observations remain essentially valid.

In the present investigation, measurements of the torque and the positions of the toe and shoulder of the load in a mill were used to establish the effects of filling and speed on the motion of the load in a mill filled with steel balls and a pulp composed of sand and water. A pulp was used in the mill, rather than dry material, so that the viscosity and friction effects that it provides would give more meaningful results. Although steel balls were used as the grinding charge, the results would also be applicable to autogenous milling.

Experimental Equipment and Method

The milling equipment used, which has been discussed in detail elsewhere[1], was designed to allow the torque to be measured to within an accuracy of 0,5 per cent. The milling chamber is joined directly to an axle mounted on load cells. A 2,5 kW variable-speed d.c. motor is slung in a cage that is coupled to the axle by bearings, and the axle is rotated by the motor through a chain-and-sprocket drive. The motor cage is restrained from rotating by a load cell connected by a flexible coupling to a projecting arm fixed to the motor cage. The output from the load cell was logged by an HP2240 measurement and control processor controlled by an HP85C computer, which calculated the torque several times during every revolution of the mill. This method of torque measurement makes allowance for losses in the drive train and bear-

* Paper presented at the Colloquium on Milling, which was held at Randburg by The South African Institute of Mining and Metallurgy on 9th June, 1987.

† Group Leader: Precious Metals, Ore-dressing Division, Council for Mineral Technology, Private Bag X3015, Randburg, Transvaal 2125.

‡ Senior Lecturer, Department of Chemical Engineering, University of the Witwatersrand, P.O. Wits, 2050 Transvaal.

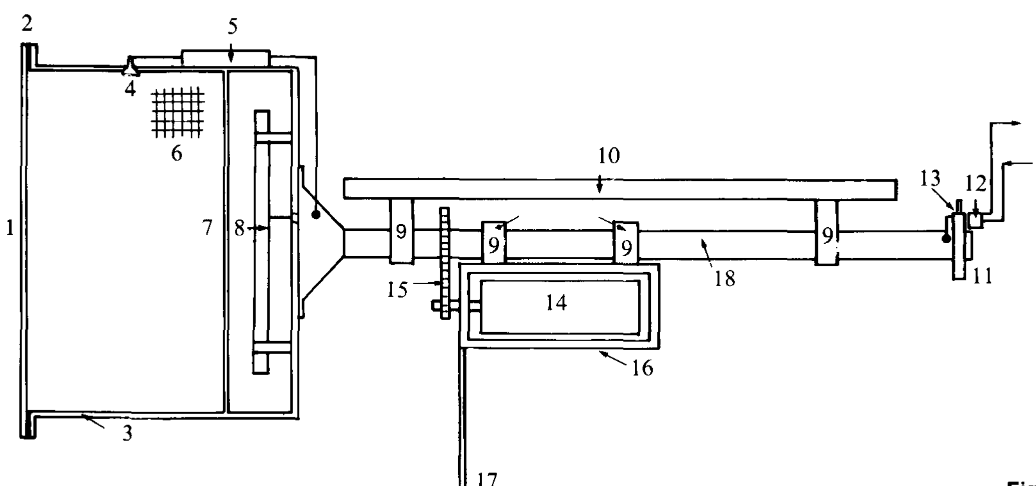
ings. The essential features of the equipment are shown in Fig. 1. The rotational speed, which was controlled by the computer to within an accuracy of 0,5 per cent, was measured by a pick-up switch activated by a cam mounted on the axle. The output from the switch was monitored by the computer and used to adjust the set point for the speed-control unit of the motor to maintain the required mill speed. A conductivity probe mounted in the mill shell showed when it was in contact with the load by indicating a change in conductivity. This change occurs because the load completes an electrical circuit between the probe and the mill liner. The probe was insulated from the liner and the shell by a coating of epoxy putty, as shown in Fig. 2.

Although the periodic signal from the probe was fairly complex, it had specific features that were repeated in every revolution. These allowed threshold levels to be set so that a simple square-wave signal could be produced by a signal-conditioning circuit for analysis by the computer. The thresholds were set by observing the periodic signal on an oscilloscope. The threshold was adjusted to cut the signal at a specific point, as shown in Fig. 3. A reference point obtained from the switch used for monitoring the rotational speed was used for the resetting of a timer in the computer at every revolution. Thus, the signals from the conductivity probe could be related to the reference point, and the angular positions of the toe and shoulder of the load could be determined. The positions are expressed as fractions of the mill circumference in the direction of rotation, with the 12 o'clock position as the datum.

The mill chamber inside the liners had a diameter of 0,545 m and an internal length of 0,308 m. The liners consisted of 13 mm woven-wire mesh, which was chosen in preference to lifter bars or wave liners for two reasons: so that the load would key into the liner thus avoiding slip, but so that the liner would not influence the motion of the load. In this way, the position of the *en masse* load could be examined.

The grinding charge consisted of steel balls varying in size from 10 to 40 mm; the balls had a bulk density of 4,81 t/m^3 and a voidage of 40,4 per cent. The volumes of pulp were chosen so that 85 per cent of the voids were filled. Previous investigations[2,3] had shown that grinding rates are at a maximum between voidage fillings of 80 and 100 per cent. The particulate material used to make up the pulp was tailing sand from a gold mine (Witwatersrand quartzite) having a d_{90} of 234 μm and a d_{10} of 62 μm. The solids content of the pulp was maintained at 70 per cent by mass (46,6 per cent by volume), which is typical for industrial mills, and the bulk density of the load was 5,42 t/m^3. This pulp exhibited properties of pseudoplastic flow, and had a viscosity of 90 mPa·s at a shear rate of 100 s^{-1}. The pulp provided the friction and viscosity necessary to ensure that the motion of the load would be realistic, i.e. like that in industrial mills.

The mill was operated in a batch mode, and was loaded with a charge of balls to give the desired filling of 30, 40, or 50 per cent (bulk load volume/mill volume). The requisite amounts of sand and water were then added to form the pulp. The mill was rotated at 75 per cent of critical speed for approximately 40 revolutions to mix the charge, and to allow the probe signal and threshold cut-point to be examined. The speed was reduced to 50 per cent of critical and, after the speed and torque had stabilized, readings of the torque and the position of the load were taken once in every revolution for approximately 120 revolutions. The speed was then increased to 60 per cent of critical, and the procedure was repeated. In



1 Polycarbonate end-plate
2 Rubber gasket
3 Mill shell
4 Conductivity probe
5 Signal processor
6 13 mm grid lining
7 Polycarbonate bulkhead
8 Fluorescent light
9 Bearings
10 Support beam (hung on load beams, which are not shown)
11 Slip ring
12 Carbon brush pick-ups
13 Switch for monitoring mill speed (activated by a rise on slip ring)
14 Motor and gearbox
15 Chain drive
16 Motor cage
17 Torque arm
18 Axle

Fig. 1—Essential features of the milling equipment

Exploded Assembled

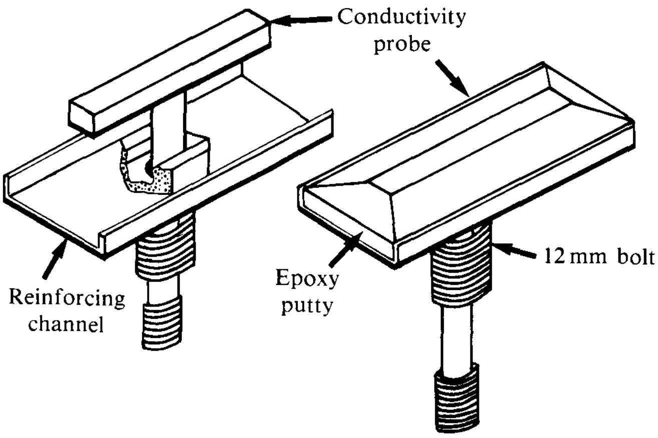
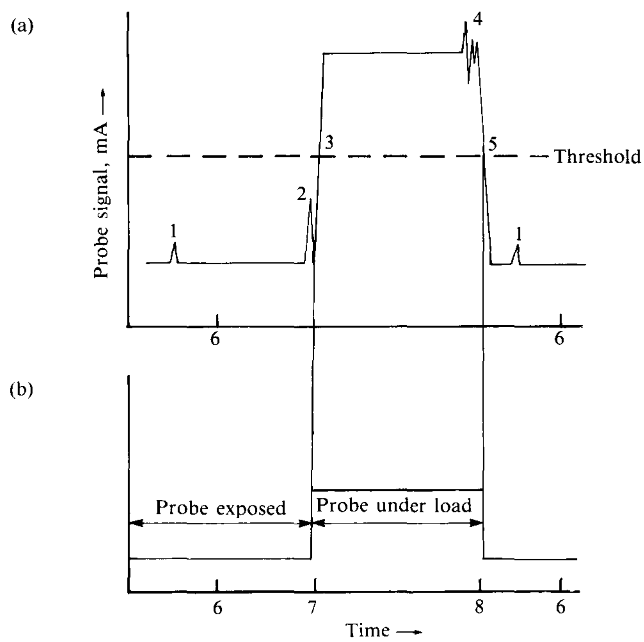


Fig. 2—The conductivity probe



1. Small peak when probe is in the 12 o'clock position, probably due to drainage of pulp
2. Small peaks before probe enters the load toe, due to splashes and rebounding balls
3. Threshold indicating toe position
4. Peaks near shoulder position, indicating some load movement
5. Threshold indicating shoulder position
6. Marker signal
7. Toe position read by the computer relative to the marker
8. Shoulder position read by the computer relative to the marker

Fig. 3—General features of the probe signal
(a) Probe output
(b) Synthesized output seen by the computer

this way, the speed was sequentially increased to 70, 75, 80, 90, and 95 per cent of critical. When the mill had run at 95 per cent, the speed was progressively reduced to 50 per cent, and the torque and load position were measured again. The averages of the two sets of measurements for speeds up to 95 per cent of critical were calculated and, in this way, the measurements for each speed were related to conditions occurring after approximately 850 revolutions.

Results and Discussion

The Effect of Mill Speed

In general, ball mills operate at speeds varying between 70 and 80 per cent of critical, whereas autogenous and semi-autogenous mills operate at speeds up to 90 per cent of critical, but where this occurs it is probably because slippage is occurring between the load and the liners, and the mill has to be run at a higher speed to overcome this and to rotate the load at an acceptable speed. There is a trend among mill manufacturers to reduce the fraction of critical speed as the mill diameter increases—presumably to reduce the increase in peripheral speeds.

Fig. 4 shows the effect of mill speed on torque for three fillings of 30, 40, and 50 per cent, as well as the interactive effects of speed and filling. At the lowest filling of 30 per cent, the torque profile is fairly shallow, and a relatively indistinct maximum occurs at 81 per cent of critical. At fillings of 40 and 50 per cent, more distinct maxima can be seen, with rapid reduction in the torque as the speed increases beyond that at which the maximum torque occurs. The rate of reduction of the torque increases when the filling is increased, whereas the rate at which the torque increases up to the maximum is similar for all the fillings.

As the speed increases from 50 to 80 per cent of critical, there is very little change in the position of the toe of the load at a given load volume, whereas the shoulder is observed to rise further up the mill (Fig. 5). For fillings of 40 and 50 per cent and speeds higher than 80 per cent of critical, the toe position rises up the down-coming side of the mill, indicating that the falling mass of grinding medium is impacting directly onto the liners rather than onto the medium at the toe. It is at these speeds that the torque shows a large reduction and, since the shoulder position rises uniformly at all speeds, the reasons for the reduction in torque at higher speeds can be inferred from measurements of the toe position.

At the higher speeds, at which the torque is decreasing, the load is in a cascading condition where a portion of it is in free flight, resulting in a reduction of the effective mass of the load. Also, the falling grinding medium lands on the liners and in the outer regions of the toe at such an angle that some of its kinetic energy is converted into a turning moment that assists in the rotation of the mill. Fig. 6 illustrates the change in the position of the load, by showing the measured positions of the toe and shoulder at speeds of 50, 75, and 90 per cent of critical (at a filling of 40 per cent), and the profiles of the upper surfaces of the load. At the lowest speed, the load is cataracting, and the upper layers of balls roll from the shoulder to the toe. At the intermediate speed (at which the maximum torque is experienced), the outer layers of falling balls have parabolic paths but still impact into the toe area; the load is probably in a condition between cataracting and cascading. At the high speed, the load is cascading, and the outer layers of balls impact onto the liners; the load is now fairly dilated.

For speeds up to about 85 per cent of critical, the toe position is independent of speed, as can be seen from the gradients of the lines in Fig. 5, which are very low. The

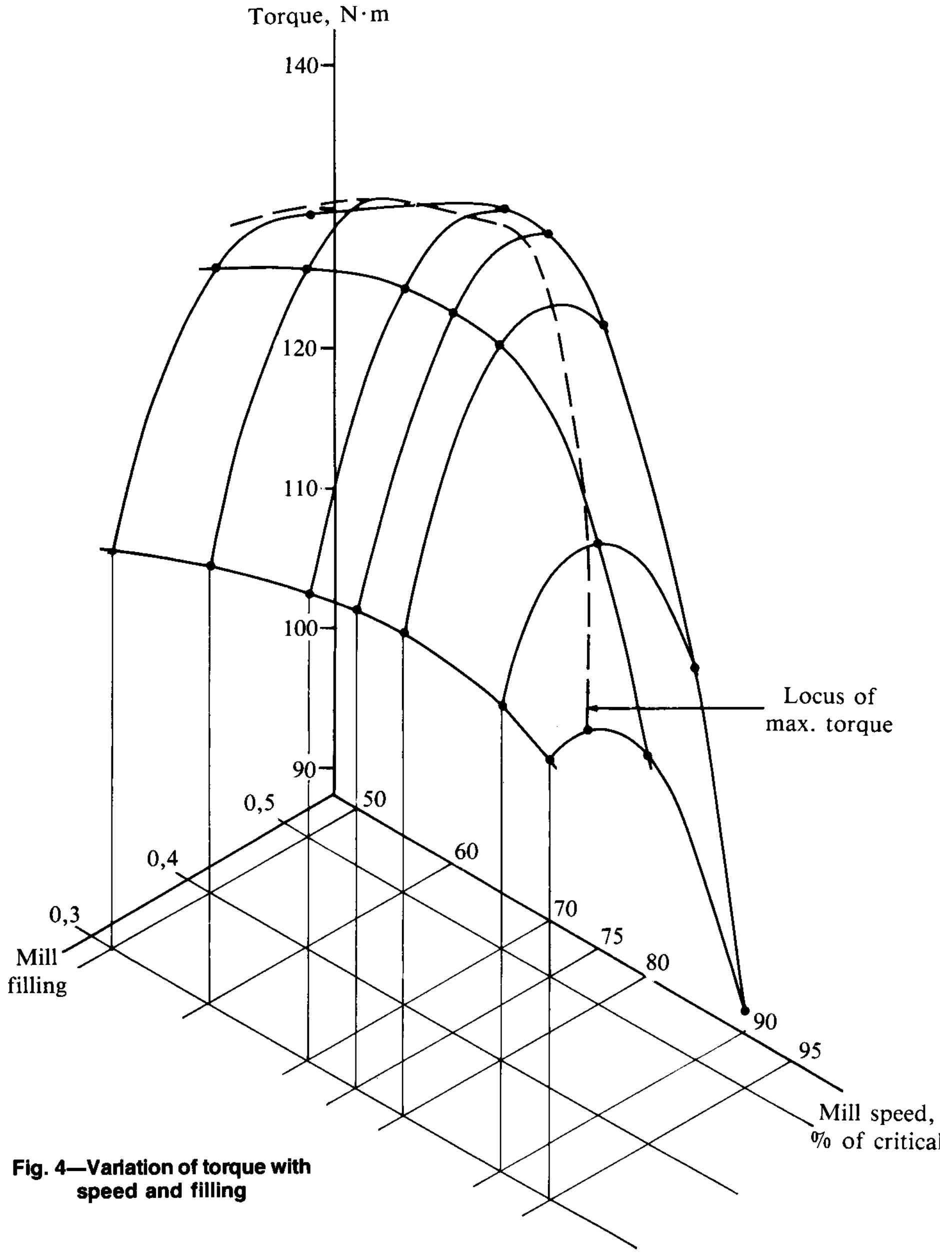


Fig. 4—Variation of torque with speed and filling

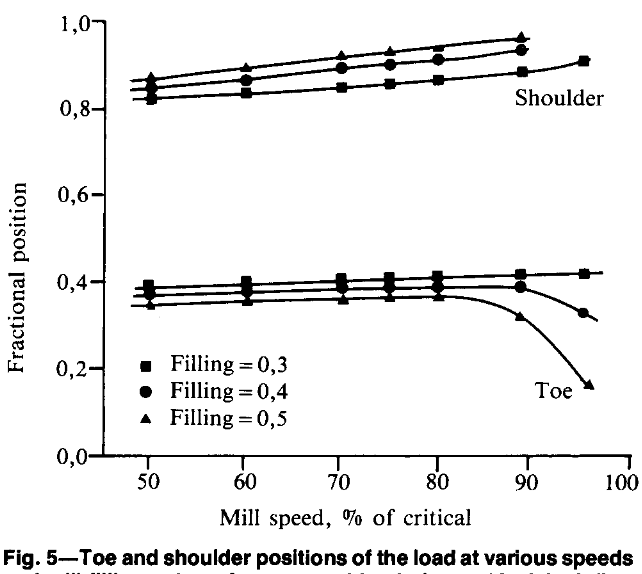


Fig. 5—Toe and shoulder positions of the load at various speeds and mill fillings, the reference position being at 12 o'clock (i.e. positions 0,0 and 1,0)

toe position has also been found to be unaffected by the solids content of the pulp in the range 60 to 75 per cent by mass[4]. This phenomenon of invariant toe position is thought to occur because the load, which can be regarded as a granular fluid, causes the toe to maintain an equilibrium position, which is determined primarily by the volume of the load within the mill.

The position of the shoulder of the load at the liner for various fillings and speeds is shown in Fig. 7, which demonstrates that an increase in either the speed or the filling causes a rise in the position of the shoulder. Also shown is the theoretical position, which is based on a force balance derived by Davis[5]. The force balance, which is for a single particle in an ideal system, where there is no crowding by other particles and no adhesion or viscosity effects due to the pulp, takes into account only the rotational speed of the mill and not the filling. In all the cases tested except that for a 30 per cent filling at speeds greater than 80 per cent critical, the actual shoulder position is higher than that predicted by Davis's

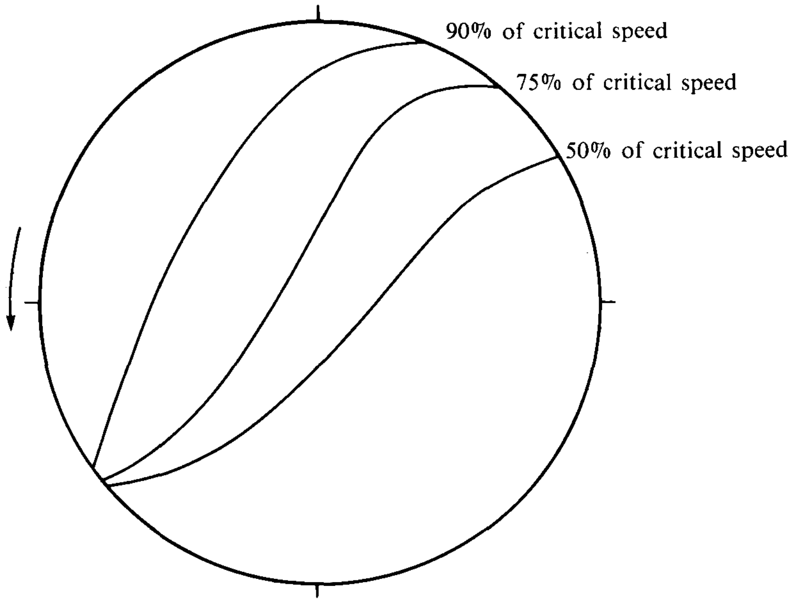


Fig. 6—Measured toe and shoulder positions of the load at various speeds, and profiles of the upper surface of the load

analysis, indicating that his analysis is too simplistic. At a filling of 30 per cent and speeds greater than 80 per cent of critical, the measured shoulder positions lie lower than those predicted by Davis because slip occurs between the load and the liner. This has been discussed in more detail elsewhere[4].

The Effect of the Degree of Filling

It has been demonstrated that mill power has a parabolic dependency on filling[6-8]. At constant mill speeds, torque is directly proportional to power, and therefore the torque can be expected to be a parabolic function of the filling at constant speed. The torques measured for each filling at a constant speed were fitted to parabolic equations, and are shown in Fig. 4; the maximum torque and the filling at which each occurs are given in Table I.

As the mill speed increases from 50 to 75 per cent of critical, the value of the maximum torque increases, while at faster speeds the value of the maximum torque decreases rapidly. Similarly, the filling at which the maximum torque occurs increases as the speed rises from 50 to 75 per cent of critical, after which there is a rapid decrease. The values of maximum power, which are also given in Table I, are seen to increase up to 90 per cent of critical because the power is a function of the rate of rotation as well as of the torque. This demonstrates that, when the condition of the load is being investigated, examination of the torque is more informative than examination of the power.

It is of interest to note that, for common operating speeds (70 to 80 per cent), the maximum torque occurs at a filling of approximately 45 per cent, which is the practical maximum to which mills can be loaded. It has also been shown[7] that the breakage rate is at a maximum when the filling is approximately 45 per cent. The equation for mill design used by Allis–Chalmers predicts that the maximum power is drawn at a filling of 53 per cent[8,9].

It has previously been demonstrated that, at up to 80 per cent of critical speed, the position of the toe is only a weak function of the mill speed but is influenced by the filling, on which it is linearly dependent, as shown

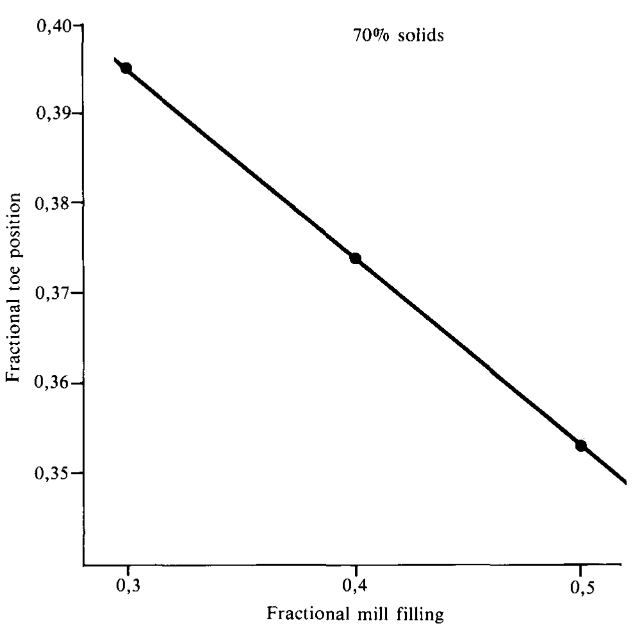


Fig. 7—The effect of filling on average toe position at 50, 60, 70, 75, and 80 per cent of critical speed

TABLE I

MAXIMUM TORQUE AND POWER AT VARIOUS MILL SPEEDS, AND THE FILLINGS AT WHICH THEY OCCUR

Mill speed % of critical	Max. torque N·m	Max. power kW	Filling at max. torque and power (J)
50	133,9	0,402	0,448
60	138,9	0,500	0,454
70	141,5	0,594	0,455
75	142,1	0,640	0,463
80	139,8	0,671	0,436
90	128,9	0,696	0,386
95	120,2	0,685	0,328

in Fig. 7. The range of fillings tested spans those commonly used in industrial applications. This phenomenon may have some potential as a parameter in the measurement and control of autogenous mills, where the load volume—and hence the power drawn—varies with time as the ore characteristics change, and it is desirable to control the feed rate so that the filling is kept at the level that constitutes maximum power draw.

The filling also has an effect on the shoulder position, as seen in Fig. 8, increasing filling causing a rise in the position of the shoulder. This is consistent with the increased crowding that occurs as the filling increases, and is also caused by an increase in the pressure exerted by the load on the liners, which assists in lifting the load to higher positions. The influence of the pressure in the outer regions of the load on the surging of the load has been examined in detail[10].

The Effect of Friction

The particles in the pulp within the mill have an important effect on the torque, because they cause friction within the load and between the load and the liners. This is demonstrated by a comparison of the variation in torque with speed for the following conditions:

(i) a glycerine solution having a viscosity of 10,7 mPa·s in place of a pulp,
(ii) A glycerine solution having a viscosity of 10,7 mPa·s with 2 kg of sand, and
(iii) a pulp of 60 per cent solids by mass.

For the glycerine solution, the torque rises continuously with an increase in the speed of the mill (Fig. 9), no maximum being attained up to 95 per cent of critical speed. When sand is added to the glycerine, the torque reaches a maximum at 78 per cent of critical speed, but reduces rapidly at higher speeds. The torque profile for the pulp containing 60 per cent solids is very similar in shape to that for the mixture of sand and glycerine solution, and the maximum torque also occurs at 78 per cent of critical speed. The difference in the magnitude of the torque for these two conditions is due to the difference in the mass of the loads. These results show that the friction within the load caused by the ore particles has an important influence on the motion of the load, and that the results of investigations in which mills are operated in the absence of particles may not be truly relevant. Examinations of the positions of the toe and shoulder show that, with the glycerine solution, the load had slumped, but the addition of sand to the glycerine solution caused the load to assume a more offset position, which corresponded to that observed when the pulp containing 60 per cent solids was used.

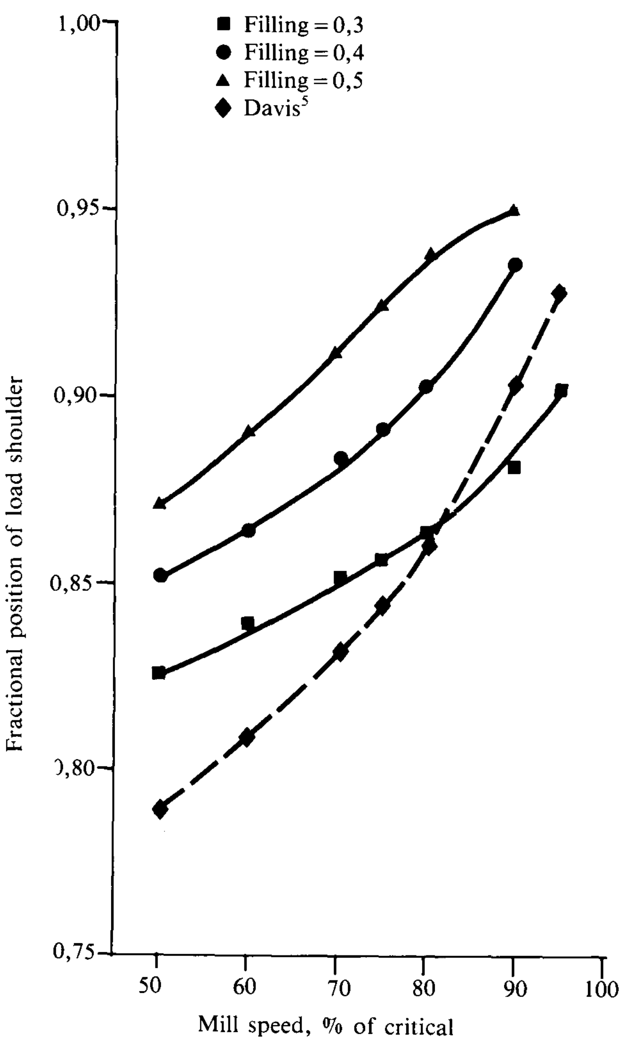


Fig. 8—Positions of the shoulder of the load at various speeds and fillings, the reference position being at 12 o'clock

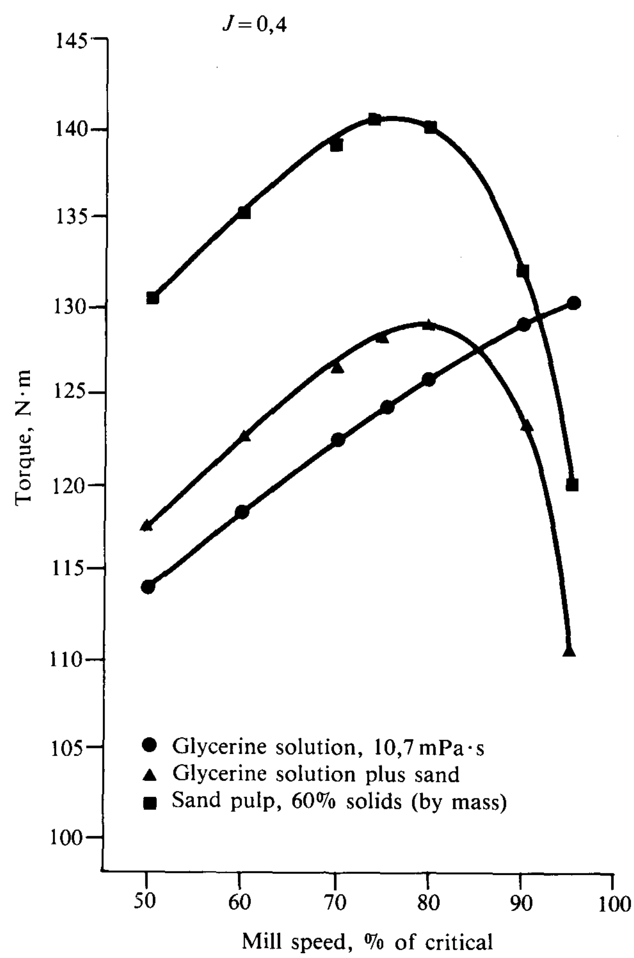


Fig. 9—The influence of friction on torque

Prediction of Mill Power

Over the years, a number of equations have been derived that predict the power drawn by a mill for given conditions of filling, density of the grinding medium, and speed. When the basis for the derivation of some of these equations was examined[4,11], it was found that they are generally based on (or reduce to) the concept that the profile of the load can be approximated by a chord drawn between the toe and the shoulder, forming an angle to the horizontal that is equal to the dynamic angle of repose of the load. This method assumes that the total mass of the load lies below the chord, and that there is a centre of gravity through which the mass acts, as shown in Fig. 10. The torque required to maintain the offset of the centre of gravity is then given by

$$\tau = m_g r_g \sin \alpha, \quad (1)$$

where τ is the torque
- m is the mass of the load
- g is the acceleration due to gravity
- r_g is the distance from the mill centre to the centre of gravity of the load, and
- α is the angle of repose.

The power is then determined by the speed of rotation:

$$P = 2\,\pi\,\tau\,N, \quad (2)$$

where N is the rotational speed (r/s).

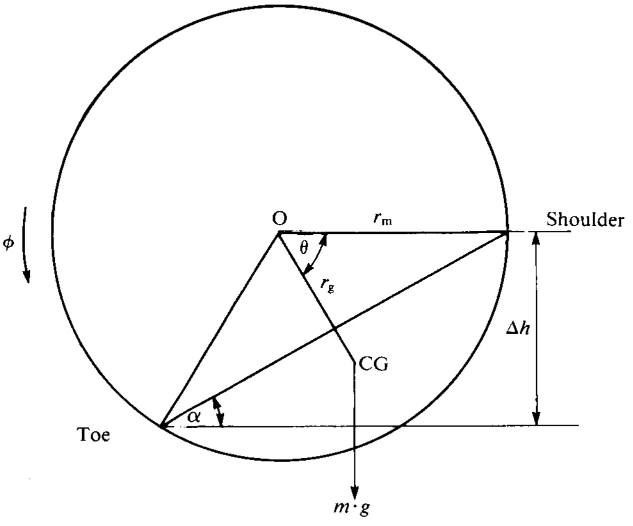


Fig. 10—The load position assumed by the equations predicting mill power

To predict mill power, Hogg and Fuerstenau[12] derived an equation based on the assumption that the profile of the load can be approximated by a chord from the toe to the shoulder, this being:

$$P = 3{,}627\ \rho_b\ \phi\ LD^{2,5} \sin^3 \theta \sin \alpha, \quad (3)$$

where P is the power,
- ρ_b is the bulk density of the load,
- ϕ is the fraction of critical speed,
- L is the length of the mill,
- D is the diameter of the mill, and
- θ is related to the filling (J) by $J = 1/\pi\ (\theta - \sin\theta\cos\theta)$.

A design equation for mills (which is in common use) was developed by Bond[9], who based it on the torque principle and modified it by the use of empirical results:

$$P = 12{,}262\ \rho_b\ \phi\ LD^{2,3}\ J(1 - 0{,}937J)\ (1 - 0{,}1/2^{9-10\phi}), \quad (4)$$

where J is the fractional filling of the load.

A further equation has recently been proposed by Harris *et al.*[11], which again utilizes the torque principle and some empirical observations:

$$P = 1{,}88\ m_g\ \phi\ D^{0,5}\ (1 - J) \sin \alpha. \quad (5)$$

They[11] observed that, in 39 operating mills of various diameters, the average angle of repose of the load was 42 degrees. Substitution of this value into equation (5) together with $m_g = \rho_b J V_{mill}$, gives

$$P = 9{,}69\ \rho_b\ \phi\ LD^{2,5}\ J(1 - J). \quad (6)$$

Fig. 11 compares the power predicted by equations (3) to (6) with the measured power at various speeds for the conditions of 40 per cent filling and 70 per cent solids in the pulp. The values of α required by equations (3) and (5), which are determined from the measurements of the toe and shoulder positions, are given in Table II. The value of θ used in equation (3) for this filling is 80,9 degrees. The power predicted by equations (3), (5), and (6) is within 10 per cent of the measured power at speeds lower than 60 per cent of critical, whereas further increase of the speed causes, in equations (3) and (5), an over-estimation of the power by larger amounts. Both these equations use the measured angle of repose, which becomes increasingly meaningless as an estimation of the load surface as the speed rises. Equation (4), which over-estimates the power by approximately 50 per cent at all speeds, contains an empirical function that reduces the power slightly as the speed rises to allow for the reduced torque at higher speeds. This over-estimation is inherent in the constant, which probably provides for a deliberate over-calculation of the power as a safety factor.

Equation (5) is generally the most accurate equation but does not contain a speed-dependent function, as can be seen from its linearity with speed. For an equation to predict the power over the entire range of speeds, the change in load motion with speed and filling, as indicated by the torque profile, must be incorporated.

Only equation (4) contains a component that allows for a variation in torque at different speeds, but the function $(1 - 0{,}1/2^{9-10\phi})$ does not accurately reflect the torque profile; furthermore, it implies that the filling has no effect on the motion of the load. The interactive effects of speed and filling on the torque, and the function contained in equation (4), are shown in Fig. 12. The torques for the range of fillings and speeds covered in this investigation have been normalized with respect to the maximum torque, which occurs at a filling of 46,3 per cent and 75 per cent of critical speed. The extreme variation in the normalized torque curves shows that the functional form of an expression describing the load motion is complex, and is probably also dependent on friction and viscosity.

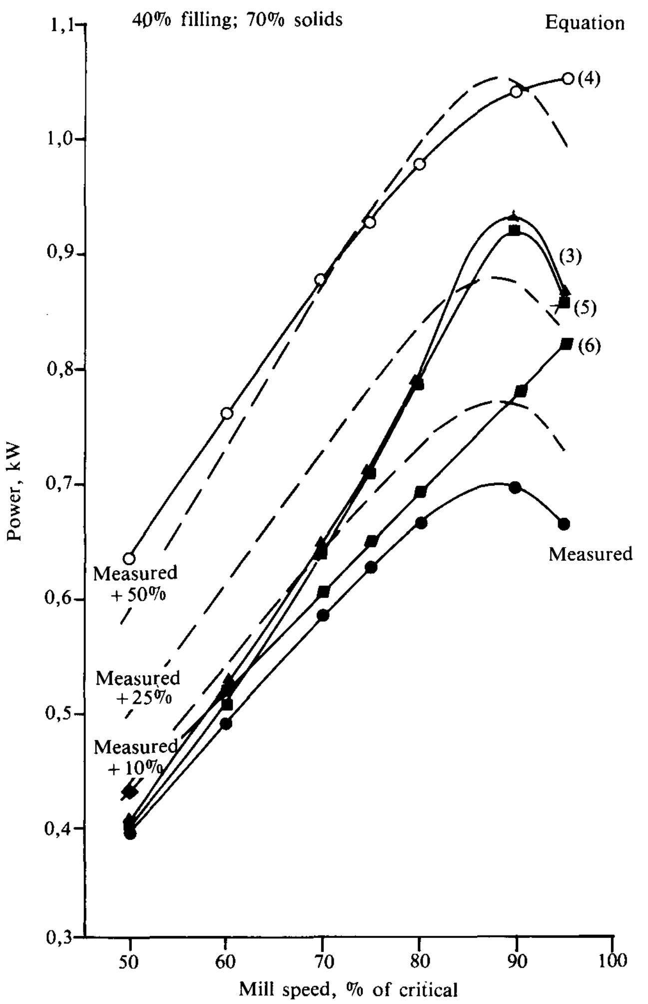


Fig. 11—Comparison of the measured power and the power predicted by the use of equations (3) to (6)

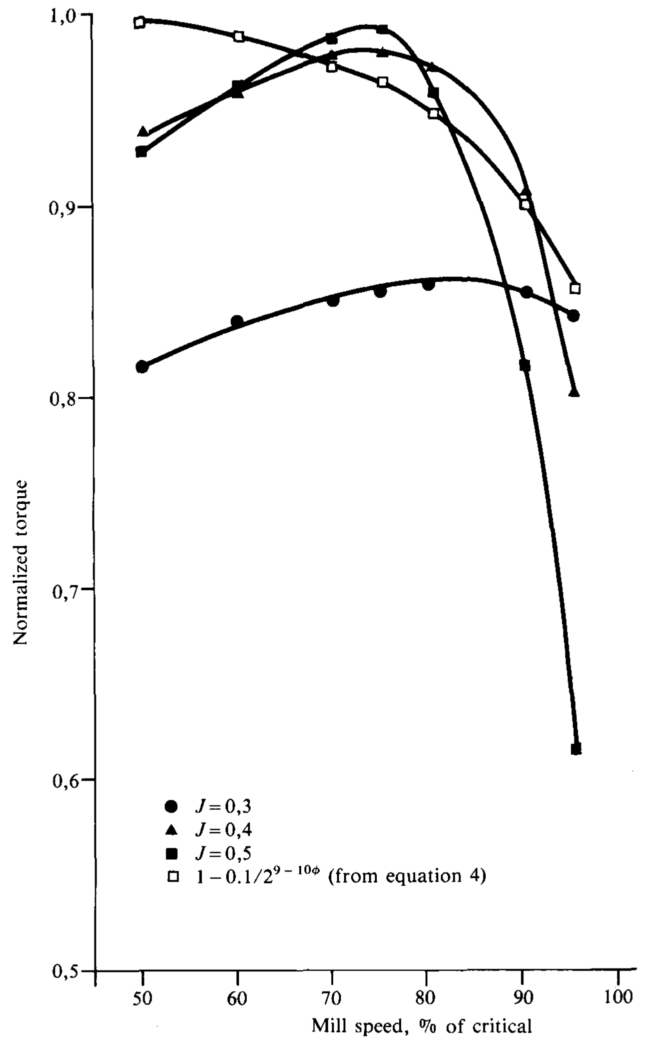


Fig. 12—The effects of speed and filling on normalized torque

TABLE II
MEASURED VALUES OF THE DYNAMIC ANGLE OF REPOSE OF THE LOAD, α, USED IN EQUATIONS (3) AND (5)

Mill speed % of critical	α degrees
50	39,5
60	42,1
70	46,0
75	47,6
80	50,2
90	53,5
95	45,0

Conclusions

The rotational speed of the mill and the degree of filling both influence the position of the ball load in the mill and, hence, the torque required to maintain the load in an offset position. The mill speed affects the torque by changing the way in which the load moves. At low speeds, the falling balls roll down the surface of the load into the toe region, the load is not dilated, and the power can be predicted reasonably well by simple torque models. At higher mill speeds, the motion of the load becomes more complex, since the falling elements of the load have rolling and hindered, as well as free, parabolic trajectories, depending on their positions within the load and the speed and filling conditions. Under these conditions, the load is fairly dilated, its bulk density has decreased, and some of the elements of the grinding medium are landing in the toe in such a way that some of their energy is contributing to the rotation of the mill. Both these factors tend to reduce the torque, and compensate for the increase in torque required to maintain the load in a more elevated position. Thus, as the mill speed increases, the torque passes through a maximum, after which it decreases rapidly.

The toe position is virtually unaffected by changes in mill speed up to approximately 80 per cent of critical. At higher speeds, the falling particles of the grinding medium impact directly onto the liners, and the toe position is influenced by the speed of the mill. Industrial mills are not commonly operated under conditions that allow the load to fall directly onto the liners, since this results in excessive wear of the liners. The shoulder position is dependent upon the speed as well as the filling.

Changes in the filling have a direct influence on the torque, because the mass of the load changes. There is an indirect effect because the motion of the load is affected by crowding, and this is reflected in the parabolic nature of the torque (or power) with the filling, the torque being zero at fillings of 0 and 100 per cent. At a filling of 100 per cent, in fact, the motion of the load within the mill ceases completely, and the mill acts as a flywheel. As the filling increases beyond the volume that results in the maximum torque, the crowding effect causes the load to impact further towards the mill shell. This exerts a greater turning moment on the mill, reducing the torque. Therefore, as the filling increases, the reduction in torque due to the recovery of energy from the falling balls outweighs the increase in torque due to the increased mass of the load, and the net torque decreases. The toe position is primarily dependent on the filling. This may be of benefit in control strategies for autogenous milling circuits. The ore particles provide the friction within the load, without which the torque does not show a maximum value at speeds up to 95 per cent of critical, indicating slippage within the load, and between the load and the liners.

An examination of several equations that have been derived to predict mill power indicated that those including the measurement of the dynamic angle of repose of the load become increasingly inaccurate for higher mill speeds, showing that the load profile at higher speeds cannot be approximated by a chord joining the toe and the shoulder. A simple equation, which was recently derived and uses an average value for the angle of repose, was found to give the most accurate prediction of power, but this equation does not allow for the effect of the motion of the load on the torque. The normalized torque, which could be used to modify equations predicting mill power, is a complex function of the filling and speed of the mill. Until the motion of a mill load can be characterized mathematically, the power drawn by the mill cannot be calculated realistically, and simplistic models will continue to be used.

Acknowledgement

This paper is published by permission of the Council for Mineral Technology (Mintek).

References

1. MOYS, M.H. The measurement of parameters describing the dynamic behaviour of the load in a grinding mill. *Mintek 50, Proceedings of the International Conference on Mineral Science and Technology*. Haughton, L.F. (ed.). Randburg, Council for Mineral Technology, 1985. vol. 1, pp. 205–219.
2. BURNS, R.S., and ERSKINE, J.G. Experience with large diameter ball mills at Bougainville Copper Ltd. *Miner. Metall. Process.*, May 1984. pp. 15–28.
3. SHOJI, K., *et al.* Further studies of ball and powder filling effects in ball milling. *Powder Technol.*, vol. 31. 1982. pp. 121–126.
4. LIDDELL, K.S. The effects of mill speed, filling and pulp rheology on the dynamic behaviour of the load in a rotary grinding mill. M.Sc. dissertation, University of the Witwatersrand, Johannesburg, 1986.
5. DAVIS, E.W. Fine crushing in ball mills. *AIME Transactions*, vol. 61. 1919. pp. 250–296.
6. ROSE, H., and SULLIVAN, R. *Ball, rod and tube mills*. New York, Chemical Publishing Co., 1958.
7. AUSTIN, L.G. Understanding ball mill sizing. *Ind. Eng. Chem., Process Des. Dev.*, vol. 12, no. 2. 1973. pp. 121–129.
8. KJOS, D.M. Grinding circuits: Current status and projected future developments. Allis–Chalmers, *Publication No.* 22P10735.
9. BOND, F.C. Crushing and grinding calculations. Allis–Chalmers, *Publication No.* 07R9235C.
10. VERMEULEN, L.A., and HOWAT, D.D. Fluctuations in the slip of the grinding charge in rotary mills with smooth liners. *Int. J. Miner. Proc.*, vol. 16. 1986. pp. 153–168.
11. HARRIS, C.C., SCHNOCK, E.M., and ARBITER, N. Grinding mill power consumption. *Miner. Process. Technol. Rev.*, vol. 1. 1985. pp. 297–345.
12. HOGG, R., and FUERSTENAU, D.W. Power relationships for tumbling mills. *SME–AIME Transactions*, vol. 252. 1972. pp. 418–423.

Obituary: Eric Livesey-Goldblatt by J.S. Freer

Eric Livesey-Goldblatt passed away peacefully on 22nd September, 1987, at the age of 66 years. He leaves his wife, 2 stepsons, a daughter, 2 married sons, and 5 grandchildren.

He was born in South Africa, but spent his youth in England, and returned to this country in 1944 with the RAF. After the war, he worked in the Research Department of AE&CI and for the Chamber of Mines Research Organization.

In 1952 he started with General Mining and Finance Corporation as Chief Research Chemist at Stilfontein and Buffelsfontein. Later (1964) he was transferred to the Group's Research Laboratories at West Rand Consolidated Mines, from where he retired in 1984 as Manager.

It was during this period that he developed his great interest in biohydrometallurgy. He foresaw the potential of bacteria for the recovery of metals by bacterial oxidation, and under his leadership, the Bacterial Film Oxidation (BACFOX) process and, more recently, the Biological Oxidation (BIOX) process were developed. These made the recovery of gold from refractory ores less expensive and environmentally safer. As a result, the first commercial Biox plant was commissioned this year at Gencor's Fairview Mine, near Barberton.

Upon retiring from Gencor in 1984, Eric set up as international consultant, dealing with Canada, France, and Zimbabwe, and started his own company—Biohydrometallurgy (Pty) Ltd or BIOMET.

He was well-known in biohydrometallurgical circles, having presented many papers dealing with this new science at international conferences around the world. He was a member of The South African Institute for Mining and Metallurgy for 25 years. While his contribution to biohydrometallurgy is greatly appreciated by his profession, he is sadly missed by his colleagues.

Sasol Mining Team wins premier award*

In November 1987, the National Award of The Associated Scientific and Technical Societies of South Africa was presented to the Sasol Mining Team, who in less than ten years brought the worlds' largest underground coal mine into production.

This Award is the most prestigious recognition that South Africa's engineers and scientists can win. In accepting the Award, the Managing Director of Sasol Limited, Mr P. du P. Kruger, said he was extremely proud of the achievements of the team.

In less than ten years, they had created from nothing a mine that could produce over 100 000 tons of coal per day from a seam only 3 metres thick at depths of 130 metres and more. In 1974 the Government had thrown down the challenge to Sasol to save South Africa from the effects of the oil embargo and, no sooner had that challenge been issued, than the Shah of Iran was overthrown and the team was asked to double its efforts.

The team had succeeded. Shaft sinking started at Brandspruit in November 1975, underground development started in June 1977, and by June 1985 the collieries had produced over a hundred million tons. Today they are well on their way to the second hundred million tons.

AS&TS had recognized a number of separate areas where the Sasol team had performed outstandingly. In a short time, they had identified and trained the hundreds of skilled workers they needed. They had developed and proved advanced mining methods. They had faced and resolved a major problem with longwall layouts and learnt how to drill kilometres horizontally in advance of the coal face in order to identify geological problems. They had introduced new equipment both for support of the roof and for hauling coal.

The team used a mixture of longwalling, pillar extraction with continuous miners, and conventional mining, not only to achieve high productivity, but also to recover up to 70 per cent of the in-place coal, compared with the national average for underground mines of less than 50 per cent.

The Sasol team currently held world production records of 62 400 tons for a week and 219 400 tons for a month of production from a single longwall.

AS&TS had noted that, while Sasol could be viewed as a capital-intensive enterprise, hundreds of jobs had been created, not only in the running and maintenance of the mines and plants at Secunda, but also in the distribution and use of Sasol's products. The success of the project was based on efficient coal mining, and in this the Sasol Mining Team had proved themselves world-beaters.

* Released by AS&TS, P.O. Box 61019, Marshalltown, 2107 Transvaal.

Dr Philip Lloyd, President of AS&TS (centre), holding the AS&TS National Award for 1987. With him are members of the Sasol Mining Team who won the award. These are (left to right) Mr N.T. Halgreen (Operations Manager, Secunda Collieries), Mr P.V. Cox (General Manager (Mining), Sasol Ltd), Mr P. du P. Kruger (Managing Director, Sasol Ltd), and Mr C.J. Cloete (General Manager, Secunda Collieries)