J. S. Afr. Inst. Min. Metall., vol. 88, no. 6.
Jun. 1988. pp. 199-206.

The measurement of rheological properties inside a grinding mill*

by A. MONTINI† and M.H. MOYS†

SYNOPSIS

A technique for the measurement of slurry consistency inside a grinding mill is described. The rate of slurry drainage from a sensing probe mounted through the mill shell is measured and correlated with the percentage solids of the slurry discharging from the mill. The response time of the measurement (obtained on a pilot ball mill) is compared with the response time of the viscosity of the mill discharge. It is shown that the new measurement should allow much tighter control of the mill behaviour, with concomitant savings in the consumption of power and steel.

SAMEVATTING

Daar word 'n tegniek om die konsistensie van flodder in 'n maalmeul te meet beskryf. Die tempo van flodderdreinering van 'n aanvoelsonde wat deur die meulromp aangebring is, word gemeet en gekorreleer met die persentasie vaste stowwe in die flodder wat uit die meul uitloop. Die responsietyd van die meting (wat met 'n proefbalmeule verkry is) word vergelyk met die responsietyd van die viskositeit van die meullading. Daar word op gewys dat die nuwe meting baie strenger beheer oor die meulgedrag behoort moontlik te maak, met die besparings wat betref krag- en staalverbruik wat daarmee saamgaan.

Introduction

The multivariable control of grinding circuits has received considerable attention[1-3]. In general, little use is made of measurements of the behaviour of the grinding mill itself, exceptions being measurements of mill power (an extremely non-linear signal) and mill mass. Control schemes have generally been focused on the control of variables such as sump level, flowrate and density of the feed to the cyclone, and particle-size distribution of the final product. Mill power and mill mass are used in various peak-seeking strategies for the control of autogenous mills. In most cases[4], solids feed rate is the manipulated variable; in two cases[5,6], both solids feed rate and water feed rate are manipulated.

Various measurements of variables (other than power and load mass) related to the behaviour of the load inside the mill have been used. Pioneer work was done by Hardinge[7] in 1939, who used a microphone to sense noise and performed on/off control of the feed rate. More recently the same principle was used by Dettmer and Sobering[8] for dry milling. Jaspan *et al.*[9] patented the use of two microphones that allow stereo-location of the point on the mill shell where noise is generated, and hence provide a more accurate measurement of load volume.

The slurry viscosity inside a grinding mill (determined largely by the percentage solids by volume) is an important variable governing the milling efficiency[10] and behaviour[11] of the load in the mill. Moys[11] presented a method of measuring the dynamic behaviour of the load in a mill using a conductivity probe showing, in particular, the strong effect that the percentage solids in a slurry has on the dynamic orientation of the load. Vermeulen *et al.*[12] used piezo-electric and conductivity probes for obtaining information from inside the mill. Montini and Moys[13] did a series of dynamic tests on a pilot ball mill in which a conductivity probe was installed, and quantified the dynamic response of this and other more conventional measurements to input changes. They then demonstrated[14] the advantages of this measurement; this is discussed further below.

The purpose of this paper is to explore further the use of a conductivity sensor to probe rheological properties of the slurry inside a mill. The probe used is a bolt isolated from the mill shell, which itself is part of the sensor. When the probe emerges from the shoulder of the load, its output is assumed to be a function of the thickness of the layer of slurry covering it, which, in turn, is a function of the viscosity of the slurry. A measurement of the probe response thus gives us an estimate of slurry viscosity (or percentage solids) inside the mill. This new measurement (which can be obtained easily and cheaply) promises to be an improved measure of the rheological properties inside a grinding mill that is adequate for process-control purposes.

Economic Significance of the Control of Slurry Rheology

Moys[15] showed that, for the pilot ball mill used in the project, the specific power consumption is related to the rheological properties of the slurry by the following expression:

$$E = 33{,}4 - 39{,}6f^2 + 11{,}05\mu \text{ kWh/(t} < 75\,\mu\text{m)},$$

---

[*] Paper presented at the Colloquium on On-stream Analysis, which was held by The South African Institute of Mining and Metallurgy in Randburg on 10th November, 1987.

[†] University of the Witwatersrand, P.O. Wits, 2050 Transvaal.

where f = mass fraction of ore (Witwatersrand quartzite) in the slurry

μ = slurry viscosity, which is related to slurry composition by the Mooney[16] equation, which for this ore is

$$\mu = 0{,}01 \exp \{3{,}85\phi/(1 - 1{,}197\phi)\}\ \mathrm{cP},$$

where ϕ = volume fraction of solid in the slurry, which is easily related to f.

Using these relationships, we can calculate an average value for E based on the assumed variation of f during normal operation of the mill. If f is assumed to be uniformly distributed between f_1 and f_2, then

$$E_{\mathrm{avr}} \int_{f_1}^{f_2} E df/(f_1 - f_2).$$

This yields the following dependence of E_{avr} on the range of f:

Range of f	0,66–0,68	0,64–0,70	0,62–0,72	0,60–0,74
E_{avr}, kWh/(t < 75 μm)	19,19	19,42	19,96	21,04
% increase over minimum	0	1,2	4,0	9,6.

Most of the increased cost results from losses in efficiency incurred by operation at high values of f.

For industrial-scale mills, a different relationship will hold, but the same conclusion will apply: accurate control of the rheological properties of the slurry can reduce the specific power consumption by a percentage that depends on how poorly these properties are being controlled in a given installation.

Steel costs are significantly affected by slurry rheology, particularly in ball mills, where a low slurry density, and hence low slurry viscosity, results in poor coating of the grinding media by slurry, leading to catastrophic wear rates. In one case[17], Moys encountered wear rates that were double the industry average.

Accurate control of the rheological properties of the slurry should thus result in significant savings in operating costs. A 2,5 MW mill operating for 330 days per year will incur power costs of approximately R1 million per year. On average, steel costs are of the same order as power costs. Thus, if improved mill operation results in a cost reduction of 5 per cent, the savings will amount to R100 000 per year. Alternatively, if more efficient milling and more stable plant operation result in an increase in gold recovery of 0,1 per cent, the increased revenue with a mill processing 100 t/h of an ore containing 8 g/t of gold would amount to approximately R170 000 per year, on the assumption that the recovery of gold is 98 per cent, the availability of the mill is 95 per cent, and the gold price is R26 000 per kilogram.

Experimental Equipment

Pilot Plant

The laboratory mill used is shown in Fig. 1. It is a ball mill 550 mm in diameter, 800 mm in length, and capable of drawing up to 2,5 kW. The mill is flanged to a 100 mm diameter axle (A) that runs on large bearings (B) suspended from two load beams (C and D). These are used to measure the mass of the mill load. The motor cage is suspended from the axle and is held in position by a rod connected to a load beam to give a measurement of the torque developed by the load. The mill speed can be varied between 0 and 120 per cent of the critical speed. For these experiments, the liner was a 12,5 mm mild-steel wire mesh, and slurry was discharged through holes drilled through the end plate.

Other instrumentation was available for measuring flowrates and densities. A Brookfield viscometer was used to measure the viscosity of the slurry flowing from the mill. The method of viscosity measurement is shown in

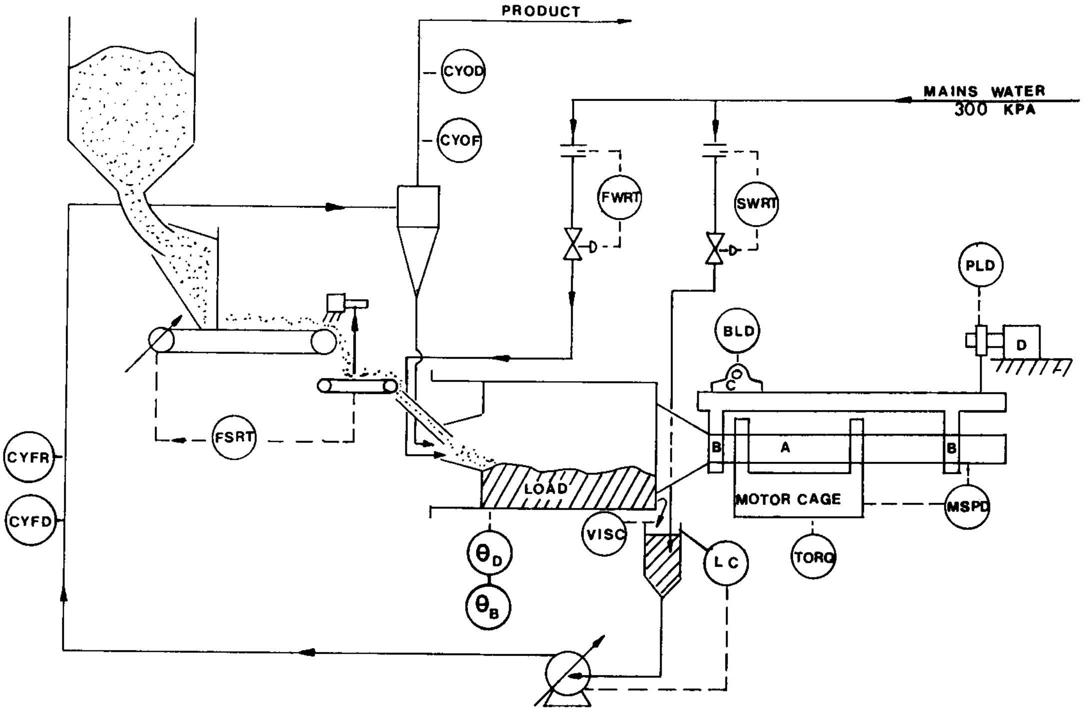

Fig. 1—Pilot grinding mill

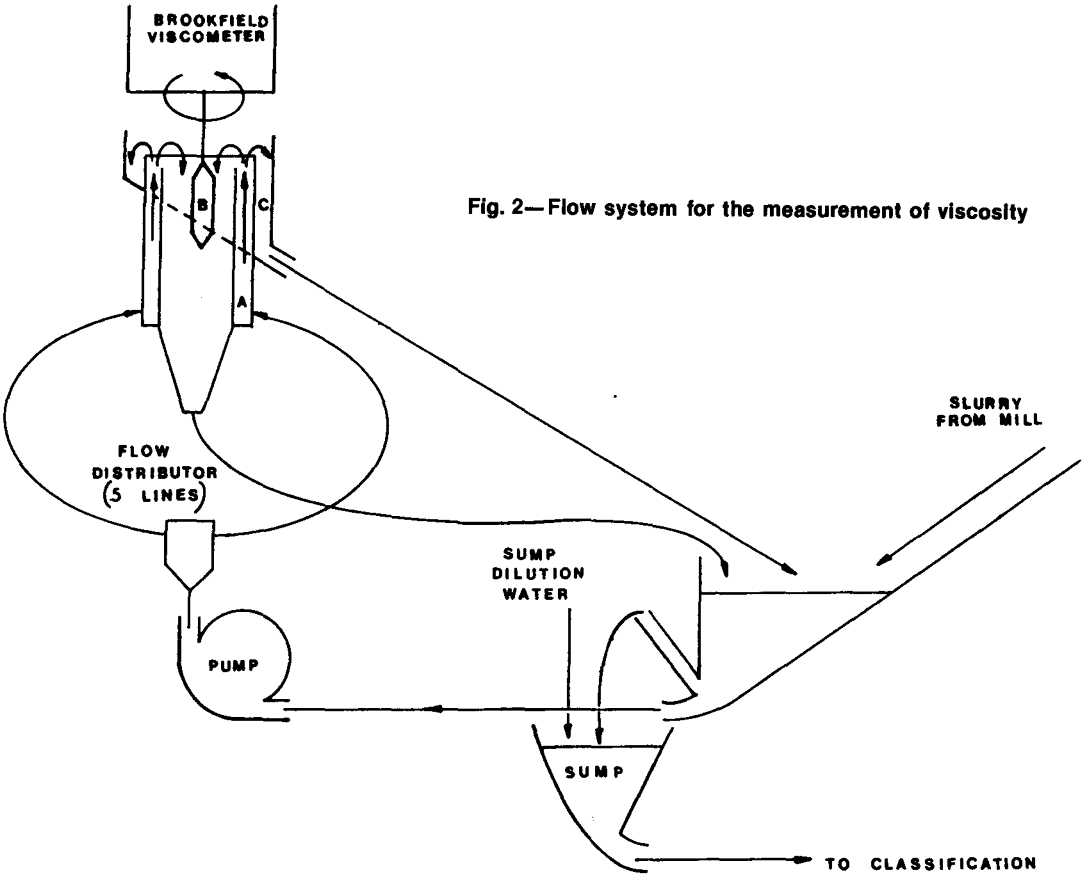

Fig. 2—Flow system for the measurement of viscosity

Fig. 2, and is based on the method developed by Debbex[18] for their commercial viscometers. The slurry from the mill flows into a small reservoir above the sump, and is then pumped through a distributor to an annulus A. A fraction of the slurry flows from the top of the annulus downwards past the rotating viscometer spindle B, while the remaining slurry flows back (C) into the reservoir. A signal proportional to the apparent viscosity of the slurry is produced. The viscometer was calibrated using solutions of glycerin and water of known concentration, so that the apparent viscosity of the slurry could be calculated.

The signal lines are interfaced to a Hewlett Packard 2240 Measurement and Control Processor coupled with a Hewlett Packard 9816S desktop computer, which was appropriately programmed to allow real-time monitoring, analysis, and storage of data.

Conductivity Probe and Signal Production

The conductivity probe is shown in Fig. 3. It is an abrasion-resistant liner bolt 8 mm in diameter, which is arranged in such a way as to project into the internal volume of the mill through a hole in the mill shell. The probe is electrically insulated from the mill shell by insulating washers. It is connected to an electronic circuit mounted on the mill shell, which stimulates the probe with a 5000 Hz ± 8 V signal. The current flows from the probe to the mill shell (ground) through the slurry and balls surrounding the probe. The signal is filtered to provide a d.c. signal proportional to the conductivity sensed by the probe. This signal is taken through a slip ring on the mill axle at E (Fig. 1) to an analogue-signal conditioner[11] before being fed to the computer real-time interface.

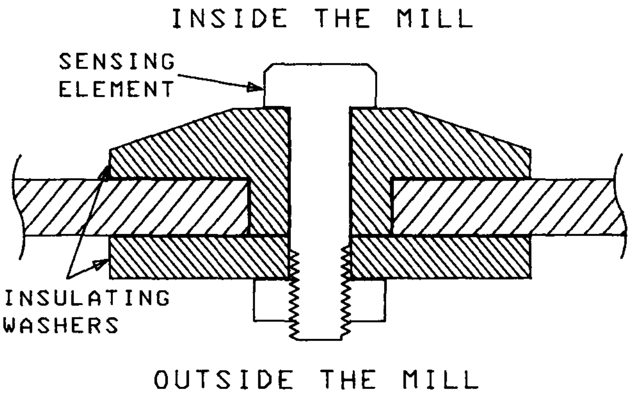

Fig. 3—Conductivity probe

Analysis of the Signal from the Probe

The profile assumed by the load within a mill rotating at a speed below about 75 per cent of critical speed is shown in Fig. 4. As the mill rotates in the direction indicated by the arrow, the probe periodically enters and leaves the load. The conductivity measured by the probe as it passes through the load will change as typically illustrated by Fig. 5. Given measurements of the time t_D, a reference time t_A when a cam switch on the mill axle is closed, and the mill revolution period T, we can calculate the dynamic angular location θ_D of the shoulder of the load (using the 12 o'clock position as reference):

$$\theta_D = \frac{t_D - t_A}{T}\frac{180}{\pi} + 45^\circ.$$

This angle is also correlated to the rheological characteristics of the slurry inside a mill for constant mill speed as described by Moys[11]. The dynamic response of this signal to step changes in mill input variables was measured by Montini and Moys[13], and is discussed below.

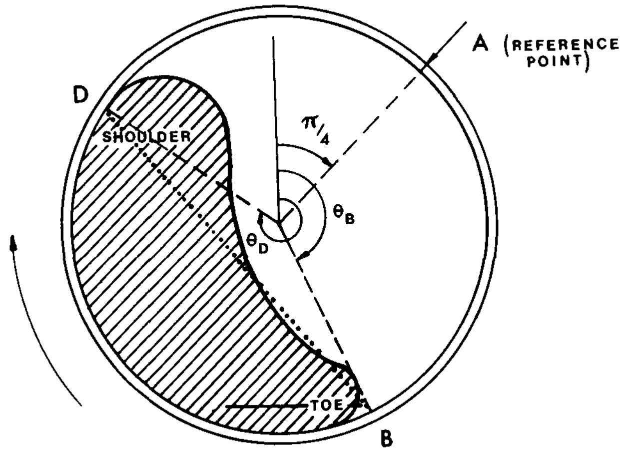

Fig. 4—Load profile within a rotary mill

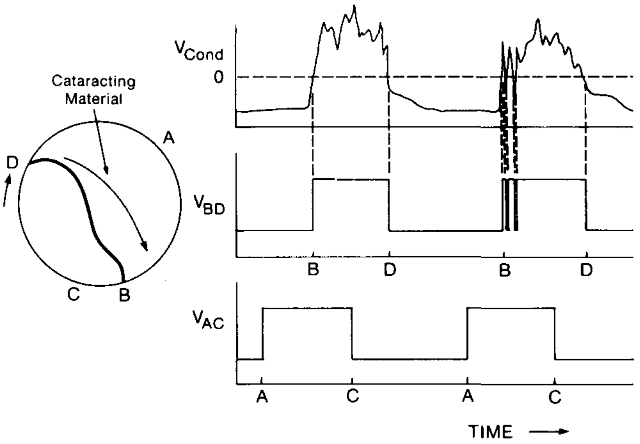

Fig. 5—Typical behaviour of a conductivity-probe signal

When the probe leaves the shoulder of the load at point D, it will be covered by a layer of slurry. The signal measured near D is shown in detail in Fig. 6. It is assumed in this analysis that, when the conductivity signal V_c (mV) drops below a certain threshold voltage V_{th} (selected after inspection of the data to be 1500 ms), the probe has emerged from the load and is no longer in contact with the steel balls in the load; current is conducted to the mill shell by the slurry only. The voltage measured after a time interval Δt after the conductivity signal has dropped below a threshold voltage V_{th} will be a function of the thickness of the layer of slurry covering the probe, and hence this voltage (termed V_{dr}) should be a function of the average rate of drainage of slurry from the probe during this time interval.

As the drainage of the slurry from the probe in this environment is a phenomenon that would be very difficult to model by the use of fundamental principles, an empirical correlation is performed as shown below.

Experimental Tests

All the supporting instrumentation was carefully calibrated. The mill had six conductivity probes mounted on the shell, which were placed in such a way that each probe subtended an angle at the centre of the mill of about 60 degrees. Furthermore, they were displaced on a spiral on the mill shell at different distances from the feed end plate. Probe number 2 in position 2, i.e. 198 mm from the feed plate, was used to obtain the conductivity profiles like that shown in Fig. 6.

Steady-state Measurements of Probe Responses

The mill, operating in open circuit, was taken to known steady-state conditions under computer control. The computer was programmed to

(1) take 30 s average of θ_D for each probe,
(2) measure each process variable and calculate their means and standard deviations,
(3) control the mill speed, and the feed rates of solids and water,
(4) print and store data at the end of each sampling interval, and
(5) perform the measurement of the conductivity profile on probe 2 near point D when required. A total of 120 points, one every 2 ms, was taken on successive revolutions and stored on disk for later processing.

The rate at which the ore was fed to the mill ranged between 3,0 and 4,1 kg/min, while the percentage solids were set at 60, 65, or 70 per cent. Steady-state operation was obtained after 12 to 15 min. The mill was considered to be at steady state when the mill torque, the slurry viscosity in the mill discharge, and the slurry hold-up (obtained from a measurement of the total mill mass) had reached stable values. At each steady state, a set of conductivity profiles was measured. The procedure followed by the microcomputer was as follows:

(a) set up an interruption to find B (Fig. 5) on probe 2,
(b) after the interruption wait 50 ms,
(c) read from the AI interface 120 points, one every 2 ms, and
(d) store data on disk, and go to step (a).

Measurements were taken at 11 steady states. Three basic steady-state levels for slurry density values (60. 65, and 70 per cent solids) inside the mill were obtained during those tests. The results are summarized in Table I. The column headed V_{dr} refers to the value of the conductivity signal taken 50 ms after the signal dropped below a threshold of 1500 mV. The standard deviation of V_{dr}, the experimental values for the viscosity of the slurry discharged from the mill, and the measured percentage solids in the mill discharge are also given. Individual conductivity profiles measured at 60 and 70 per cent solids are shown in Fig. 7. Several average profiles for different percentages of solids in the slurry are shown in Fig. 8 (10 individual profiles being used to produce each profile in this diagram). A clear correlation exists between the profiles and the three levels of percentage solids. The relationship between V_{dr} and percentage solids obtained from these data is presented in Fig. 9, which shows

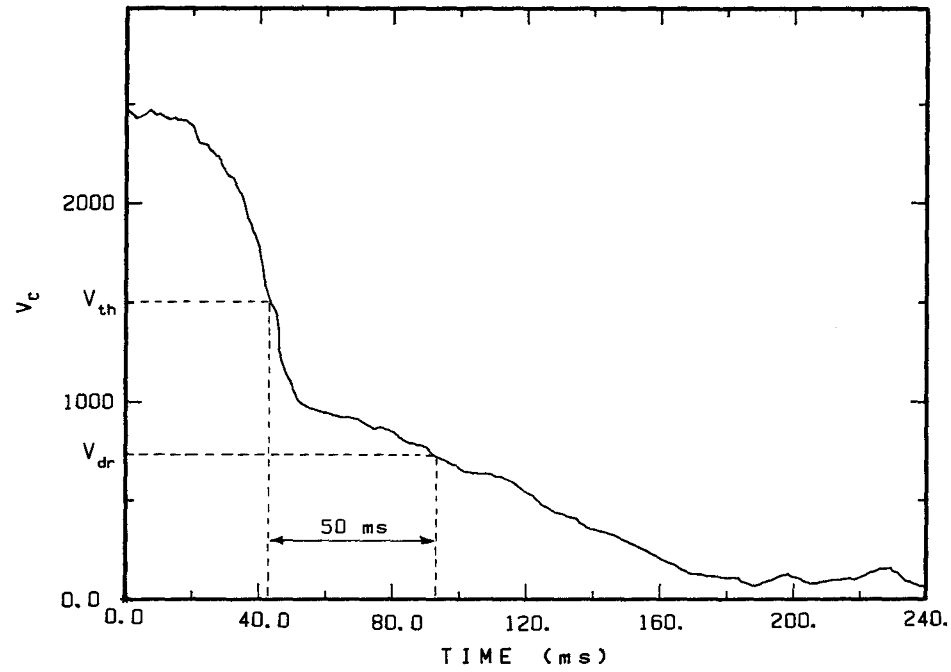

Fig. 6—Typical response of the conductivity probe, illustrating the definitions of V_{th} and V_{dr}

TABLE I
RESULTS OF STEADY-STATE TESTS

Run	Solids feedrate kg/min	Water feedrate kg/min	Solids, %		V_{dr}, mV		Viscosity cP
			Setpoint	Measured	Av.	Std dev.	
1	3,5	1,88	65	65,8	406	136	240
2		1,50	70	69,8	868	149	580
3		2,33	60	58,8	135	160	52
4	4,33	2,33	65	65,7	459	119	218
5		1,85	70	70,8	847	126	570
6		2,88	60	59,9	141	92	67
7		2,33	65	65,2	491	129	200
8	3,5	2,33	60	59,8	122	71	50
9		1,50	70	69,0	792	143	600
10		1,885	65	64,0	439	110	70

a good linear relationship between these variables.

Dynamic Response of the Probe

Measurements of the dynamic response of the probe signal to changes in input variables were not taken since the experiments were designed to obtain the response of θ_D and μ to such changes. A brief review of the results of this work[14] is useful here. The dynamic characteristics of these measurements are as follows:

Variable	*First-order lag*, s	*Transportation delay*, s
θ_D	100	15
μ	230	100

The large transportation lag in μ is expected, since the slurry has to pass through the mill before changes in the

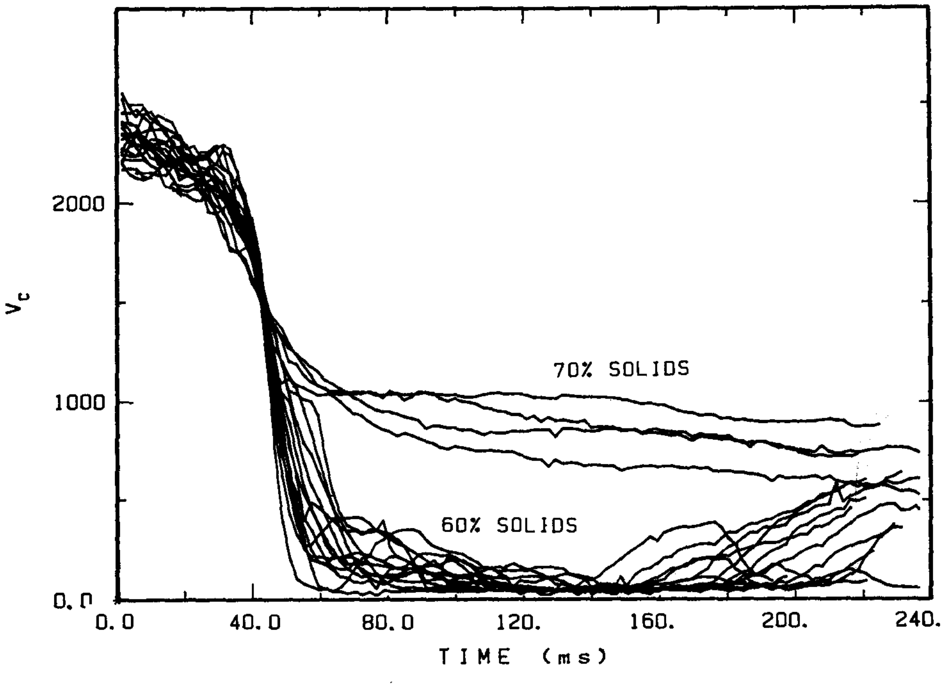

Fig. 7—Individual probe responses for two levels of percentage solids

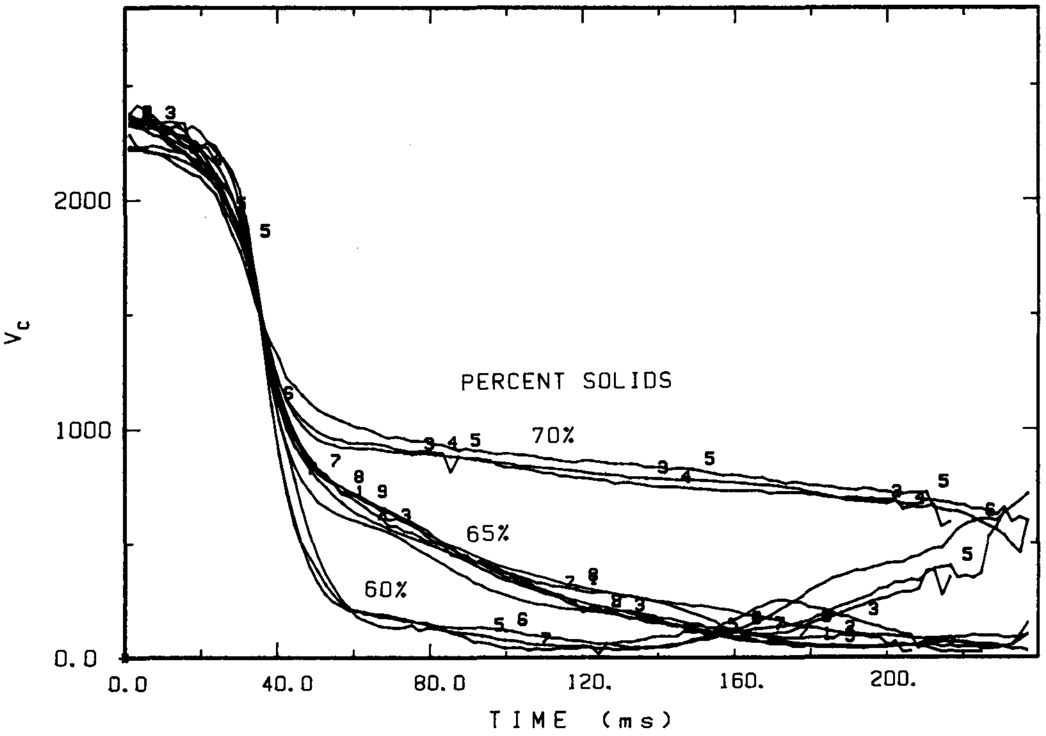

Fig. 8—Average probe responses at three levels of percentage solids

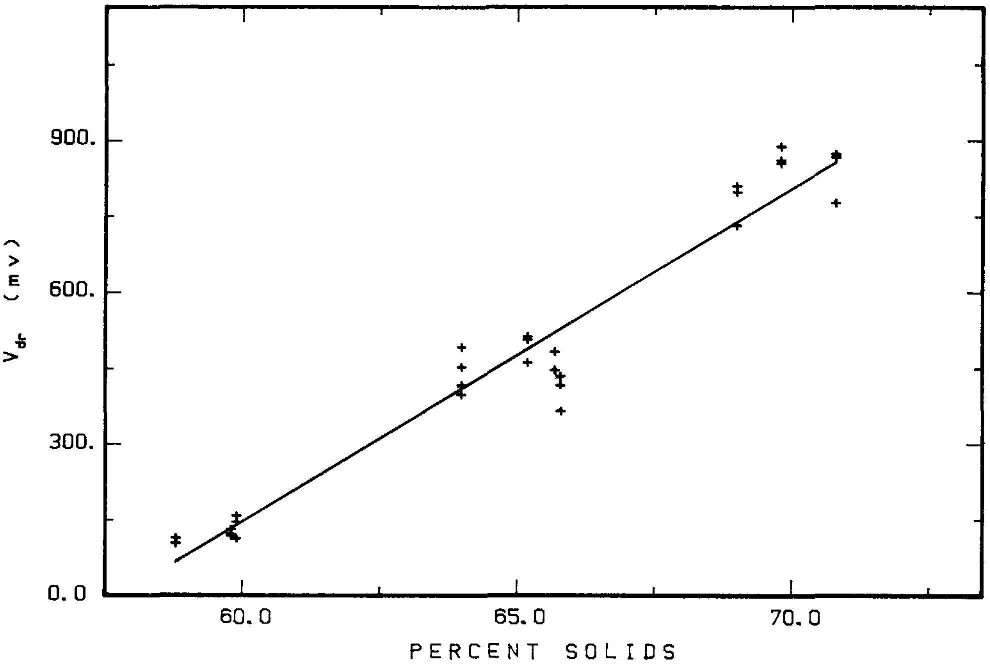

Fig. 9—Correlation between V_{dr} and percentage solids

properties of the mill discharge begin to manifest themselves. However, it presents a serious problem to the control engineer, and the settling time of a computer-simulated μ-FWRT control scheme was approximately 25 minutes compared with 10 minutes for a θ_D-FWRT scheme. However, as θ_D is subject to drift as a result of changes in the size distribution of the medium and the load volume, it had to be used in a cascade control scheme in which measurements of μ were employed to adjust the setpoint of a θ_D-FWRT loop. Also, θ_D is an extremely noisy signal, with a variance approximately equal to its range of variation.

V_{dr} is not subject to drift, since it is a function of only the rate of drainage of the slurry from the probe. It is also far less noisy, with a standard deviation of approximately 20 per cent of its range of variation. Each point in Fig. 9 represents the average of 10 consecutive readings (one per revolution), which for this mill means a measurement period of 14 s; for a mill of 4,5 m diameter the equivalent time requirement would be 40 s, which is considerably smaller than typical slurry residence times in such mills (5 to 8 min). If necessary, several probes could be monitored, resulting in an increasing rate of data acquisition.

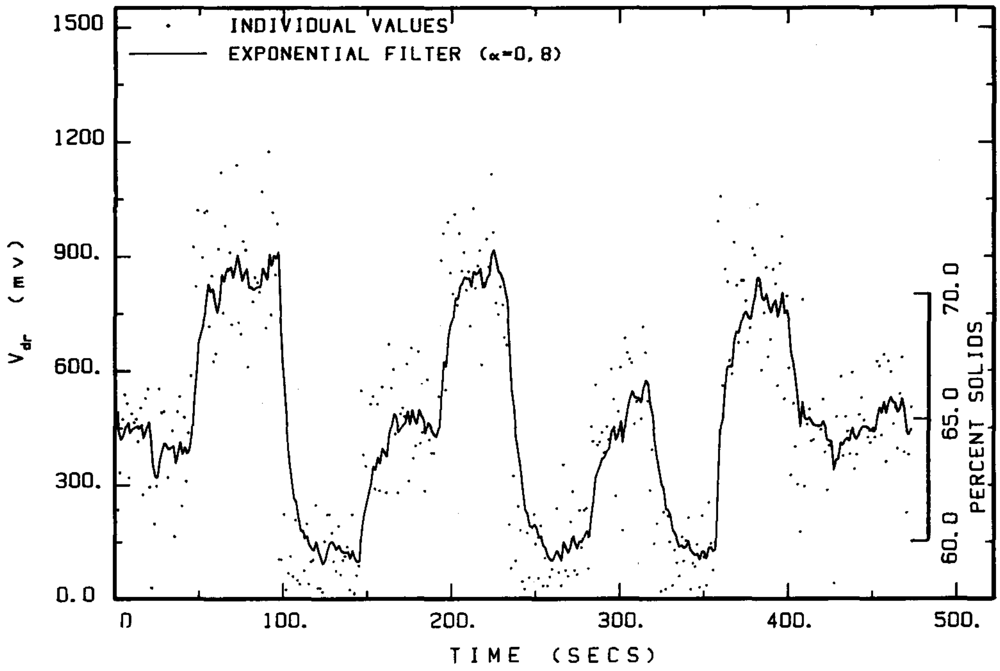

Fig. 10—Variation of individual V_{dr} measurements at the 10 steady states defined in Table I, together with the response of an exponential filter to these data (see text for definition of time-axis)

Some of the dynamic characteristics of the V_{dr} signal at the various steady-states listed in Table I are shown in Fig. 10. Individual measurements (one per revolution) are plotted versus the cumulative measurement time (i.e. the time between experiments when dynamic changes were made is ignored), together with a signal produced by a simple exponential filter defined by

$$V_{dr,filt} = (1-\alpha)V_{dr} + \alpha V_{dr,filt,prev},$$

where $\alpha = 0{,}8$. This filter responds rapidly to changes in V_{dr} (in this case the changes are artificial) while being able to produce a signal that is well correlated with the three levels of percentage solids used in the tests.

Conclusions

This is a new measuring technique to sense the rheological properties of a slurry from inside a grinding mill. The sensor probe is simply a liner bolt isolated from the mill shell, or an insert into a liner bolt, while a simple electronic interface measures the response of the probe. The physical phenomenon used by the sensor is the rate of slurry drainage from the sensor when this comes out of the load region, together with the conduction of the film of slurry covering the probe. The signal produced by the sensor, one per mill revolution, is analysed by computer. It is shown that a reliable estimate of the percentage solids in the slurry inside a mill can be obtained from this signal. The use of this measurement in mill-control strategies should significantly reduce milling costs while producing more stable operation of the circuit (with possible implications for improved downstream plant behaviour).

Acknowledgements

The pilot grinding plant used in these investigations was made available by the Council for Mineral Technology (Mintek), and the ore was supplied by Simmergo Gold Mining Company Ltd. The support of these two organizations is gratefully acknowledged.

Nomenclature

(Some variables appear only in Fig. 1)

BLD	Balance load, kg
CYFR	Flowrate feed to the cyclone, l/min
CYFD	Feed density to the cyclone, kg/l
CYOF	Cyclone overflow rate, kg/min
CYOD	Cyclone overflow density, kg/l
E	kWh/(t < 75 μm material)
f	Mass fraction of solids in slurry
FSRT	Solids feed rate, kg/min
FWRT	Water feed rate, kg/min
MSPD	Mill speed, % critical speed
PLD	Pivot load, kg
RHE	Rheology sensor
SWRT	Feed water added to the sump, kg/min
T	Period of revolution
t_D, t_A	Reference times for θ_D analysis
TORQ	Torque, kg·m
V_{dr}	Drainage voltage
θ_D, θ_B	Dynamic angles of load orientation
VISC, μ	Viscosity of the slurry, cP

References

1. Gossman, G.I., Hulbert, D.G., and Buncome, A. Application of multivariable control to a milling circuit at the East Driefontein Gold Mine. Colloquium on Control and Simulation in the Minerals Industry, The South African Institute of Mining and Metallurgy, Sep. 1984.
2. Herbst, J., and Rajamani, K. The application of modern control theory to mineral processing operations. *Proceedings, 12th CMMI Congress*. Glen, H.W. (ed.). Johannesburg, The South African Institute of Mining and Metallurgy, 1982.
3. Hulbert, D.G. Software for the design of multivariable control systems by use of the Inverse Nyquist Array. Randburg, Council for Mineral Technology (Mintek), *Report* M31, Jun. 1982.
4. Flook, W.R. Automatic control of feed of autogenous grinding media. *J. S. Afr. Inst. Min. Metall.*, vol. 76. Oct. 1975. pp. 60–64.
5. Krogh, S. Automatic control of autogenous and semi-autogenous mills. Autogenous Grinding Seminar, Trondheim (Norway), 1979.
6. Pauw, O.G., King, R.P., Garner, K.C., and Van Aswegen, P. Control of pebble mills at Buffelsfontein Gold Mine using a multivariable peak-seeking controller. Colloquium on Control and Simu-

lation in the Minerals Industry, The South African Institute of Mining and Metallurgy, Sep. 1984.

7. Hardinge, H. The 'electric ear', a device for automatically controlling the operation of grinding mills by their sound. *Trans. AIME,* vol. 134, Milling methods. 1939.
8. Dettmer, P.B., and Sobering, A. Pilot and commercial dry autogenous grinding of Labrador iron ore, Carol Lake. 7th International Mineral Processing Congress, New York, 1964.
9. Jaspan, R.K., Young, G.J.C., and Mellor, M.S. ROM mill power draft control using multiple microphones to determine mill load. *GOLD 100. Proceedings of the International Conference on Gold,* vol. 2. Johannesburg, The South African Institute of Mining and Metallurgy, 1986.
10. Klimpel, R.R. Slurry rheology influence on the performance of mineral/coal grinding circuits. *Min. Engng,* Pt 1 (34), pp. 1665–1668 and Pt 2 (35) pp. 21–26. 1983.
11. Moys, M.H. The measurement of parameters describing the dynamic behaviour of the load in a grinding mill. *MINTEK 50. International Conference on Recent Advances in Mineral Science and Technology,* Council for Mineral Technology (Mintek), 1984.
12. Vermeulen, L.A., Ohlsen de Fine, M.J., and Schakowski, F. Physical information from the inside of a rotary mill. *J. S. Afr. Inst. Min. Metall.,* vol. 84. 1984. pp. 247–253.
13. Montini, A., and Moys, M.H. Developments in the control of grinding circuits. 3rd Symposium on Control Theory and Applications, University of Natal, Durban, Jun. 1985.
14. Moys, M.H., and Montini, A. The use of conductivity measurements (obtained from a probe mounted in the mill shell) in the control of grinding mills. 88th AGM of CIM, 1986 (accepted for publication in the *CIM Bulletin*).
15. Moys, M.H. The effect of grate design on the behaviour of grate-discharge grinding mills. *Int. J. Miner. Process.,* vol. 18. 1986. pp. 85–105.
16. Mooney, M. The viscosity of a concentrated suspension of spherical particles. *J. Colloid Sc.,* vol. 6. 1951. pp. 162ff.
17. Austin, L.G., Klimpel, R.R., and Luckie, P.T. Process engineering of size reduction: Ball milling. New York, SME–AIME, 1984.
18. Reeves, T.J. An on-line viscometer for mineral slurries. *Trans. Instn Min. Metall.,* vol. 94. Dec. 1985. pp. C201–C208.

Management of uranium mill tailings

The Tenth Annual Symposium on Uranium Mill Tailings Management will be held on 12th and 13th September, 1988, at Colorado State University, Fort Collins, Colorado.

The following general topics and themes have been selected for emphasis at the Symposium:

- *Reclamation*
  Regulation and Policy
  Design and Review Technology
  Case Histories
- *Groundwater*
  Regulation and Policy
  Seepage Impacts
  Groundwater Restoration
  Detection and Compliance Monitoring Plan
  Case Histories
- *Site Issues*
  Decommissioning
  Cleanup
  Restoration
- *Other*
  Norm waste
  Treatment and Discharge
  Operational Standards
  In Situ Leaching
  Heap Leaching
  The Future of the Industry.

For information contact

Janet Lee Montera
Uranium Mill Tailings Symposium
Department of Civil Engineering
Colorado State University
Fort Collins, CO 80523
USA.
Telephone: 303-491-7425
Telex: 910 930 9000 ENGR CSU FTCN.

Ion exchange

Plans are being made to hold another International Conference and Industrial Exhibition on ion-exchange processes entitled 'Ion-Ex 90'. The Conference will be held at The North East Wales Institute, Cartrefle College, Wrexham, Clwyd, Wales, UK, from 9th to 11th July, 1990.

The Conference will deal with the following areas:

- Instrumental Developments
- Environmental Analysis
- Inorganic Analysis
- Organic Analysis
- Development of New Materials
- Biological Analysis
- Ion-exchange Membranes
- Ion-exclusion Chromatography
- Ion Chromatography and Associated Techniques
- Fundamental Studies of Ion-exchange Processes and Materials
- Water Analysis
- Applications in the Nuclear Industry
- Pharmaceutical Analysis.

Further information is available from

Mr Haydn Hughes
The North East Wales Institute
Connah's Quay
Deeside
Clwyd CH5 4BR
UK.
Telephone: 0244-817531 ext. 276
Telex: 61629 NEWI G.