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The control of pebble mills at Buffelsfontein Gold Mine by use of a multivariable peak-seeking controller

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SYNOPSIS

The relationships between mill power and pebble load, bulk density of the load, and circulating load were investigated on the pebble mills in the grinding circuit at Buffelsfontein Gold Mine. This paper describes the most significant relationships among the operating and control variables on the plant, and illustrates these by reference to experimental data gathered from the plant during operation.

The results were used for the development of very successful multivariable peak-seeking controllers for the pebble load and bulk density of the load on these pebble mills. The peak-seeking control algorithms are described in detail.

The control system has operated successfully at Buffelsfontein for more than 18 months and is still in operation.

SAMEVATTING

Die verwantskap tussen meuldrywing en rolklip vrag, hoopdigtheid van die vrag en sirkulerende vrag, is ondersoek. Die ondersoek is gedoen op die rolklipmeulens in die vermalingstroombaan van Buffelsfontein Goudmyn. Hierdie referaat beskryf die belangrikste verwantskappe tussen die bedryfs- en beheerveranderlikes op die aanleg. Die verwantskappe word geïllustreer d.m.v. data wat van die aanleg ingewin is tydens normale bedryf.

Die resultate is gebruik vir die ontwikkeling van baie suksesvolle meerveranderlike pieksoekende beheerders vir die rolklip vrag en hoopdigtheid van die vraag op bogenoemde rolklipmeulens. Die pieksoekende beheeralgoritmes word volledig beskryf.

Die beheerstelsel het suksesvol gefunksioneer op die aanleg gedurende die afgelope 18 maande en is steeds in bedryf.

Introduction

Much attention has been focused in recent years on the control of grinding circuits. The essential features of milling control systems have been fairly thoroughly researched, and several different control strategies have been proposed and tried. Lynch[1] has reviewed some of the early work and discussed several case studies undertaken at the Julius Kruttschnitt Mineral Research Centre.

Hulbert *et al.*[2] initiated a significant advance in the design of control systems for mills by recognizing that these systems are essentially multivariable. They used Rosenbrock's Inverse Nyquist Array to design a decoupled bivariate control system for the East Driefontein mill. This idea has since been used successfully at the Vuonos concentrator at Outokumpu (Niemi *et al.*[3]), and is likely to be extended to the control of ball-milling circuits in the future.

Milling circuits are significantly subjected to random disturbances, and this has prompted several studies on the problems of real-time estimation that arise when milling circuits are controlled automatically. King and his co-workers[4-6] and Herbst and his co-workers[7] have made important advances in this area.

Pebble mills can be separated from the circuit conceptually, and can be regarded as being linked to the circuit via only the circulating load. Operating variables in the pebble mill (the pebble load and the bulk density of the load) have to be controlled and optimized so that the pebble mill can process the ore particles comprising the circulating load in the most efficient way.

Pebble mills pose a special control problem in that they require a continuous feed of pebbles to make good the loss of pebbles due to abrasion. Williamson[8] was the first to design a peak-seeking controller that controlled the addition of pebbles to keep the mill power draft at a maximum. Further improvements to the controller design, although not the principle, were implemented by Flook[9]. The principle of maximum power draft at optimum operating conditions is commonly used in South Africa, and is apparently also used in other countries[10].

Few attempts have been made to control the bulk density of the load in industrial pebble mills. This loop usually consists of a ratio controller, a calculated value of the cyclone underflow being used as measurement input[11].

This paper describes the successful implementation of peak-seeking controllers with an on-line digital computer to implement the logic. Both pebble feed and water addition were used as control variables, the measurement of mill power being the only measurement input on both controllers. The pebble-mill controllers described here were developed as an integral part of a comprehensive grinding-circuit control system for the rod mill–pebble mill circuit at Buffelsfontein Gold Mine[12].

The Grinding Circuit

Fig. 1 shows one of the three parallel grinding circuits at the mine, and important pebble-mill data are summarized in Table I.

The objective in the control of the grinding circuit was the maximization of the production of fines at constant fineness of grind.

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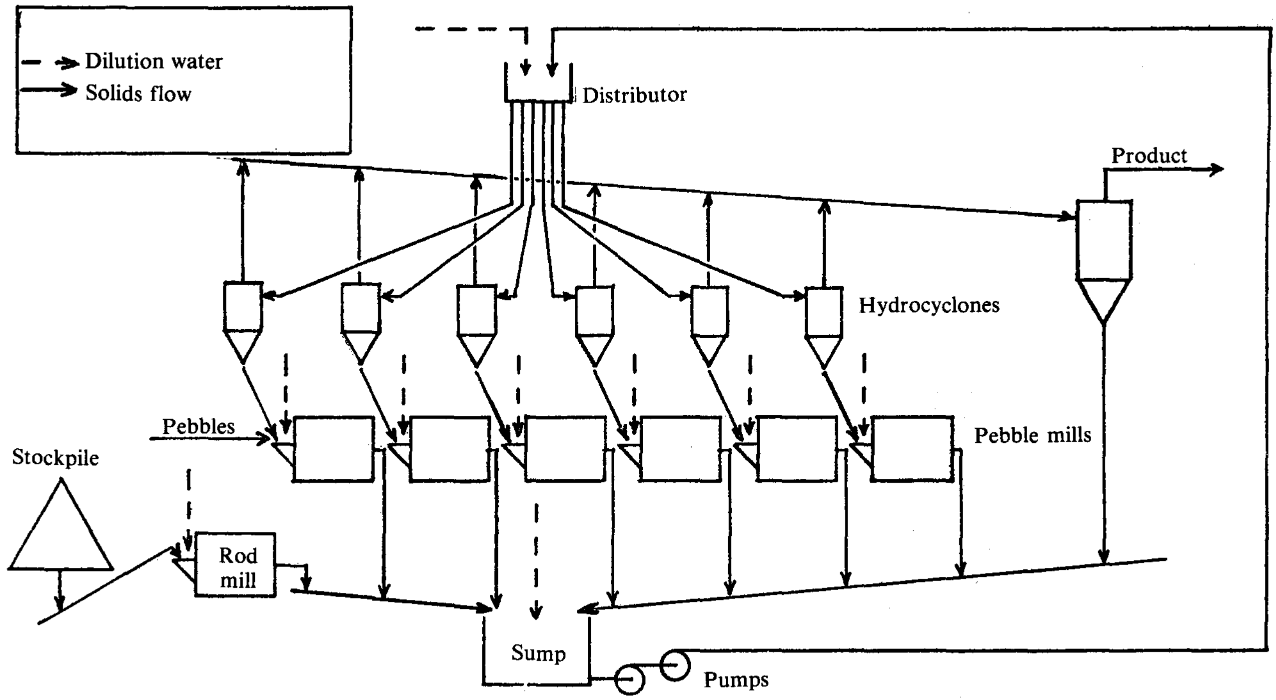


Fig. 1—Flowsheet of the grinding circuit

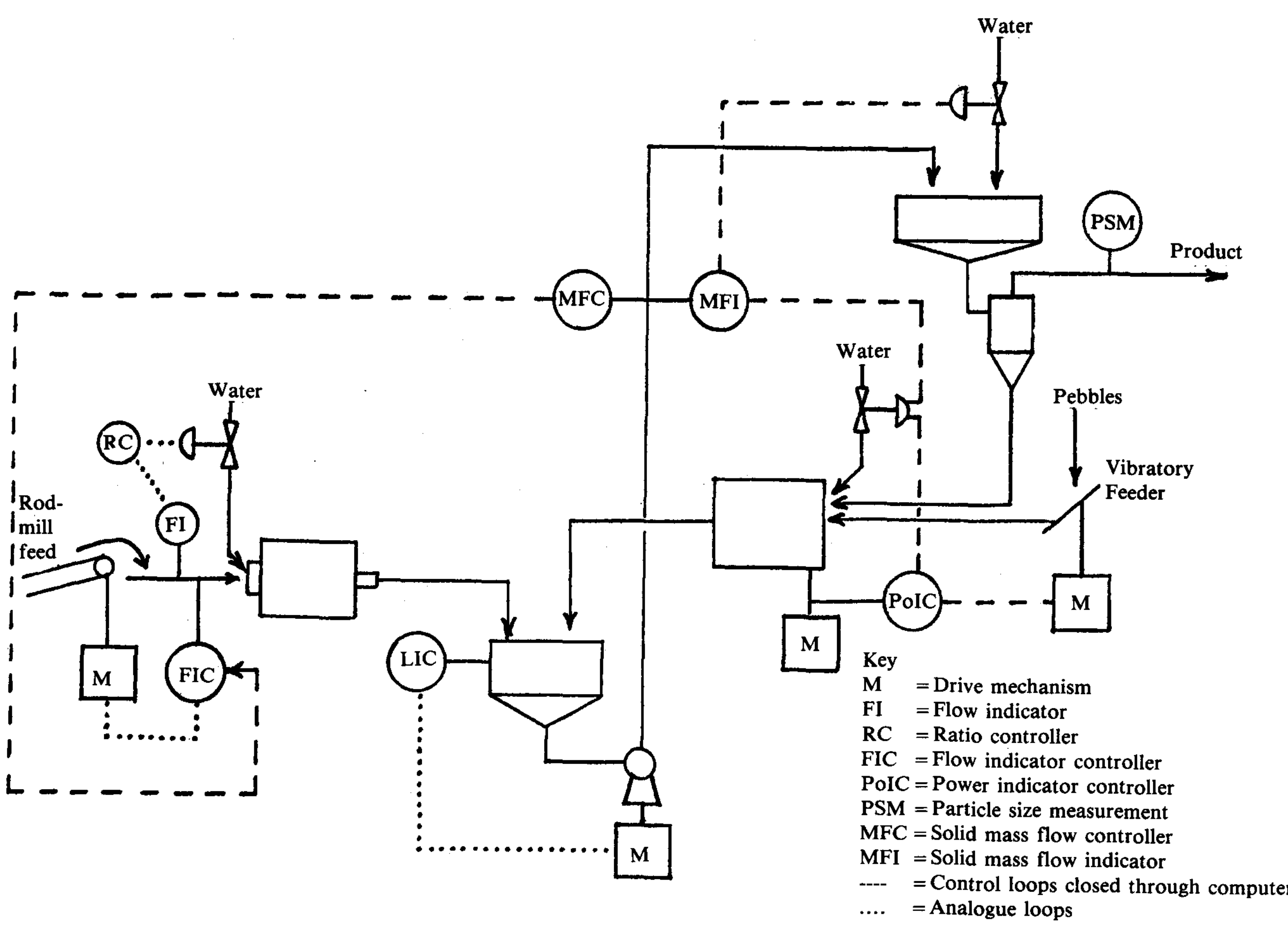


Fig. 2—Schematic diagram of the control loops

TABLE I
PEBBLE-MILL DATA

Mill size (length × inner diameter)	3,40 m × 3,00 m
Liner type	Osborn bars
Discharge type	Grate and lifters
Pebble size (feed)	> 60 mm < 100 mm
Rotational speed	85 per cent of critical
Circulating load	1000 %

The circuit control scheme (Fig. 2) consists of the following control loops.

(1) The circulating load is controlled through the manipulation of the feed rate of fresh solids to the rod mill.

(2) Dilution water added to the distributor (i.e. cyclone feed) controls the particle-size distribution of the product stream.

(3) The sump level is controlled by variation of the speed of the sump discharge pump.

(4) The addition of rod-mill dilution water is controlled at a constant ratio to the feed rate of dry solids to the rod mill.

(5) The pebble load and the bulk density (or the addition of dilution water) are the controlled variables for the pebble mills. (The details of these two controllers are given later.)

The measurement of mill power was the only measurement available on the plant from which either the pebble load or the bulk density of the load of any given pebble mill could be inferred. The relationships between these variables and mill power were therefore investigated in some detail.

The equipment used in the investigation consists of a process control computer, vibratory pebble feeders for all six pebble mills with on/off control, and an automatic valve on the dilution-water line to one of the pebble mills. The flowrate of water through the valve can be varied by the changing of the diaphragm position of the valve as the result of a 4 to 20 mA signal from the process control computer. A flowmeter is thus not incorporated in this facility.

The mill-power signal used for control was filtered with low-pass analogue and digital filters.

Operational Variables Affecting Mill Power

The relationships between mill power and the three most important variables are shown schematically in Fig. 3. The variables are as follows:

(1) *Load*

The typical single-maximum relationship between mill load and mill power is well documented, and was confirmed on the plant under discussion.

(2) *Bulk Density*

No detailed information on the relationship between the bulk density and the power of industrial mills is available in the literature. The results of an investigation on the plant are presented schematically in Fig. 3 and in greater detail in Fig. 4. The data presented in Fig. 4 were obtained during stable circuit operation, and no pebbles were added during the period. Mill power shows a general decreasing trend in Fig. 4a, which is due to the continuous reduction in the mass of the pebble load because of the wear of pebbles. More important, however, are the responses in mill power to the small step changes in the feedrate of mill water and the clear peaks in mill power corresponding to intermediate values of valve position (i.e. water flowrate) at 33 and 62 minutes. These data reduce to the curve provided in Fig. 3.

It should be noted that the relationship for peak power presented here has been confirmed on only one plant. The position of the peak in mill power is influenced by design parameters, especially by the rotational speed of the mill.

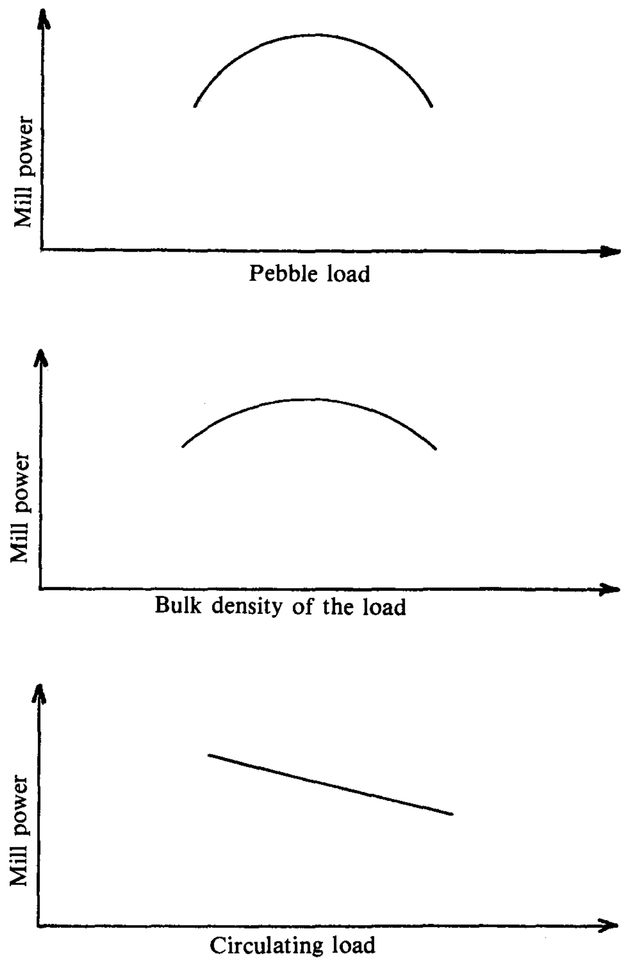


Fig. 3—Relationship of pebble-mill power to the other operating parameters

(3) *Relationship between Circulating Load and Mill Power*

This relationship was obtained by an evaluation of the response of mill power to rapid changes in the circulating load. The results are presented schematically in Fig. 3.

Typical transient responses of mill power to changes in the dilution water added differ at high and at low bulk density. Typical transients are shown in Fig. 5, and recorded results in Fig. 8. The response at high density is of particular importance. Firstly, it suggests that the grinding mill should not be approximated as a perfect mixer and, secondly, that great care should be taken when transient mill-power response is evaluated for control purposes. The transients last for approximately 5 minutes.

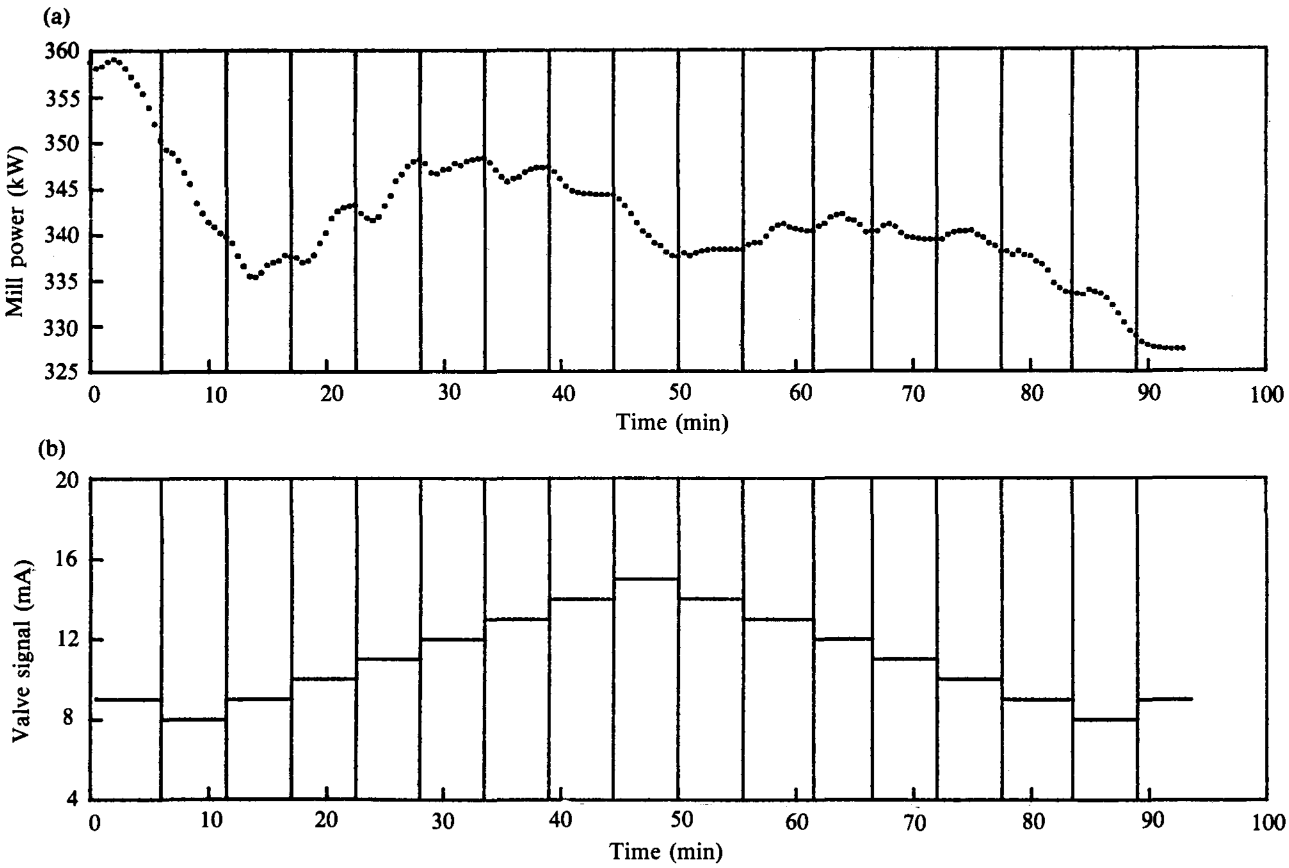


Fig. 4—Response of mill power to changes in the flowrate of dilution water

Control Principles

Although the mill-power relationships of the pebble load and load density have been identified, one still has to determine the point on the curve for mill power at which these two variables should be controlled so that the objective of the grinding-circuit control can be satisfied.

It is generally accepted that a volume of mill load corresponding to peak mill power results in maximum grinding rates in autogenous mills[1]. The present study was not concerned with the validity of this assumption on the circuit, but peak mill power was chosen as the objective for pebble-load control in view of the historical precedence.

The bulk density of the mill load is normally controlled manually by the maintenance of the relative density of the mill discharge at 1,83. Sampling of the mill discharge stream indicated that peak mill power (as a function of bulk density) was obtained at a mill-discharge relative density of approximately 1,83, which is an acceptable operating condition from a metallurgical point of view. Maximization of mill power through the manipulation of the water addition of the mill was thus selected as the control objective for the bulk-density controller.

When the total non-linearity of the relationship between mill power and the two variables to be controlled is considered, it is apparent that classical or modern control theory, which is based on linear mathematics using linear dynamic models, is simply not applicable.

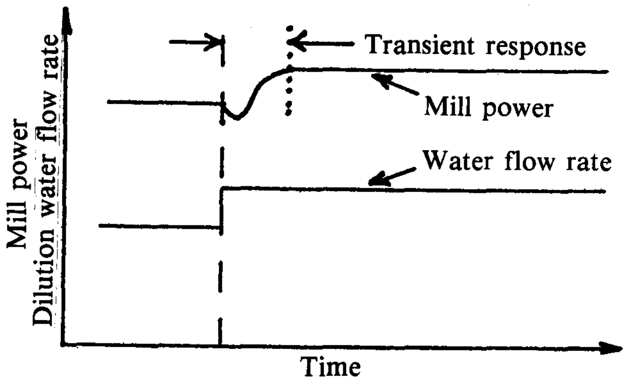
The approach in the work described was the design of logic algorithms that aimed at maximizing the mill power (i.e. so-called peak-seeking controllers, which are similar in some respects to the Digicon controller used on autogenous mills[9]).

The principle of operation of peak-seeking controllers can be explained[13] with reference to Fig. 6. The mill-power measurement does not fully define the state of the mill load, as is proved by the fact that pebble loads corresponding to points A and B both yield the same value for mill power. However, if the pebble load is increased at point A, the mill-power response will be positive. At point B, an increase in pebble load yields a negative mill-power response. The state of the pebble load can therefore be determined uniquely by the combination of the absolute value of mill power and the response of mill power to a positive change in the load.

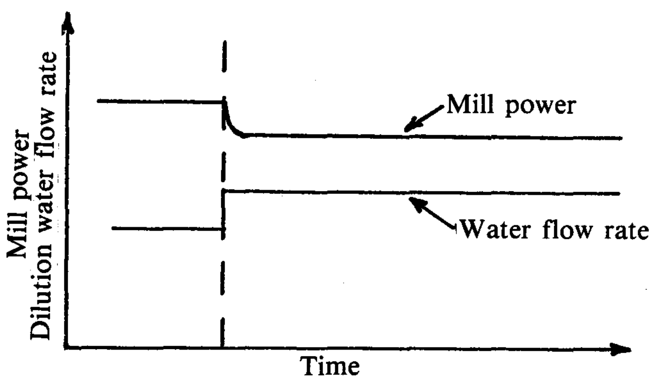
Pebble-load Control Logic

The control scheme allows the pebble load to be reduced to a value below peak power, and pebbles are then added to increase the load to a value corresponding to peak power. The pebbles are added intermittently in pulses of 80 seconds duration. Greater definition in mill-power response is ensured than with the continuous loading of pebbles. Fig. 7 is an example of the controller's operation under stable circuit conditions.

The operation of the controller can be divided into two distinct cycles.



(a) Mill power response at high bulk density



(b) Mill power response at low bulk density

Fig. 5—Characteristic mill-power response to step changes in the flowrate of dilution water

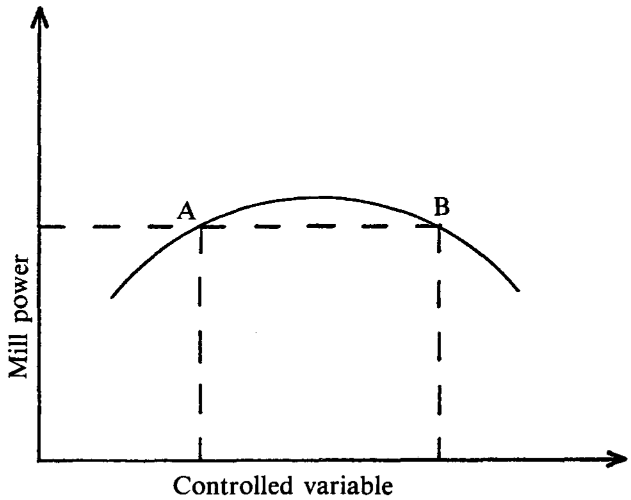


Fig. 6—The absolute value of mill power does not define the state of the controlled variable uniquely

Load Cycle. This cycle is initiated after a certain fall in power has been attained.

1. Add pebbles for 80 seconds.
2. Wait 6 minutes.
3. Evaluate mill-power response:
   Positive: Pebble load is still below peak power, return to point 1.
   Negative: Peak power has been attained, continue to wait cycle.

Wait Cycle

4. Initiate wait cycle.
5. Maintain a record of the highest mill-power value (P_{max}) since the initiation of the wait cycle.
6. Compare the current value of mill power with P_{max}. If a preset fall in mill power (approximately 2 per cent of P_{max}) has been attained, then terminate the wait cycle and return to point 1. If not, continue.
7. Wait 30 seconds. Return to point 5.

The typical duration of the wait cycle is 45 minutes and of the load cycle 30 minutes, but these time periods vary greatly depending on a wide range of circuit variables. This variation is an indication of the flexibility of this algorithm compared with a fixed-time-period algorithm.

Control Logic for Bulk Density

When the pebble-load controller is in the wait cycle, no pebbles are added. The mill-power signal is thus available for the control of bulk density during these periods. The mill-power response to the actions of the bulk-density controller is small and does not disrupt the wait cycle of the pebble load controller. The bulk-density controller is de-activated during the load cycle of the pebble-load controller, resulting in constant valve position and rate of water addition. Time sharing thus ensures that both the pebble load and the bulk density can be controlled with the mill-power signal as input measurement.

An example of the operation of the bulk-density controller is provided in Fig. 8. Step changes in the rate of water addition of alternating signs are made continuously, with a waiting period of 8 minutes between steps. The mill-power response to a step is evaluated at the end of the 8-minute waiting period, and is compared with the mill-power response to the previous step. A positive response to a positive step indicates that the density is too low; a negative response to a positive step that the density is too high, and *vice versa* for a negative step. (*Positive* implies more positive or less negative than the mill-power response to the previous step.)

Depending upon the outcome of the evaluation of the mill-power response to the previous steps, a small control addition is made to the size of each step in order to increase or decrease the average valve position. This is demonstrated in Fig. 8, where the mill-power response at the beginning of the period indicates that the bulk density is too high. The average valve position is increased gradually in order to increase the water flowrate.

The characteristic mill-power response to step changes in the flowrate of water at high bulk density is clearly illustrated in Fig. 8.

Discussion

The examples presented in Figs. 7 and 8 can be seen as ideal cases. Mill power is a function of several operational variables and is normally less stable than in these examples. The control constants were tuned through

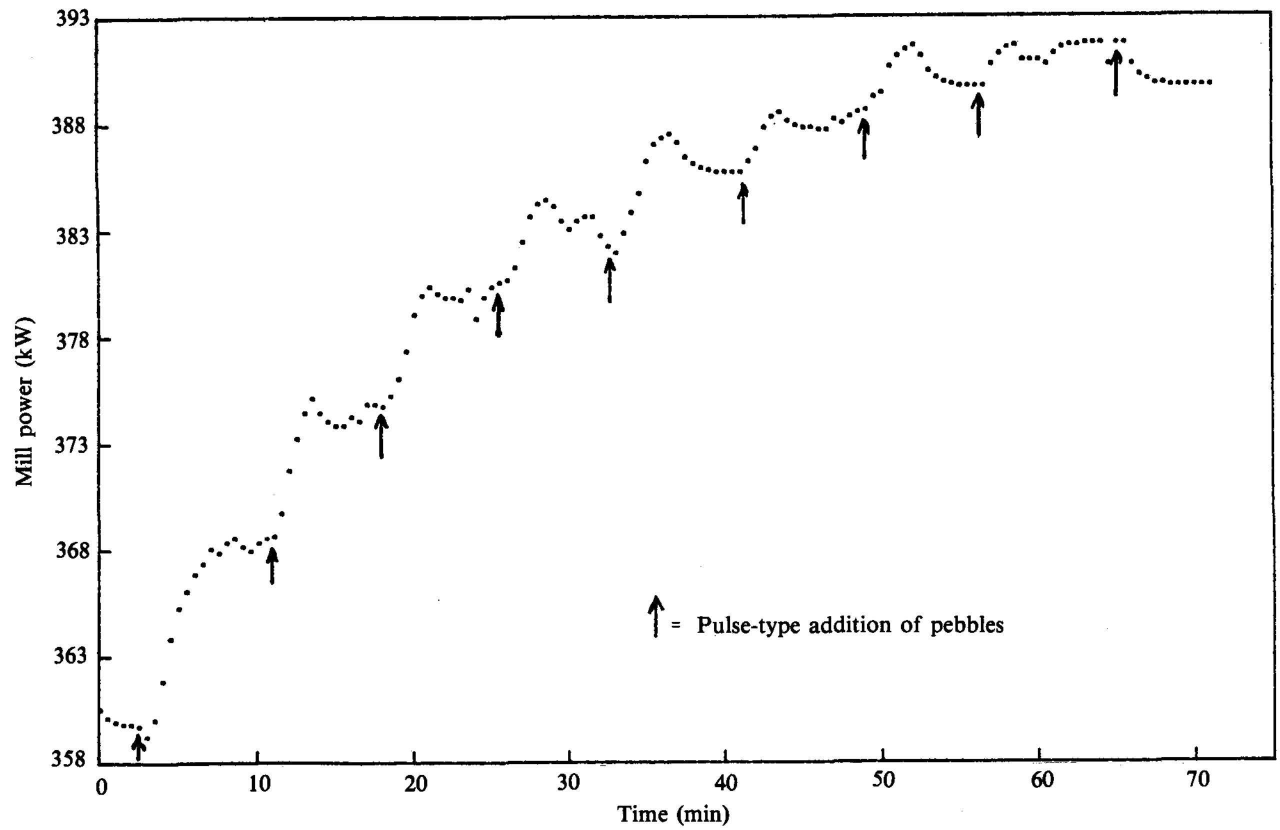


Fig. 7—Mill-power response to the addition of pebbles during the load cycle of the pebble-load controller

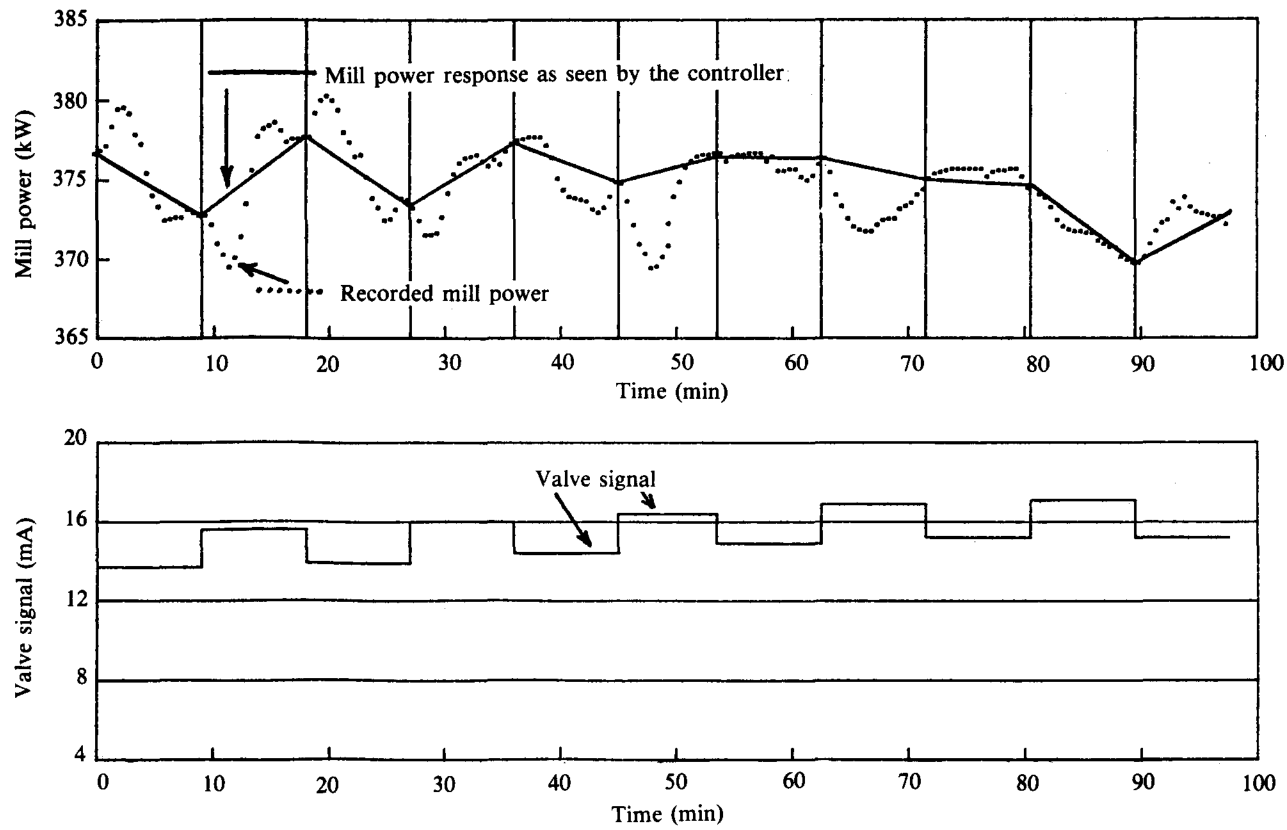


Fig. 8—Operation of the bulk-density controller

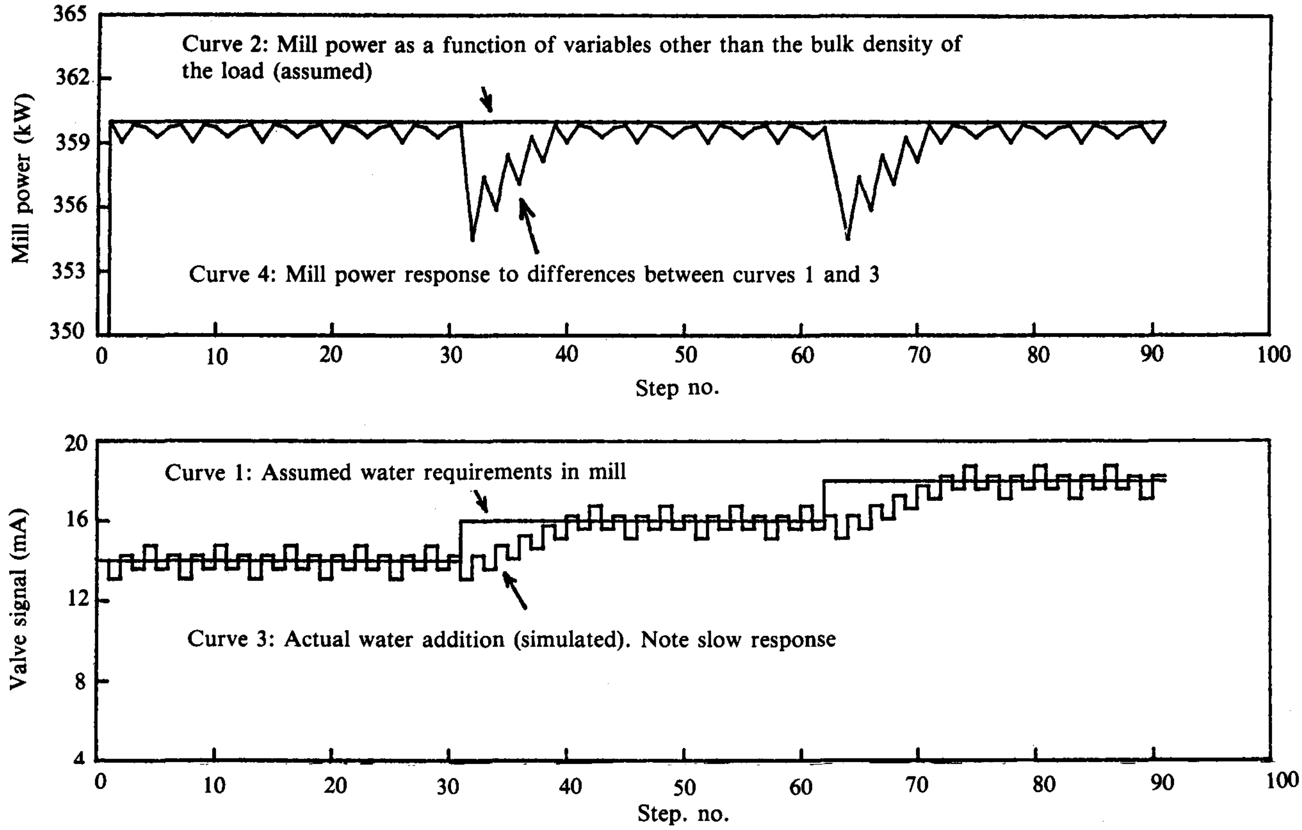


Fig. 9—Slow response of the peak-seeking bulk-density controller

careful on-line and off-line work in order to optimize controller performance for the noise levels encountered on the plant. It has been shown that the circulating load is an important variable affecting mill power. The stabilization of the circulating load by the circuit control loops has improved the stability of the mill-power signal, as implied by Garner *et al.*[14]. Improved mill-power stability (i.e. reduced noise level) results in more efficient operation of the pebble-load and bulk-density controller.

The pebble-load controller, which has been in continuous operation on six pebble mills for 18 months, was found to be particularly reliable. The stability of the circuit has improved, pebbles being loaded in pulses of 80 seconds duration. Interlocking ensures that only one pebble mill can be loaded at any given time. Manual control practice involves the simultaneous loading of all six pebble mills for a period of between 5 and 10 minutes, and the resultant increased hold-up of pulp in the mills causes a circuit disturbance.

The most important economic benefit is a 1 to 3 per cent increase in tonnage throughput (rod-mill feed) when the pebble load is controlled automatically. There is some evidence of increased pebble consumption, but this could not be fully substantiated owing to the manual pebble accounting system. Another obvious benefit will be that, when automatic control has been extended to all three grinding circuits, the operator will be relieved of the tedious task of loading twenty pebble mills regularly. He will therefore have more time to observe the circuit performance closely.

Operator interference was found necessary from time to time with the peak-seeking bulk-density controller. The reason is the slow response of the controller to changes in water requirement in the mill. This point is illustrated in Fig. 9. After a major disturbance in water requirement in the mill (curve 1), the controller has to make 7 steps in actual water flowrate (curve 3) before the required water flowrate is attained. At a waiting period of 8 minutes between steps in curve 3, the controller requires 56 minutes to fully respond to the disturbance.

It is known that the dilution water required in a mill is a function of the circulating load. Although a measurement of circulating load was not available on individual mills, a measurement of the total circulating load through all six pebble mills in the circuit was available. This measurement was used to develop an additional feed-forward control loop for the control of the bulk density. The controller changes the flowrate of dilution water being added to the mill at a constant ratio to changes in the circulating load. Thus, if the circulating load increases, the controller increases the flowrate of dilution water, and *vice versa*. These changes in water flowrate are small compared with the steps in water flowrate induced by the peak-seeking density controller, with the result that the mill-power response to these changes is very small. The feed-forward controller does not therefore disrupt the operation of either the peak-seeking bulk-density controller or the pebble-load controller.

The fact that the feed-forward controller is operated continuously, even during periods of pebble loading, has greatly improved the response time of the bulk-density controller.

The combination of the feed-forward and the peak-seeking bulk-density controllers has been in continuous operation for a period of four months. Operator interference is still required occasionally, but the controller has been in operation for periods of up to one week without the need for any manual interference.

The benefits of the bulk-density control system can be evaluated only once control has been extended to all six pebble mills.

Summary and Conclusions

The relationship between mill power and pebble load, bulk density of the load, and circulating load were determined on the plant under discussion.

Peak-seeking controllers were developed for pebble-load and bulk-density control on the pebble mills, mill power being used as the only measurement input.

The pebble-load controller has operated reliably over extended periods of time, has improved the stability of the circuit, and has resulted in a 1 to 3 per cent increase in tonnage throughput at a given fineness of grind.

A novel method was developed for control of the bulk density of the load. When this peak-seeking controller was coupled to a feed-forward control loop that uses the measurement of the circulating load as input signal, a controller with acceptable response time was obtained.

The combination of two peak-seeking controllers operating together has been found to be stable and effective. This is the first known application of multivariable peak-seeking controllers on an operating plant.

Although not the subject of this paper, it is worthy of mention that the peculiar transient mill-power response to changes in water flowrate (Fig. 5) led to the development of a model of charge motion in the mill[15]. This model predicts not only the transient mill-power response, but also the peaks in the mill power as a function of pebble load, bulk density of the load, and mill rotational speed. Details of the model will be published in due course. This exercise served to illustrate that the development and implementation of process controllers have not only direct financial benefits (potentially), but also secondary advantages in terms of an improved understanding of the process, which can lead to process optimization.

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