The control of milling circuits

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SYNOPSIS

The general behaviour of mills is described in an attempt to find a control philosophy that will permit milling circuits to produce a constant particle size. Although the experimental work has been confined to a single section of the milling circuit of one mine, it is felt that the findings are applicable to other milling circuits.

SAMEVATTING

Die algemene gedrag van meule word beskryf in 'n poging om 'n beheerbeleid te vind wat maalbane wat 'n konstante partikelgrootte sal lewer moontlik sal maak. Hoewel die eksperimentele werk wat gedoen is, beperk was tot 'n enkele afdeling van die maalbaan van een myn, word daar gereken dat die bevindings ook op ander maalbane van toepassing is.

INTRODUCTION

The purpose of milling is the reduction in size of rock to the point where liberation of valuable minerals takes place. Thus, a milling circuit must yield a product that is of known and, preferably, controllable size. This almost self-evident truth tends to be obscured in the milling literature by a fixation with capacity-determined factors, for it is also necessary that a milling circuit must accept a certain number of tons of feed per day. However, it has been extremely difficult until recently to determine particle size continuously and in real time, whereas feed rates are determined relatively easily. Thus, much of our milling philosophy has been oriented towards dealing with an adequate tonnage of ore, and the question of whether an adequate size is being produced by the circuit has been left both to random checks on the circuit itself, and to experience in handling the product stream once it has been fully mixed after leaving the circuit.

However, instruments for the continuous monitoring of particle size are now available commercially. The availability of these instruments makes it possible to consider the control of milling circuits to ensure that they produce a product of consistent particle-size distribution at all times. In principle, therefore, it is possible to extend the control to ensure that the optimum particle size is produced. This is a more difficult operation, because it must vary with the nature of the ore, the value of the metal contained in the ore, the nature of the process downstream of the mill, and the cost of the milling process.

However, it is reasonable to assume that the nature of the ore on the typical South African gold mine is relatively consistent. Certainly, mines can decide in advance what particle-size distribution is required in the product from the milling process, and can operate for long periods with a size distribution close to that specified, without there being much evidence that changes in recovery are related to changes in the nature of the ore. Only when there is a marked change in the relative tonnages mined from the various reefs on any given mine is it necessary to consider a change in the specified particle size. Thus, it can be assumed that ore variability need not be taken into account in the design of any control system to yield an optimum particle size in the South African gold-mining industry.

To a large extent, the value of the metal contained in the ore sets the permissible grind; in many metallurgical procedures, the cost of milling is a large proportion of the total treatment cost. In the South African gold-mining industry, however, the value of the gold contained in the ore fed to the mill has long been relatively constant, because there has been a fixed gold price and ore grades have moved upwards with costs. Accordingly, it has been possible to fix the size of the mill product. Recent increases in the price of gold have removed this restriction on particle size, however, and it becomes possible to consider a reduction in particle size to increase the recovery, although this may not be possible without the installation of additional capacity. There is thus at the present stage a greater incentive to examine the optimization of mill performance than there has been for many years.

The processes downstream of the mill influence the optimum particle size because finer sizes may affect either the capacity or the efficiency of those processes, or both. For instance, filter duty is fairly dependent on particle size, and, the finer the size, the lower the duty, and thus the greater area of filters needed to treat a given tonnage. Similarly, the metallurgical efficiency of flotation drops off markedly in the finer size ranges. In the gold-mining industry, however, capacity limitations on finer grinding appear to be more important than efficiency limitations, and, other things being equal, it is believed that finer grinding will lead to improved efficiency. In the context of a higher gold price, such improvements in efficiency are naturally desirable. However, the efficiency of extraction has always been very high, and it is thus difficult to estimate the benefits resulting from any changes. Long-term tests under carefully controlled conditions are therefore necessary to demonstrate

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statistically whether any of the anticipated improvements in efficiency are obtained in practice. It is thus clear that some form of control must be introduced to ensure long-term stability of operation if the magnitude of potential benefits is to be determined.

This paper concentrates on the actual behaviour of mills, in an attempt to identify a control philosophy that will permit mill circuits to produce a constant particle size. This study is by no means complete at the present stage, and this paper must be viewed as a progress report. In addition, the experimental work has concentrated on a single section of a milling circuit on one mine, and the results are not necessarily generally applicable. However, some of the phenomena observed have been sufficiently large and sufficiently unexpected to suggest that there may be merit in looking for such effects in other circuits.

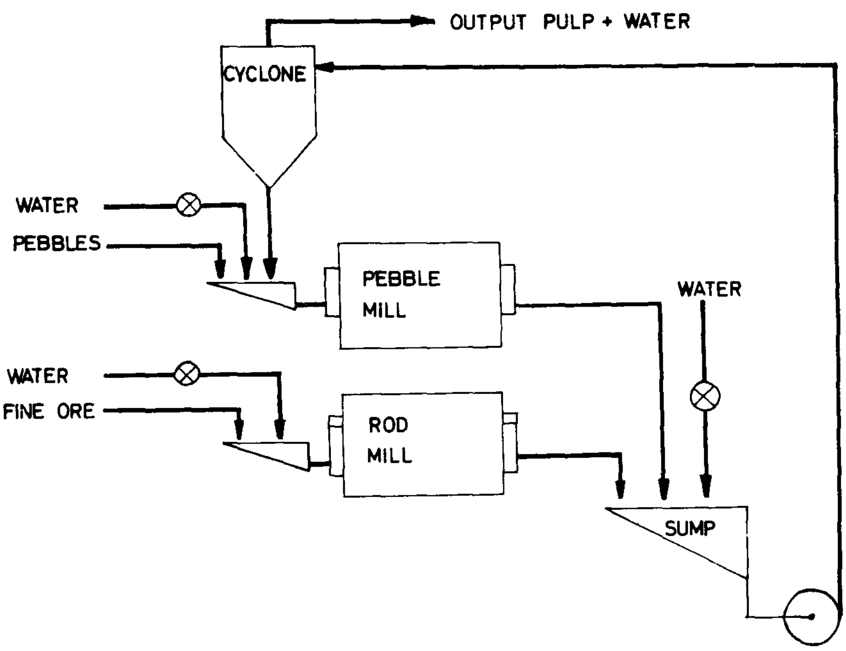

Fig. 1—A typical mill-classifier circuit.

THE BEHAVIOUR OF A MILL CIRCUIT

In attempting to develop a control system for a milling circuit, it is necessary in the first instance to understand the nature of the changes that occur in the product, and that are to be controlled. Thus, the first part of this study concentrated on an attempt to understand the dynamic behaviour of mill circuits.

Changes in mill circuits occur as follows:

(1) in the inputs to the circuit, e.g., the rate of feed to the mills, the size distribution of the feed, or the rate of water addition at

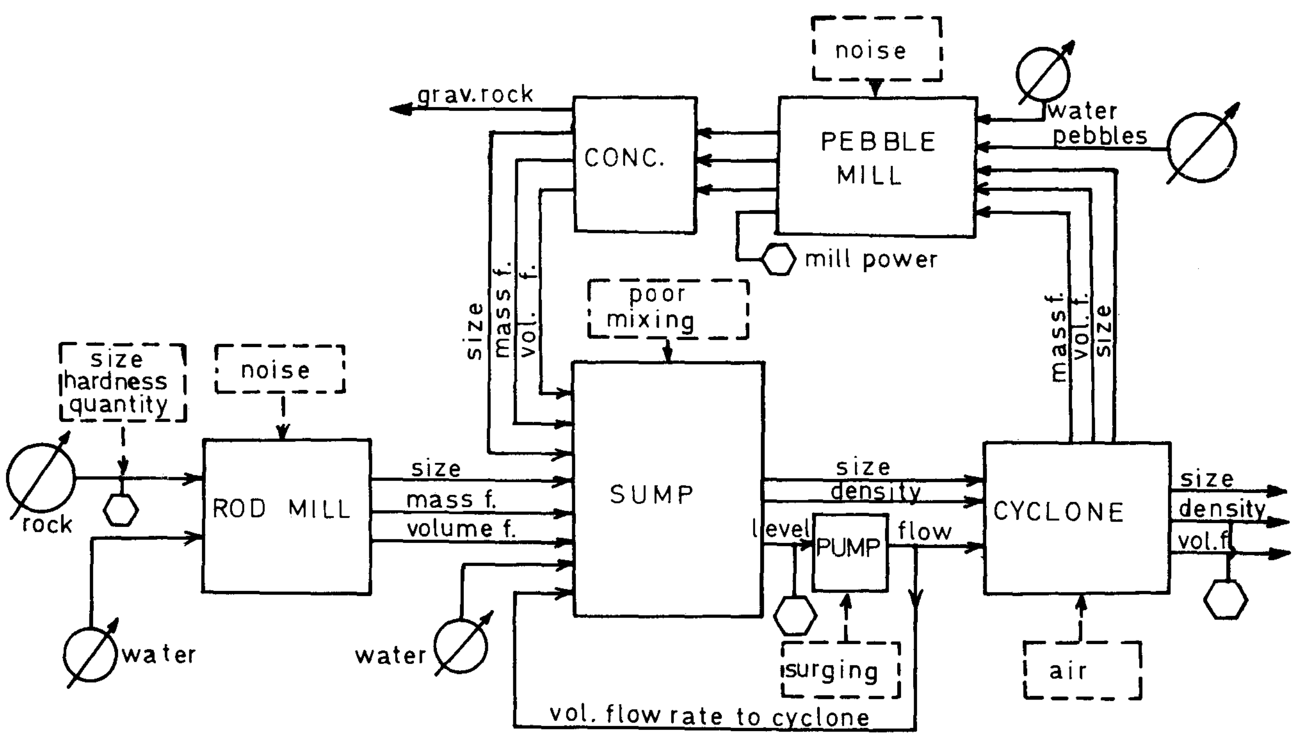

Fig. 2—Signal-flow block diagram of the milling circuit.

various points;
(2) in the operation of the circuit, e.g., the stopping of a rod mill to feed rods, or the stopping of a cyclone to clear a choked spigot, and
(3) in the operation of the circuit because of instability within the circuit that causes 'noise' (i.e., random shifts of varying and generally small amplitude about a constant mean value), for example, the flow from a pebble mill, which varies as the pebble charge cascades within the mill.

A dynamic model of a typical mill circuit was constructed by standard digital techniques[1]. The circuit that was modelled is shown in Fig. 1, and the signal-flow diagram applicable to this model is given in Fig. 2. The mills were treated as a series of delay elements with plug flow within each element[2,3], and the cyclone model was that of Rao[4] as adapted by Lees[5]. The scale of the model was that of a typical modern mill circuit installed on a gold mine, which would accept approximately 80 tonnes of fresh feed per hour and yield a product containing, on average, about 60 per cent by mass of minus 75 μm material. In practice, a single rod mill will feed two pebble or ball mills operated in parallel, but, for the purposes of the model, perfect symmetry between the pebble mills is assumed and therefore only half of this circuit is examined.

The results of the simulation in which the rod-mill was stopped for three minutes are shown in Fig. 3. Three cases were considered. In the first there was no control in the circuit, and the effects were
(a) a significant excursion in the density of the product stream and in the fineness of the products, and
(b) a drop in the sump level.

In the second, the sump level was controlled by the addition of water, which reduced the density of the pulp and increased the magnitude of the excursions in product pulp density and fineness. In the third, the sump density, and thus the cyclone-feed density, was controlled, and, while there was an excursion in the sump level, shifts in product pulp density and fineness were negligible.

By this type of simulation, it was possible to demonstrate in principle that
(i) simple control systems can be designed to cope with disturbances of reasonable magnitude both external to the circuit and within the circuit, and
(ii) many suggested control systems had been insufficiently analysed, and, as a result, there was a need in such systems for excessive instrumentation to meet the requirement of a constant particle size. As an example of this, the control of sump level by simple water addition, which has been applied fairly widely in the industry, can be shown to increase the amplitude of excursions in particle size in all cases. Similarly, an on-off controller on a pebble mill feeder can be shown to require a very short cycle time if it is not to affect flow from the mill, and thus the particle size, adversely. In practice, the cycle time of such a controller is often tied to the power drawn by the mill, and the period of measurable excursions in this latter parameter is far too great for adequate control.

In further simulations, the effect of noise within the circuit was studied. Fig. 4 shows a typical result. In this simulation, both the flowrate from the pebble mill and the density of the pulp leaving the sump were allowed to vary randomly by up to about 10 per cent and 2 per cent of their average values, respectively. It is clear that, in this case, there are very large shifts in the particle-size distribution of the product, and it can be shown that these shifts are caused more by the changes in the

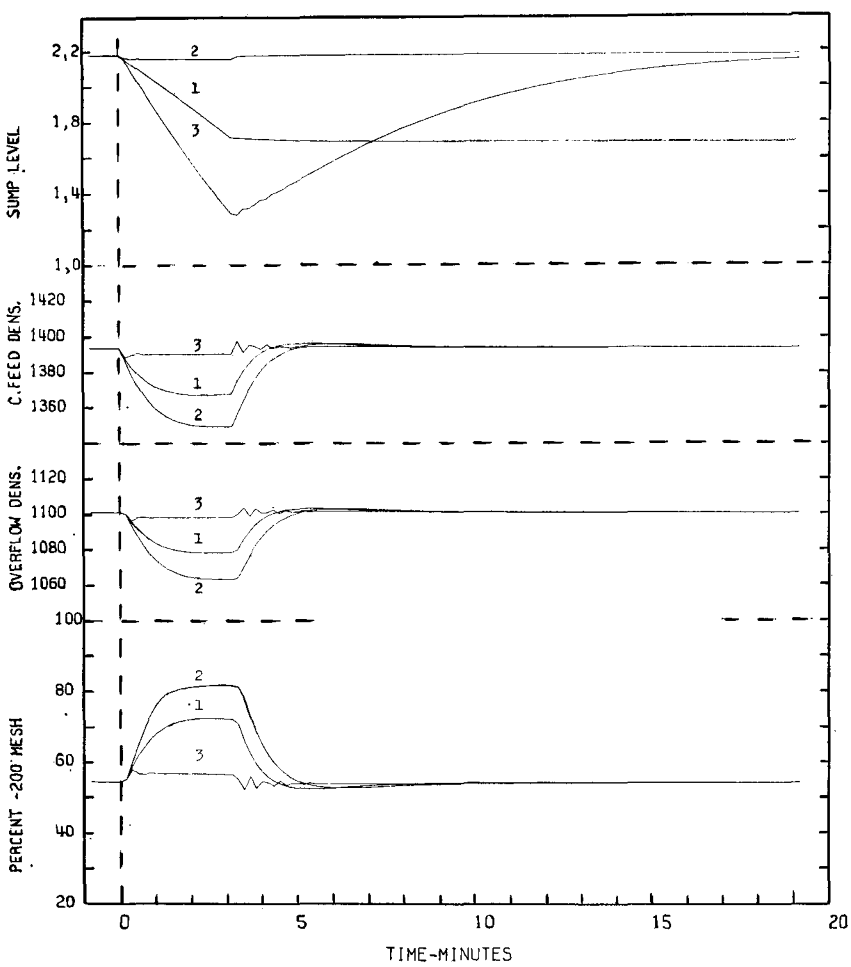

Fig. 3—A computer simulation to demonstrate the response of the milling circuit to a disturbance caused by the stopping of the rod mill for 3 minutes. 1, No control. 2, Control of the sump level by water addition. 3, Density and sump-level control.

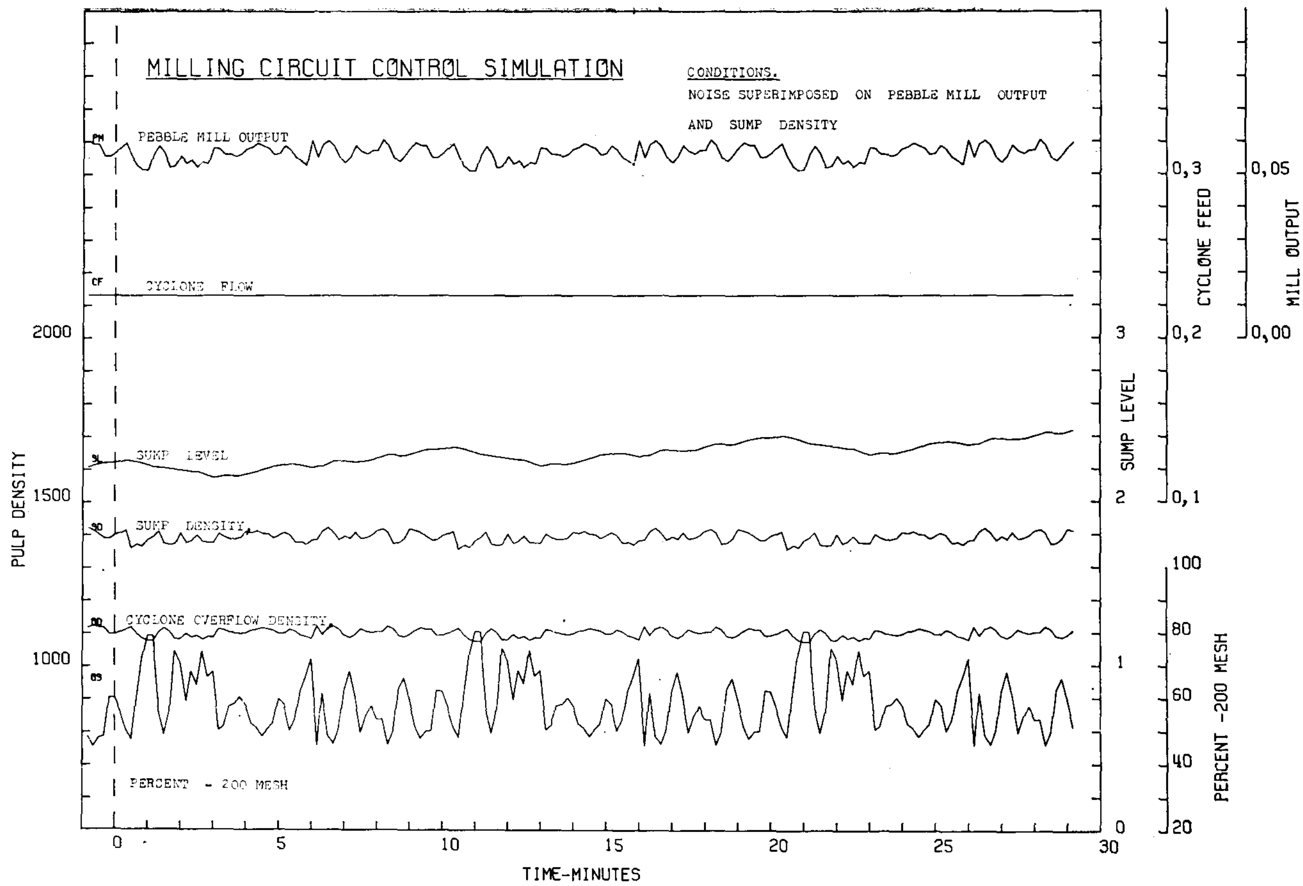

Fig. 4—A computer simulation to demonstrate the effect of poor sump mixing

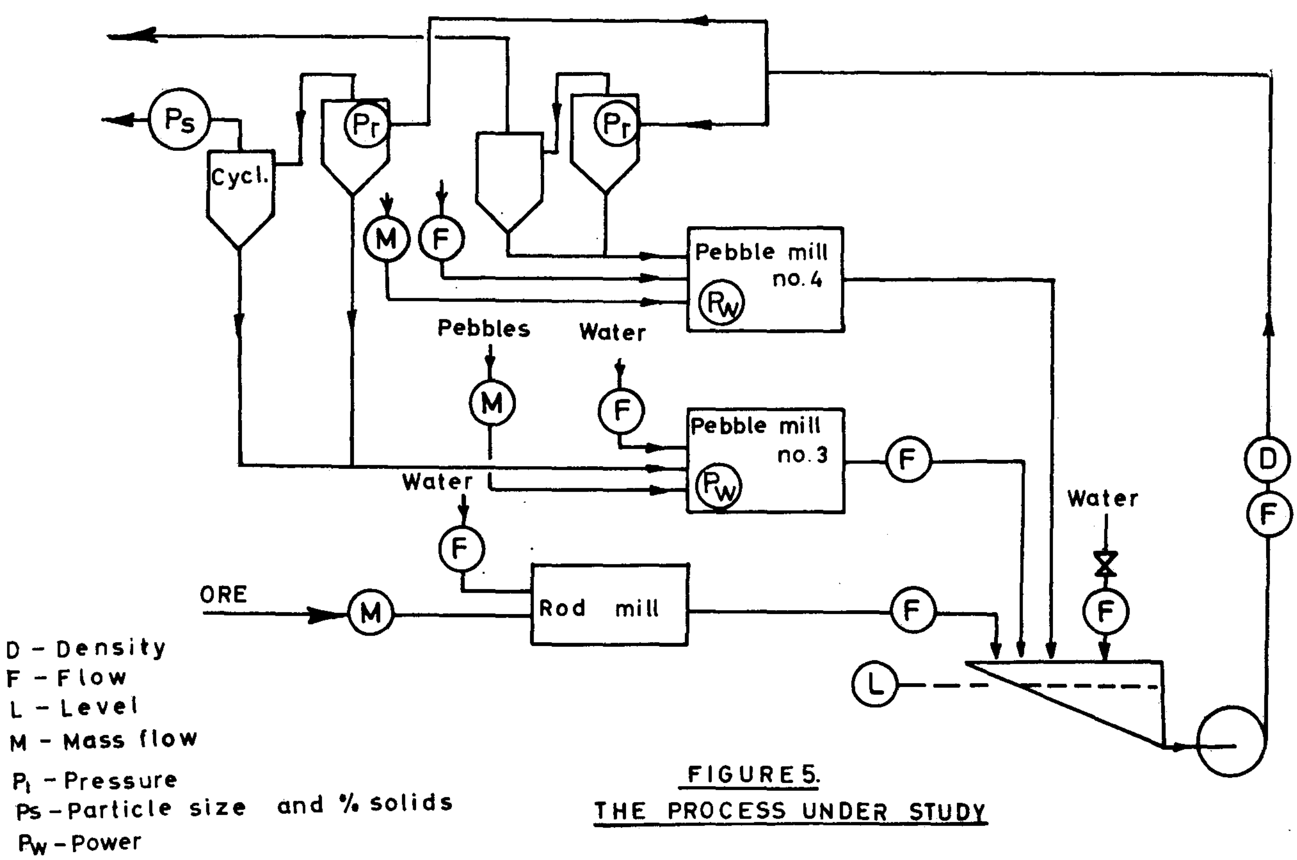

Fig. 5—The process under study.

sump density than by those in the mill output.

It was a general finding of the simulation studies that the sump was a critical component in the dynamic behaviour of the whole plant. In the circuit shown in Fig. 1, the sump receives the output of both mills and the dilution water. The flowrate of these streams may vary, and the density and grading analysis of the mill outputs may vary. If the cyclone is to operate satisfactorily and yield a consistent product, the sump must deliver from these potentially variable inputs an output that is consistent in density, reasonably constant in particle size, and at a known flowrate.

The simulation studies have been followed by measurements on an actual circuit. The process diagram and the instrumentation being installed are shown in Fig. 5. Some of this instrumentation has been yielding results for several months, and it is thus possible to make a preliminary assessment of the behaviour of the plant. The instrumentation that has been used includes the following:

1. an on-line particle-size analyser, which yields a record of both the particle size (percentage by mass of minus 75 μm material) and the slurry density in the cyclone-overflow pulp;
2. a gamma-ray density gauge and a magnetic flowmeter on the cyclone feed line;
3. an ultrasonic gauge for the sump level;
4. an integrating impact meter on the feed bin to the pebble mill, which permits an estimate to be made of the pebble feed rate and the pebble size;
5. ammeters to estimate the mill powers; and
6. a load-cell weightometer on the rod-mill feed.

The output of these instruments is recorded continuously. As the other instruments shown in Fig. 5 are installed, they are also to be tied to the recording system, which at present consists of multipoint paper-chart recorders, but which is to include a data logger using punched tape to permit assessment of the records by computer.

The first results from the system showed that there were large fluctuations in the cyclone-feed density, with corresponding shifts in the cyclone-overflow density and particle size. These were traced to erratic manual control of the sump level, and automatic control was therefore introduced. This reduced the amplitude of the disturbances from this source and permitted the identification of other sources of disturbance.

A record indicating relatively stable operation is given in Fig. 6. The apparently high frequency of large-amplitude disturbances is surprising, but it can be noted that the record of the whole day's operation showed reasonable stability for 18 out of 24 hours (i.e., 75 per cent of the time), whereas the average record during the six-week period of study showed an equivalent level of sta-

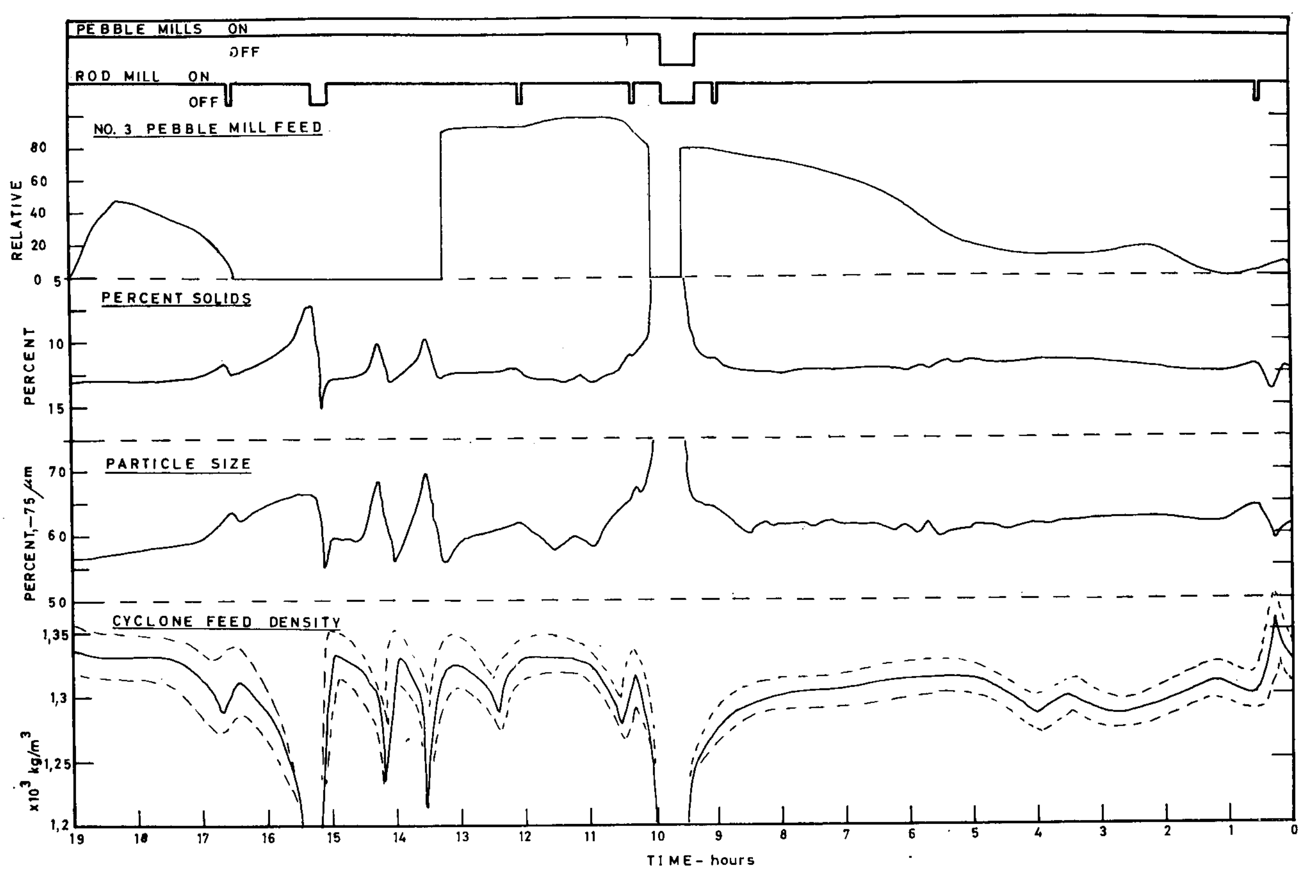

Fig. 6—A typical good record of plant performance.

bility for only about 45 per cent of the time.

Five types of disturbance are indicated on this record:

(a) a complete shut-down between 09.30 and 10.00 hours;
(b) a rod-mill shut-down between 15.10 and 15.25 hours;
(c) five rod-mill feed stoppages of about five minutes each, at 00.20, 09.00, 10.20, 12.10, and 16.40 hours;
(d) two pebble-mill feed stoppages of several hours duration, which occurred at 13.30 and 14.10;
(e) a 'noise' in the cyclone-feed density, which is indicated by dotted lines on either side of the record. A noise of similar amplitude was present in the cyclone-product density and particle size. This probably arises from inefficient mixing in the sump.

Many of these disturbances are avoidable in the sense that they should not occur in the normal running and maintenance of the circuit. These include the stoppage of pebble-mill feed due to overfeeding or lack of feed, stoppages of fresh feed for similar reasons, and stoppages to clear chokes in cyclones. It seems possible that adequate instrumentation could lead to a marked reduction in both the frequency and duration of this type of stoppage. Stoppages for unavoidable reasons take only about 2 hours in total from each day's operation, and each stoppage is associated with a disturbance of equilibrium lasting about 1 hour. It seems probable that some form of planned stoppage could be introduced to reduce the frequency of such unavoidable stoppages, each of which involves a disturbance of an hour. It can be concluded that adequate instrumentation may permit the operation of the circuit in a close-to-equilibrium condition for over 80 per cent of the time, without recourse to excessive or expensive control. Some form of control may be of assistance in ensuring that the time taken to reach equilibrium is minimized, but at present it is not possible to recommend a suitable control system.

At the present stage of understanding of the behaviour of the circuit, it is felt that there are two very valuable instruments on the circuit that deserve wider applica-

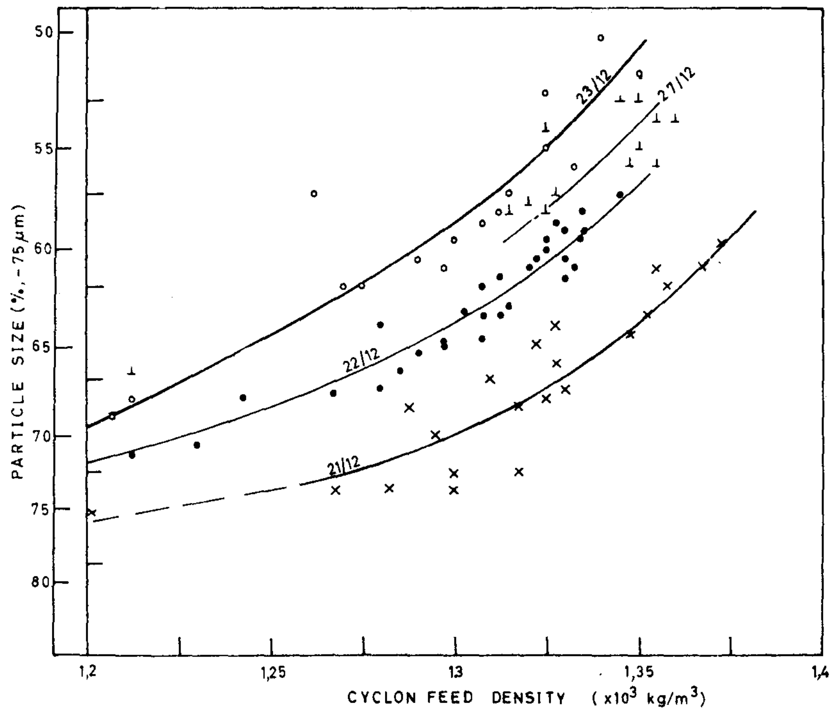

Fig. 7—Correlation between particle szie and cyclone-feed density

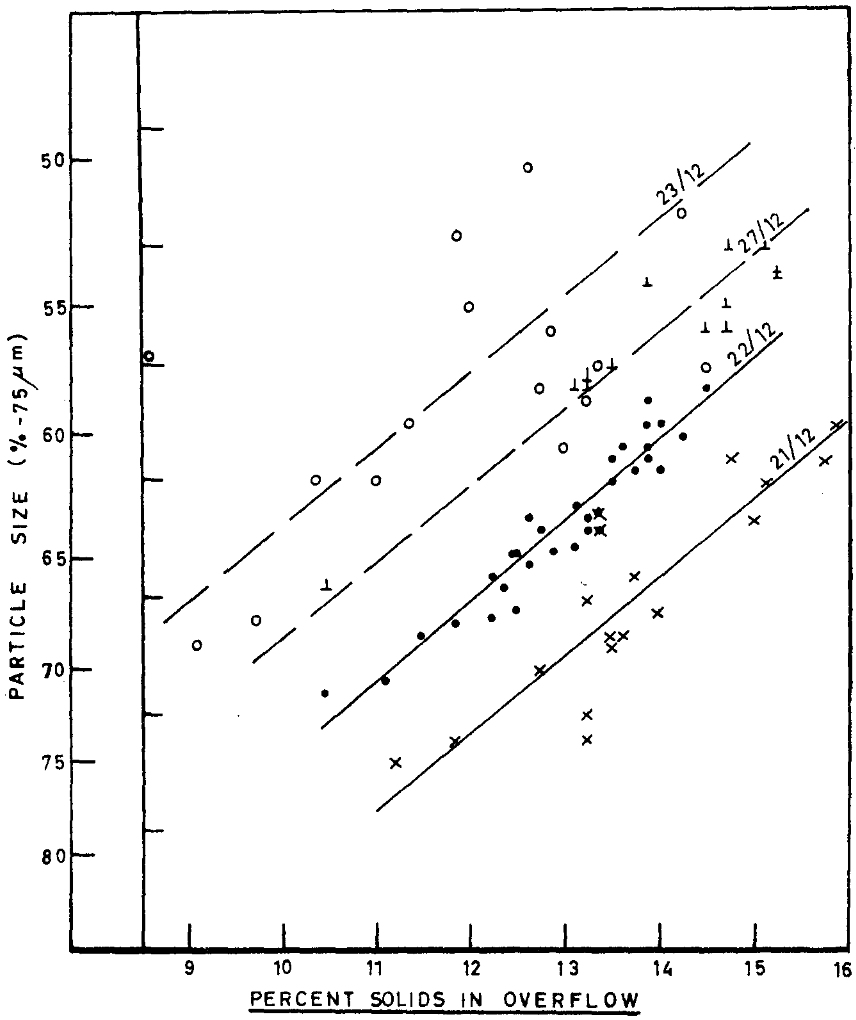

Fig. 8—Correlation between particle size and cyclone-overflow density.

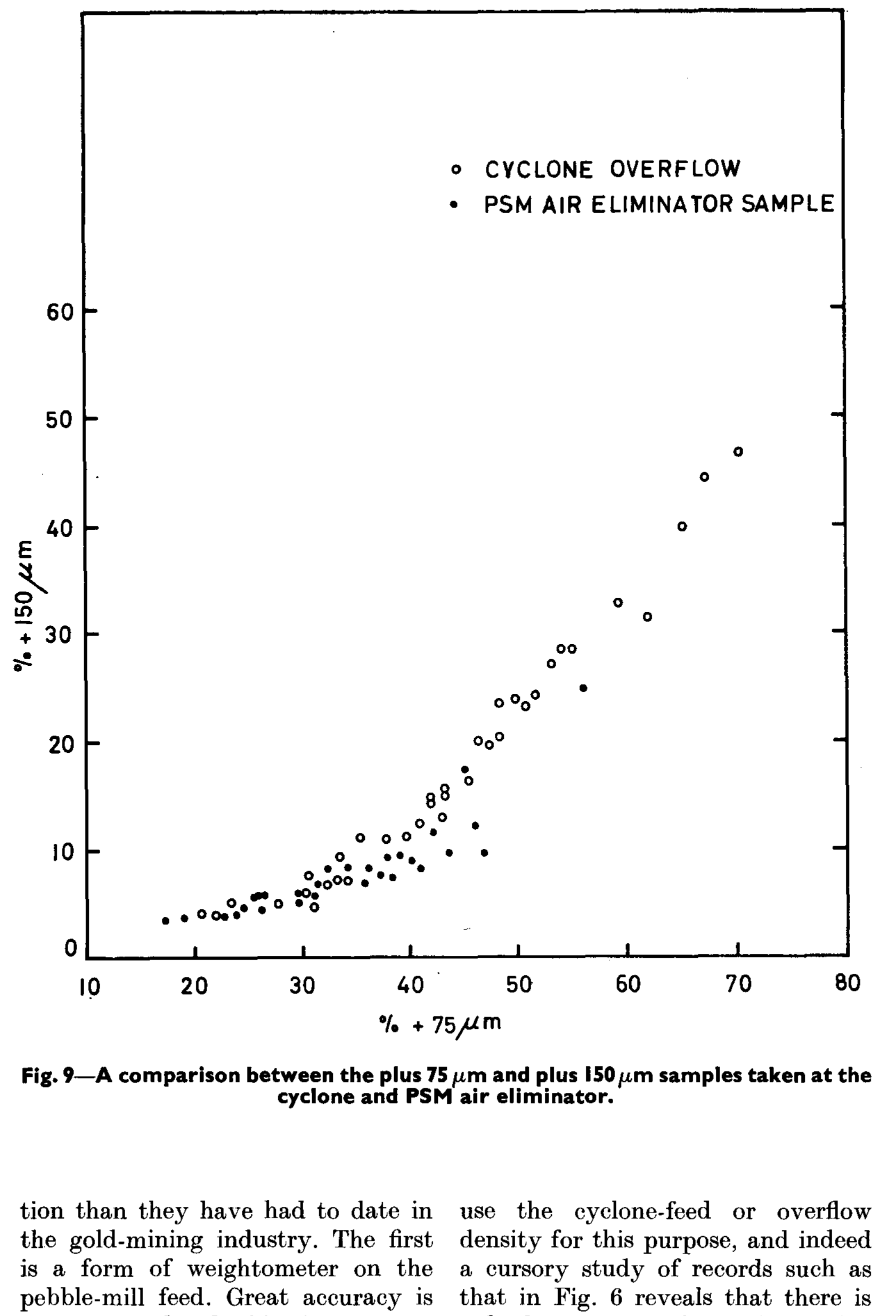

Fig. 9—A comparison between the plus 75 μm and plus 150 μm samples taken at the cyclone and PSM air eliminator.

tion than they have had to date in the gold-mining industry. The first is a form of weightometer on the pebble-mill feed. Great accuracy is not required of this instrument, because the ultimate control must be via the mill power. However, many disturbances could be avoided by ensuring a steady rate of pebble-feeding, and that rate could then be adjusted manually to ensure a maximum mill power demand.

The other instrument is a continuous particle-size analyser. There has been a great deal of controversy over the need for such an instrument, but from the experience to date it appears that this instrument is the most sensitive indicator available for diagnosing the state of the circuit. Many attempts have been made to use the cyclone-feed or overflow density for this purpose, and indeed a cursory study of records such as that in Fig. 6 reveals that there is indeed a degree of correlation between particle size and either of these densities. However, closer study reveals that, even under apparently steady-state conditions, the absolute value of either density is no guide to the absolute value of the particle size. This is indicated more clearly in Figs. 7 and 8, in which daily correlations between particle size and density are given. Plainly, any correlation is of a very short-term nature, and thus inadequate for particle-size control.

One aspect of possible concern in the continuous particle-size analyser is that it uses a single particle size (the percentage of minus 75 μm material) to represent the entire size distribution. This would be valid only if it could be shown that any one fraction at a chosen particle size corresponded to a unique particle-size distribution.

One method of checking this is to show that the fraction at any one particle size is related to the fraction at another particle size in a constant manner, as the overall size distribution changes. For the circuit under study, this is indicated in Fig. 9, in which the percentage of plus 75 μm material is plotted against the percentage of plus 150 μm material. These two fraction sizes are related over a wide range, which indicates that it is valid to use the fraction passing a chosen particle size to describe the entire particle-size distribution.

CONCLUSIONS

The study of the dynamic behaviour of a mill circuit has taken two forms to date. Firstly, computer simulation has indicated that both disturbances and noise can contribute significantly to the production of off-specification material. The study also showed that the behaviour could be predicted by a fairly simple model of the mill itself, and that it is essential to consider the behaviour of the circuit in the design of a control system because serious interaction between control circuits can occur. Intuitive designs for control systems may actually increase the amplitude of excursions in particle size.

Experiments on a full-scale plant under manual control have indicated that the magnitude and frequency of disturbances can be larger than is generally appreciated. However, an analysis of the reasons for these disturbances has shown that a combination of improved instrumentation and modified operating procedures may reduce the frequency of these disturbances to the point where the incentive to introduce complex control systems is slight. At the present stage, it appears that only one or two control loops may be necessary to ensure a consistent output from the circuit under study, and it is expected that one of these control loops will be based on the use of an on-line particle-size analyser because there is little reason to suppose that the particle size of the product can be inferred from any other measure such as density.

Studies of the plant downstream of the milling circuit have shown that a model can be developed for the prediction of plant efficiency. This model is sufficiently accurate and sufficiently sensitive to particle size to suggest that it will indeed be useful for determining the effect of improved consistency of operation in a portion of the mill circuit.

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