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The use of dynamic simulation in the development of control systems for backfill plants

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SYNOPSIS

Tailings from metallurgical plants, when deslimed with hydrocyclones, provide a valuable source of material for the backfilling of mines. The effectiveness of this material as a support medium is a sensitive function of its particle-size distribution and water content. It is therefore important that the hydrocyclone-classification plants used to prepare the backfill are operated efficiently, and that the effects of feed disturbances on the composition of the backfill are minimized.

This paper addresses the problem of the design, control, and optimization of classification plants to satisfy this need. The development of a computer program to simulate the dynamic behaviour of a hydrocyclone circuit of any given configuration is described. The use of the simulator to investigate the relative performance of conventional and innovative control strategies for single-stage and two-stage circuits is discussed in depth. The results of simulation studies are presented that indicate there is considerable scope for improving the performance and cost-effectiveness of backfill-classification plants.

SAMEVATTING

Wanneer dit met hidrosiklone ontslyk word, verskaf die uitskot van metallurgiese aanlegte 'n waardevolle bron van materiaal vir die terugvulling van myne. Die doeltreffendheid van hierdie materiaal as 'n stutmedium is 'n sensitiewe funksie van sy partikelgrootteverspreiding en waterinhoud. Dit is dus belangrik dat die hidrosikloon-klassifikasie-aanlegte wat gebruik word om die terugvulsel voor te berei, doeltreffend bedryf word en dat die uitwerking van toevoerversteurings op die samestelling van die terugvulsel tot die minimum beperk word.

Hierdie referaat is toegespits op die probleem van die ontwerp, beheer en optimering van klassifikasie-aanlegte om in hierdie behoefte te voorsien. Die ontwikkeling van 'n rekenaarsprogram om die dinamiese gedrag van 'n hidrosikloonkring van enige gegewe konfigurasie na te boots, word beskryf. Die gebruik van die simuleerder om die relatiewe werkverrigting van konvensionele en innoverende beheerstrategieë vir een- en tweetrapkringe te ondersoek word indringend bespreek. Die resultate van simulasiestudies word aangegee wat daarop dui dat daar heelwat geleentheid vir die verbetering van die werkverrigting en koste doeltreffendheid van terugvulselklassifikasie-aanlegte is.

INTRODUCTION

The use of hydrocyclone-classified tailings as backfill in South African gold mines has increased significantly in recent years[1]. However, in implementing backfilling systems, mines have encountered many technical problems, and costs have been unexpectedly high[2].

Some of the problems encountered can be attributed to the failure of the backfill to meet the desired composition specifications. For example, if the backfill has too much material finer than 10 μm, it will take an unacceptably long time to drain and stabilize.The backfills currently placed are usually specified to have not more than 10 per cent solids finer than 10 μm. High-quality fills that drain very rapidly require less than 4 per cent solids finer than 10 μm. The relative density of the backfill pulp is also an important variable. Ideally, the relative density should be not less than about 1,75. Densities lower than this can result in excessive loss of fines during placement and in mud-handling problems.

When backfilling is practised on a mine-wide scale, it is necessary to ensure not only that the composition is properly controlled but also that the amount of backfill produced is sufficient to fill the mined-out areas to their practical maximum. The maximum is about 80 per cent of the area stoped. This implies that between 45 and 50 per cent of the solids fed to the hydrocyclone plant must be recovered as backfill after the porosity of the placed material has been taken into consideration. Recoveries as high as this require the use of small-diameter hydrocyclones (diameters less than 250 mm) capable of yielding cut-sizes of less than about 30 μm.

The composition and recovery of the backfill are affected not only by the design and operation of the hydrocyclone plant, but also by variations in the flowrate and composition of the raw tailings to the plant. A common way of reducing the effects of feed disturbances is to make use of large stock tanks, which serve as buffers between the source of the raw tailings and the hydrocyclone plant. Alternatively, the effects of feed variations can be compensated for by the use of efficient control schemes.

At present, very rudimentary control systems are used to maintain the quality of backfill. These systems are usually aimed at stabilizing the flowrates and pulp densities of the hydrocyclone feed. Flowrates can be stabilized by control of the pulp level in the pump sumps feeding the hydrocyclones. Unless sump levels are kept within narrow limits, significant changes in the total dynamic head associated

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with the pumps will occur, resulting in undesirable surges in flowrate. Variations in level can be compensated for by manipulation of the flowrate of pulp from the feed stock tanks. The density of the material fed to the hydrocyclone can be controlled by variations in the flowrate of dilution water to the pump sumps. The backfill produced is usually delivered to large storage tanks at the mine shaft before being sent underground. The density of the backfill pulp in these tanks can be upgraded to the desired specification by decantation dewatering[2]. However, if the backfill delivered to the storage tanks does not meet the required particle-size specification, it must be discarded. How effective are these control schemes? Can the need for expensive stock or storage tanks be reduced or even avoided? What scope is there for the implementation of better control schemes? Very little work appears to have been done on these matters, and this paper attempts to address some of these questions.

Evaluation of Control Systems

The evaluation and development of control systems on industrial plants are extremely expensive and time-consuming processes. The expense implied by some control options may make their evaluation impossible. For example, is it worth while to install a particle-size measuring device on the final product line? One feasible way of measuring particle-size distributions on-line is by laser-diffraction techniques[3]. However, such analysers can be very expensive and poorly suited to plant environments. Another approach is to use ultrasonic particle-size analysers[4]. Unfortunately, although ultrasonic analysers have been used extensively for the monitoring of hydrocyclone-overflow products, their suitability for underflow products has yet to be demonstrated. It would be preferable if a control strategy could be developed that relied on inexpensive instrumentation with a proven history of dependability in a production environment.

A cost-effective method for the evaluation of competing control strategies is provided by dynamic simulation techniques[5]. These rely on the availability of suitable mathematical models of the various units used in the process under consideration. These are available for backfill plants, as discussed later. Once a reliable simulator for a plant has been developed, it is possible to perform 'experiments' on the simulated plant at negligible cost. One such experiment might be an investigation into the likely performance of a control system in which the particle-size distribution is 'measured' direct with an accurate particle-size analyser, albeit a hypothetical one. Additionally, there is no need for one to make gross simplifying assumptions, such as system linearity, when attempting a theoretical analysis of the control problem. The physical limitations of equipment can be included, such as the maximum head that can be supplied by a pump. Control systems of any complexity can be tested and compared.

The development of a dynamic simulator for backfill plants of various configurations is discussed in this paper. The characteristics of several conventional measurement and control schemes using Proportional-Integral-Derivative (PID) controllers are evaluated and compared with more innovative schemes.

Development of the Simulator

A survey of existing backfill-classification circuits indicated that a wide range of equipment and flowsheets is used in the industry. Circuits may be based on the use of one, two, or three stages of classification with and without the recycle of some of the outlet streams. In some cases, hydrocyclones are fed by a pump connected to a sump or small dilution tank while, in others, feeding is by gravitation from a steady-head tank. Stream splitters may also be present in the flowsheet. Examples of single-stage and two-stage classification flowsheets are shown in Figs. 1 to 3.

It was decided that, owing to the large variations in backfill-classification practice, a general classification dynamic simulator needed to be developed, rather than a simulator that allows only the simulation of several pre-defined flowsheets. In general, a flowsheet consists of the following equipment, connected in an appropriate way:

- Hydrocyclones
- Storage or dilution tanks connected to a pump
- Gravity-discharge tanks
- Stream splitters
- PID controllers
- Measuring devices (mass flowmeter, level detector, etc.).

These units can be categorized according to their dynamic behaviour. In the present work, it was assumed that only the tank–pump unit and the gravity-discharge tank unit have significant dynamic characteristics. Each of these units can be represented mathematically as a system of first-order differential equations that quantify the rate of change with time of the holdups of water and solids in individual size classes in the units. This rate of change can be equated to the difference in the input and output flowrates. All the other units were assumed to have such small residence times that they behave in a steady-state manner, with the outputs at any instant in time being dependent only on the inputs at the same time. Thus, the behaviour of the flowsheet can be simulated by the solving of an appropriate system of differential equations (for the dynamic units) and a system of non-linear algebraic equations (for the steady-state units).

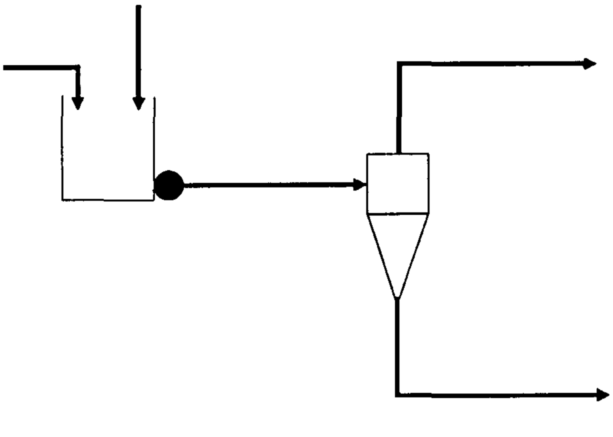

Fig. 1—The single-stage circuit

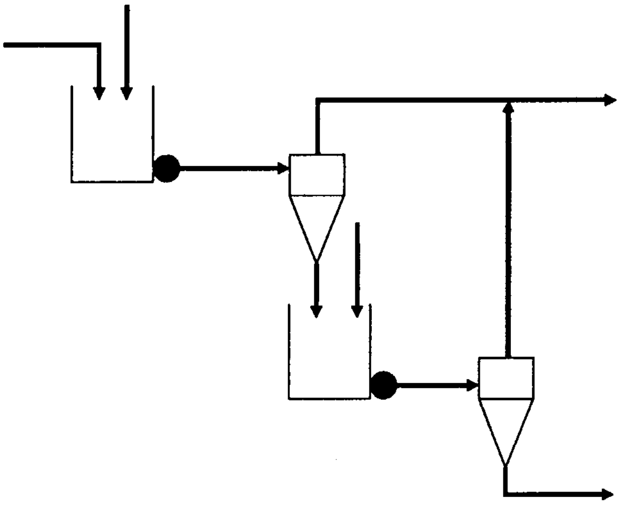

Fig. 2—The two-stage circuit without recycle

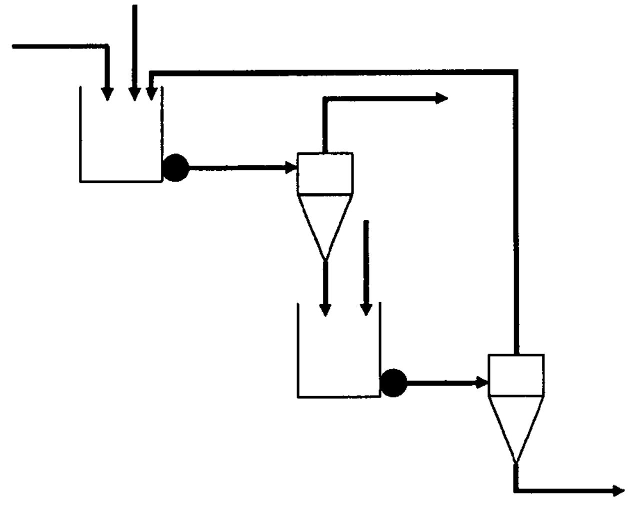

Fig. 3—The two-stage circuit with recycle

Because of the general nature of the problem, the simulator was designed by a modular approach. In this technique, a flowsheet is decomposed into a series of unit-operation calculations (modules) that are carried out in a particular sequence. The simulator calls each unit model in a particular sequence so that the system of derivatives defining the dynamic behaviour of the flowsheet can be evaluated. These equations are then integrated simultaneously to simulate the behaviour of the particular flowsheet. Various-order Runge–Kutta algorithms with variable-integration step length and global-error control were implemented[6].

This approach is more complex than the development of a simulator for a specific flowsheet (or for several specific flowsheets) since it must be able to analyse and simulate a general flowsheet. However, once the simulator structure has been designed and implemented, it is simple to add improved models, as well as models for different unit processes.

The hydrocyclone model used was the Plitt model[7], with modifications that allow accurate simulation of backfill systems involving tailings from Witwatersrand gold mines[8]. The dynamic models (storage and steady-head tanks) were derived by use of the standard approach involving differential mass balance and incorporating limiting behaviour (i.e. when a tank overflows or runs dry). The pump was modelled on the assumption that the relationship between pump head and flowrate can be represented as a quadratic equation. This equation was then incorporated in the energy balance performed across the tank, pump, and pipe in order to derive a tank–pump model. The PID model was based on the algorithm presented by MacLeod[9].

The simulator was coded in Turbo Pascal v5.5 for MS–DOS machines. The following are some of the pertinent details.

- Data input is accomplished by use of pop-up menu/windowing routines, making the simulator easy to use.
- The data are output to disk file, the printer, as well as to the graphics screen. The disk files are formatted so that they can readily be imported into a spreadsheet program such as Lotus 1–2–3 or Quattro. The amount and type of data to be output can easily be customized by the user. A comprehensive output system, including a process alarm system, is implemented.
- A steady-state simulation facility is included, which is very useful for the optimization of flowsheets, as well as for the sizing of pumps and steady head.
- The user can easily set up one or more single-input single-output (SISO) control loops using PID controllers. The inputs to the controllers can be almost any measurement (tank level, pressure drop, cutpoint, size distribution, flowrate, etc.), and the controller outputs can be any parameter that can be physically manipulated on the plant. There is also an option to use the Cohen–Coon method[10] for controller tuning.

Investigation of Control Systems

A number of different control systems were investigated. Three different circuit configurations were studied, these being single-state classification, and two-stage classification with and without recycle. These flowsheets are shown in Figs. 1 to 3. It was assumed in each case that the feed to the hydrocyclone was not buffered by a stock tank and that the principal source of disturbance to the hydrocyclone plant was a variation in feed rate. Feed properties (flowrate, solid-to-liquid ratio, and size distribution) were based on measurements made on typical feed to a backfill plant.

In all the studies, the quality of the backfill product, which depends on the cumulative percentage solids finer than 10 μm, was taken to be of primary importance. Thus, the object of the control system was to control the amount of material finer than 10 μm as closely as possible. It will be recalled that this amount should not exceed 10 per cent and, for high-quality backfills, should be less than 4 per cent. Other important variables such as the recovery and density of the backfill were also monitored.

Single-stage SISO

The first study involved the use of simple SISO control loops on a single-stage plant (Fig. 1). A number of control strategies were devised and tested, as summarized in Table I. Steady-state simulation indicated that the variables having the most influence on the fines content of the hydrocyclone-underflow product are the pulp density in the hydrocyclone feed and the pulp flowrate through the hydrocyclone. The pressure drop across the hydrocyclone is directly related to the volumetric flowrate through the hydrocyclone. Thus, if the hydrocyclone-pressure drop and the pulp density in the hydrocyclone feed can be controlled, good control of the fines content in the backfill product can be expected. The control schemes in Table I were devised with this aim.

The control of the sump level was always by the use of proportional control (no derivative or integral action), while full PID control was used for all the other control loops. Fig. 5 shows a typical dynamic response obtained for the single-stage system.

The strategies were evaluated through a study of the response of the controlled system due to step changes in the total flowrate to the system. The information studied consisted of the percentage minus 10 μm material in the product, the pressure of the hydrocyclone feed, the densities of the hydrocyclone feed and the product pulp, the flowrate of product material, and the sump level.

Table II summarizes the results obtained for each control strategy. The results are in the form of the steady-state values attained after the control system had reacted to the step change in the total flowrate (ore and water) to the system.

It can be seen from Table II that strategies A, B, and D are unacceptable since the fines content, as well as the pulp relative density of the backfill product, varies over a wide range. As discussed above, it is necessary to control both the hydrocyclone pressure and the pulp density of the hydrocyclone feed to maintain the fines content of the hydrocyclone product at the setpoint. Strategies A, B, and

TABLE I
CONFIGURATIONS FOR SINGLE-STAGE SISO CONTROL

Config.	Measured variable	Manipulated variable
A	Pulp density of cyclone feed Sump level	Dilution-water rate Pump speed
B	Pressure of cyclone feed Sump level	Dilution-water rate Pump speed
C	Minus 10 μm in product, % Sump level	Dilution-water rate Pump speed
D	Sump level Pressure of cyclone feed	Dilution-water rate Pump speed
E	Splitter 1 (Fig. 4) Splitter 2 (Fig. 4) Pulp density of cyclone feed Pressure of cyclone feed	Maximum sump level Minimum sump level Dilution-water rate Pump speed

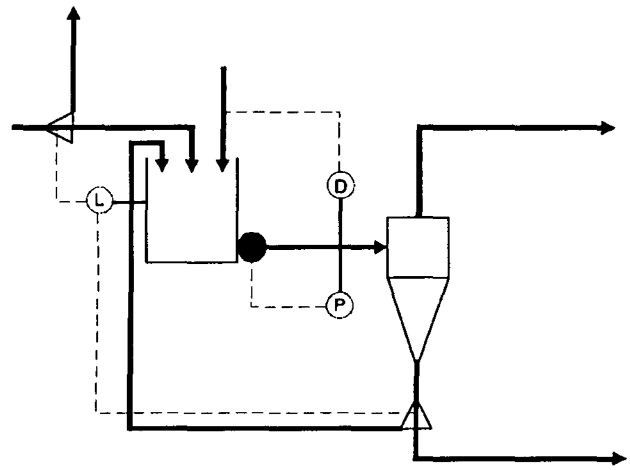

Fig. 4—Control strategy E

D can control only one of these variables at a specified setpoint.

Strategy C, for which it was assumed that an on-line particle-size monitor (PSM) is used to provide a direct measurement of backfill quality, works very well in terms of controlling the size distribution of the product. The relative density of the product varies significantly. However, this is of secondary importance since decantation techniques could be employed to adjust the relative density of the backfill before the material is transported underground.

Unfortunately, because the technology for real-time particle-size analysis of classified tailings is poorly developed, this strategy would be difficult to implement in practice. Ideally, one requires a control scheme that exhibits the behaviour exhibited by strategy C (i.e. good control of the fines content of the product) without the disadvantage of requiring unproven instrumentation. This matter is addressed in more detail later in the paper. Fig. 6

TABLE II
EFFICIENCY OF SINGLE-STAGE SISO CONTROL

Configuration	Step*	Recovery %	Relative density	Minus 10 μm %
	Before step	52	1,57	9,8
A	–	52	1,37	17,6
	+	53	1,71	7,0
B	–	59	1,37	5,0
	+	53	1,57	19,6
C	–	53	1,38	9,8
	+	52	1,66	9,8
D	–	59	1,37	5,0
	+	53	1,57	19,5
E	–	46	1,88	1,6
	+	31	1,57	9,8

*+ = Increase in total feed flowrate – = Reduction in total feed flowrate

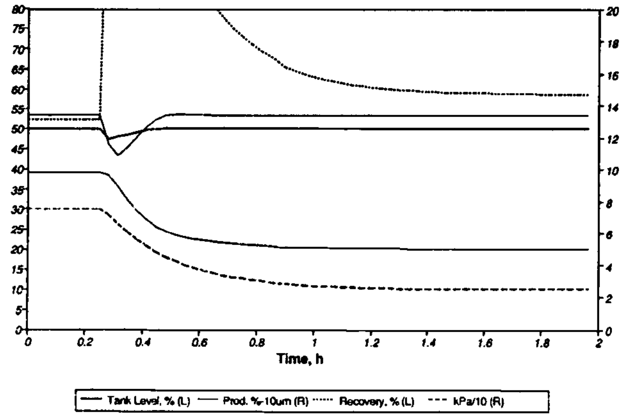

Fig. 5—Typical dynamic response obtained from strategy B (single stage): A decrease in feedrate at $t = 0,25$ h

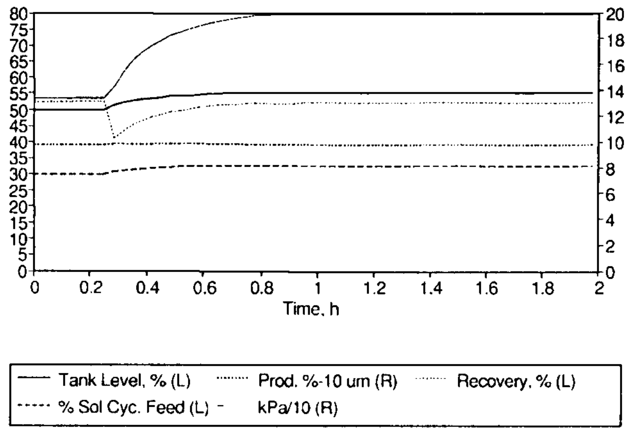

Fig. 6—Dynamic response obtained from strategy C (single stage): An increase in flowrate at $t = 0,25$ h

illustrates the dynamic response of several variables to the step change in feed flowrate when control strategy C is used.

Strategy E was devised in an attempt to meet the requirement of independent control of the hydrocyclone-feed pulp density and pressure drop. In order to do this, the sump-level control must not interfere with the hydrocyclone pressure and feed pulp density. A system of splitters can be used to control the level of the sump. For the case where the flowrate to the system is increasing, splitter 1 (Fig. 4) diverts an appropriate amount of the feed material to the tailings. When a decrease in the flowrate of the feed occurs, splitter 2 diverts some of the hydrocyclone underflow in order to ensure that the sump does not run dry. The pulp density and pressure of the hydrocyclone feed can then be controlled independently by manipulation of the pump speed and the addition rate of dilution water.

The behaviour of the system in response to a decrease in feed flowrate (Fig. 7) displays some interesting characteristics. As the sump level decreases, splitter 2 diverts the hydrocyclone underflow to the sump that controls the level. This results in the material in the sump becoming coarser, as well as denser. The addition rate of dilution water increases to maintain a constant pulp density, thus aiding in level control (the total flowrate of material into the sump increases). As the other two control loops ensure

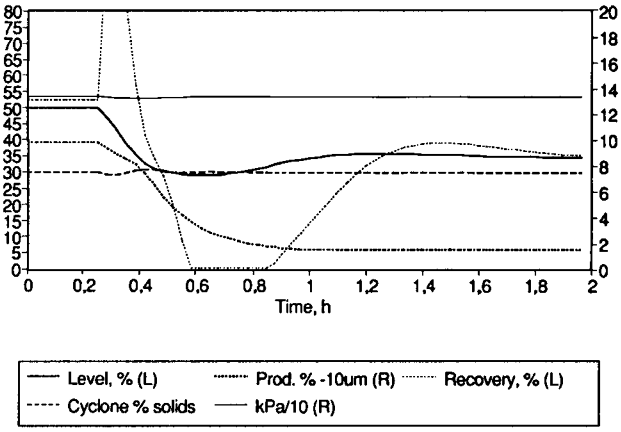

Fig. 7—Dynamic response obtained from strategy E (single stage): A decrease in flowrate at $t = 0,25$ h

that the pulp density and drop in hydrocyclone pressure are controlled at appropriate settings, the coarser hydrocyclone feed results in a large reduction in the amount of material finer than 10 μm, and hence a significant improvement in the quality of the backfill that is produced.

Because of the way in which the level is controlled for strategy E, an inherent disadvantage of this scheme is that the recovery of backfill material is decreased significantly. For the case where the flowrate to the circuit is increased, the extra material is simply diverted with no attempt being made at processing this material. When the feed flowrate decreases, the recycling of hydrocyclone underflow results in a decrease in circuit product. However, the particle-size distribution of the material that is produced compares favourably with size distributions that could otherwise be generated only by the use of two stages of classification.

Strategy E has the advantage that it will produce backfill with a low fines content (or significantly better-quality material) under a wide range of flowrates. The strategy does not require expensive or complex instrumentation. Because of the problem of poor recoveries and the need to discard feed material, it would be an acceptable control strategy for use on a plant where only a portion of the total tailings is used for the production of backfill.

It should be noted that a variation of strategy E could be readily applied to the case where the circuit feed is derived from a large stock tank. In that case, the sump level would be controlled by the flowrate of pulp from the stock tank, with a fixed proportion of the hydrocyclone underflow being recycled to the sump. The amount of recycle selected and of sump dilution water would depend on the size distribution required in the product.

Two-stage SISO with and without Recycle

The two-stage flowsheets investigated are illustrated in Figs. 2 and 3. The basic SISO loops were the same as in the single-stage case. Strategies C and E were not tested since the single-stage study had shown that, although these strategies work well, they have some disadvantages. The same benefits and disadvantages would be expected for multi-stage classification circuits. The strategies tested were implemented with appropriate combinations of the SISO strategies described in Table I. For example, A–D indicates that the primary hydrocyclone was controlled

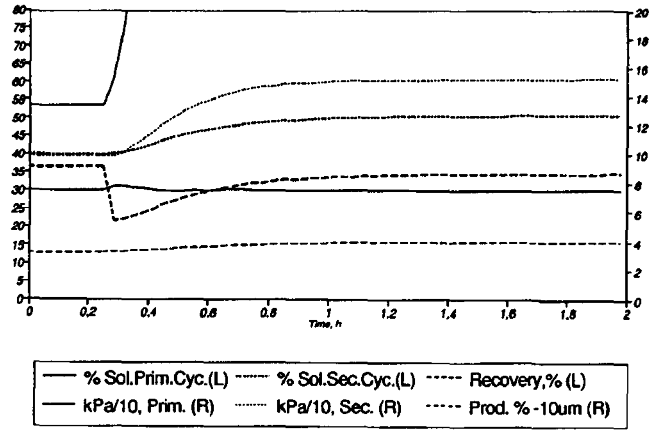

Fig. 8—Dynamic response obtained from the two-stage system without recycle: Primary cyclone = strategy A, secondary cyclone = level

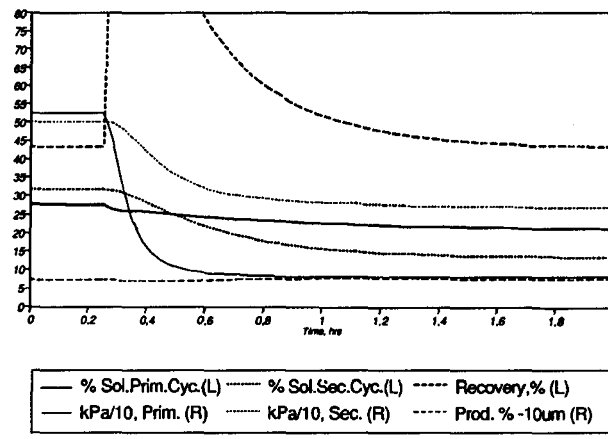

Fig. 9—Dynamic response obtained from the two-stage system with recycle: Primary cyclone = strategy A, secondary cyclone = level

according to strategy A, while the secondary hydrocyclone was controlled according to strategy D. It should be noted that L indicates that only proportional control of the tank level was implemented. The results of the investigation, with and without recycle, are summarized in Tables III and IV. As expected, the performance of the single- and two-stage circuits was significantly different.

The motivation for the use of different control strategies on the primary and secondary classification stages was that the SISO strategies would interact favourably to make the overall control of the circuit more efficient. This occurs to a significant extent only for control strategies A–L and A–D, where the variation of the backfill quality is fairly small. In other cases, the interactions between the systems are detrimental, leading to large variations in backfill quality (D–L, B–B, and D–D).

The results indicate that suitable control of the backfill product for two-stage circuits can be achieved by use of strategy A–L. This is a simple, robust strategy, based on standard level and pulp-density control. The variations in the quality of the backfill when this strategy is used should be sufficiently small to be acceptable for most applications. Fig. 8 illustrates the dynamic response of the two-stage system with no recycle when subjected to a step change in which the flowrate of the total feed is increased. Fig. 9 illustrates the dynamic response of the two-stage recycle system when subjected to a step change in which the total feed flowrate is decreased.

Model-based Control

The results illustrate that good control of backfill quality can be achieved for single-stage circuits by use of an expensive PSM-based strategy (C). For two-stage circuits, a relatively simple strategy (A–L) results in acceptable product control. If a robust, effective control system could be devised for the single-stage circuit, which does not require the use of stock tanks and a real-time particle-size analyser, a large saving in operating and capital costs could result.

From a study of the dynamic response of the single-stage circuit using control strategy C, as shown in Fig. 6, it can be seen that the effect of the direct control of fines content in the product is to change the drop in hydrocyclone pressure and the pulp density of the hydrocyclone feed in such a way that the fines in the underflow remains constant. This prompts the following question: Can a simple mathematical relationship or profile between hydro-cyclone pressure and feed pulp density be developed for a given backfill size distribution? The existence of such a profile could then be exploited in the implementation of a model-based control strategy.

The simulator was used to investigate this by finding the hydrocyclone-feed pulp density required at a number of different hydrocyclone-pressure drops that results in a constant fines content in the hydrocyclone product. The data were generated by a number of simulations, carried out according to control strategy C for various feed flowrates. It was found that the relationship between feed pulp density and pressure drop (at a constant fines content of the product) is also affected by the size distribution of the feed. As expected for a finer size distribution in the feed at the same feed pulp density, a larger pressure is required to maintain the fines content in the product at the setpoint. The data are plotted in Fig. 10, which shows the required profile between the hydrocyclone-pressure drop and the hydrocyclone-feed density to maintain a constant fines content in the product for three different feed-size distributions (normal, fine, and coarse). Also plotted in Fig. 10 is the relationship between the solids in the hydrocyclone overflow and the hydrocyclone-pressure drop (or feed pulp density) for each feed size distribution along these profiles.

One-variable Model

The data illustrated in Fig. 10 suggest the following model-based control strategy.

- Develop a correlation between the density of the hydrocyclone feed and the pressure drop required for constant fines in the product. This was done by use of the data from the 'Fine' curve shown in Fig. 10. This is the model describing the required hydrocyclone pressure for different feed pulp densities if the product quality is to be kept constant.
- The control scheme illustrated in Fig. 11 can then be used. In this scheme, the tank level is controlled by

TABLE III
EFFICIENCY OF SISO CONTROL FOR TWO-STAGE FLOWSHEET WITH NO-RECYCLE

Configuration	Step	Recovery %	Relative density	Minus 10 μm %
	Before step	37	1,72	3,3
A–L	–	38	1,56	3,5
	+	35	1,69	4,0
A–A	–	33	1,47	10,7
	+	37	1,90	1,6
B–L	–	47	1,63	1,0
	+	34	1,72	8,3
B–B	–	50	1,67	0,6
	+	56	1,65	15,6
D–L	–	46	1,63	1,0
	+	34	1,72	8,2
D–D	–	50	1,67	0,6
	+	33	1,65	15,5
A–D	–	39	1,55	2,3
	+	37	1,67	5,9

TABLE IV
EFFICIENCY OF SISO CONTROL FOR TWO-STAGE FLOWSHEET WITH RECYCLE

Configuration	Step	Recovery %	Relative density	Minus 10 μm %
	Before step	43	1,80	1,8
A–L	–	44	1,57	1,9
	+	47	1,79	2,3
A–A	–	39	1,46	7,6
	+	45	2,03	0,8
B–L	–	53	1,58	0,7
	+	39	1,79	4,7
B–B	–	53	1,57	0,6
	+	40	1,64	12,6
D–L	–	53	1,58	0,6
	+	40	1,78	12,1
D–D	–	53	1,57	0,6
	+	40	1,64	12,4
A–D	–	47	1,52	1,1
	+	49	1,65	3,4

manipulation of the rate of dilution water entering the pump sump, and the hydrocyclone-pressure drop is controlled by use of the pump speed as described for strategy D. The model is used to estimate what pressure is required, based on the correlation developed from Fig. 10 and the measured hydrocyclone-feed density. This prediction is then used to continually update the pressure setpoint for the controller regulating the pump speed.

- The correlation is based on the data for the 'Fine' feed distribution, since this will result in a backfill product of better quality (possibly at the expense of recovery) for any feed material that is coarser than this distribution.

Two-variable Model

As shown in Fig. 10, a change in the size distribution of the feed causes a shift in the correlation between hydrocyclone pressure and feed density. This can be compensated for, as described above, by use of the most conservative correlation, i.e. that for the 'Fine' feed size distribution. However, from Fig. 10 it can be seen that a change in the particle-size distribution of the feed is also reflected as a change in the mass percentage solids in the hydrocyclone overflow. This suggests a more sophisticated approach to the model of pressure versus feed density.

A correlation between the drop in hydrocyclone pressure required (for a constant fines content in the product) and the mass percentage solids in both the hydrocyclone feed and the overflow was developed from the data illustrated in Fig. 10. It was found that the data are well-correlated by a function of the form

$$P_{-10 \mu m} = a_0 + a_1 \ln\left(\frac{X}{Y}\right),$$

where

- a_0 and a_1 are constants estimated from the data,
- $P_{-10\,\mu m}$ is the pressure required to keep the fines in the hydrocyclone product at the setpoint,
- X is the percentage solids in the hydrocyclone feed,
- Y is the percentage solids in the hydrocyclone overflow.

Practical methods of measuring overflow densities that avoid the problems of air entrainment have been described by Hinde[11] and by Gupta and Eren[12].

The same strategy as used for the one-variable model is then employed, as illustrated in Fig. 11, the only exception being that an additional measurement (the percentage solids in the overflow) is required for the correlation used to update the pressure setpoint for the SISO controller regulating the pump speed.

It should be pointed out that, if additional instrumentation is available to establish a complete solids mass balance across the hydrocyclone, a more accurate estimate of the feed size distribution could be obtained, as suggested by Plitt and Kawatra[13]. However, in view of the level of precision that was potentially achievable with the one- and two-variable models described above, it is doubtful whether much would be gained by the making of additional measurements.

Evaluation of Model-based Control

The model-based control strategies were tested for step changes in the flowrate of total feed, as well as for step changes in the pulp density of the feed stream for different size distributions. Very good control was achieved under all conditions for both the one- and the two-variable models. Typical dynamic responses for model-based control are shown in Figs. 12 and 13 for the two models.

A summary of the performance of the model-based control system for different size distributions in the feed in response to step changes in the flowrate of total feed is shown in Table V.

Table V shows that very good control is achieved with this approach. The control is very much better than all the SISO single-stage strategies (except for C, in which the size distribution of the product must be measured on-line), as well as for most of the two-stage control strategies.

It is pertinent to note that the addition of a separate measurement that gives some indication of the size distribution in the feed (i.e. the two-variable model) results in very tight control of the fines content in the product. The one-variable model simply controls the fines content in a narrow band and, under advantageous conditions (coarse feed), a better product results. However, during the simulation it was noted that the two-variable model introduces an integral action in the control system, keeping the fines content in the product very close to a constant value. This can be seen from an examination of Figs. 12 and 13. It is believed that this is due to the introduction of an extra variable in the correlation, allowing a better prediction of the required hydrocyclone pressure for different pulp densities, as well as for different size distributions in the feed.

The model-based strategies are better than the other strategies studied since they allow consistent backfill to be produced from a single-stage plant. In addition, the strategies can be implemented by use of standard proven instrumentation. They would be particularly appropriate when high recovery is required (i.e. strategy E cannot be used).

TABLE V

EFFICIENCY OF THE MODEL-BASED SYSTEMS

Configuration	Step	Size of feed distribution	Recovery %	Relative density	Minus 10 μm %
	Before step		52	1,57	9,8
1–variable	–	Normal	53	1,47	8,7
	+		52	1,65	11,3
1–variable	–	Fine	50	1,34	10,1
	+		49	1,62	13,2
1–variable	–	Coarse	56	1,49	7,6
	+		55	1,68	9,7
2–variable	–	Normal	53	1,46	9,9
	+		52	1,63	10,2
2–variable	–	Fine	50	1,45	9,7
	+		50	1,62	10,6
2–variable	–	Coarse	55	1,47	10,1
	+		55	1,64	10,1

Conclusions

The dynamic simulator developed, which (by the use of PID controllers) can simulate both the open-loop and the closed-loop behaviour of a general classification circuit, has proved to be a most useful tool for the development and evaluation of process-control strategies. The simulator uses efficient numerical techniques, has a user-friendly interface, and runs on an MS–DOS personal computer. The simulator can be used both for the design of new plants and for the optimization of existing facilities. It allows the design and control of a classification circuit to be undertaken on an individual basis, and takes into account the idiosyncrasies of a particular plant, rather than relying on broad, general principles that may not be totally

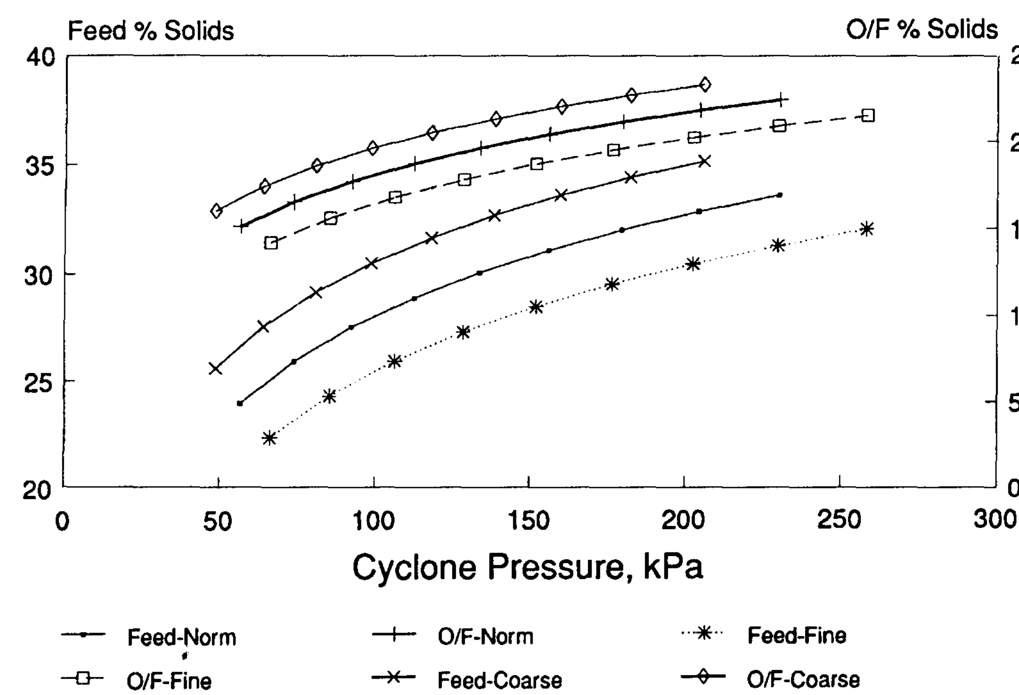

Fig. 10—Solids content versus hydrocyclone pressure

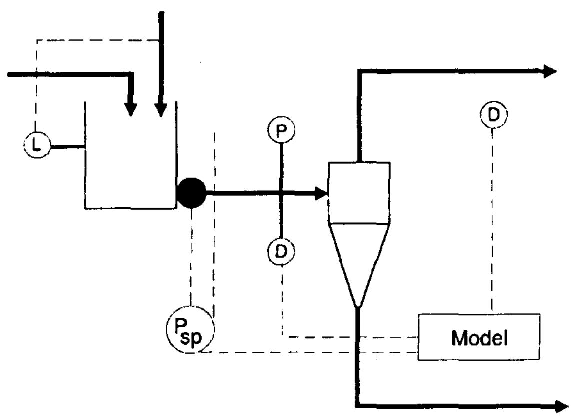

Fig. 11—The single-variable model

appropriate for a specific problem.

When the simulator was used in a study of various control strategies for single-stage and two-stage (with and without recycle) backfill-classification circuits, it was found that most simple SISO PID control strategies are not at all effective for single-stage circuits, where the principal source of disturbance is a variation in feed flowrate, except when a direct measurement of the fines content of the product stream is available. This is a difficult and expensive measurement to make.

A control scheme in which pulp is recycled from the hydrocyclone underflow in order to control the level of the feed sump while independently controlling the pulp density of the hydrocyclone feed and the pressure drop was also investigated. Good control of the fines content in the product was achieved but, owing to the nature of the method used to control the sump level, the recovery was poor. The advantages of the method are that it can be implemented by the use of only PID controllers and standard instrumentation. It is thus ideal for applications in which the recovery of backfill is not a critical issue. However, it is not inconceivable that the problem of reduced recovery could be overcome throuth optimization of the hydrocyclone geometry and operating conditions.

This lastnamed control scheme also highlighted the interesting effects of the recycling of hydrocyclone underflow. This results in a coarser hydrocyclone feed, and therefore a much better backfill product. The use of this strategy in the classification of backfill has not been studied in depth, and it is believed that this may be a fruitful area for further research.

For two-stage circuits, certain combinations of simple PID and SISO strategies result in satisfactory control of the backfill product. These strategies can easily be implemented by the use of standard equipment. Two-stage circuits were found to be capable of consistently producing high-quality backfills with a solids content of less than 4 per cent finer than 10 µm.

In the model-based strategy for a single-stage hydrocyclone circuit that was developed, the hydrocyclone pressure required to produce a constant product was correlated with the mass percentage solids in the hydrocyclone feed and overflow. The model is used as part of a PID-based control system, with the model continually updating the pressure setpoint for the controller regulating the pump speed. This is a most effective strategy, resulting in excellent control of the backfill product over a wide range of feed flowrates and size distributions, use being made of only one stage of classification. The results of the simulation indicate that the need for large and expensive stock tanks could be reduced or even obviated. In addition, the control strategy can be implemented by the use of standard equipment. This strategy can be used for the control of a hydrocyclone in any circuit, and it is believed that the application of this technique to an integrated system involving closed-circuit grinding, froth flotation, and backfill preparation may be most beneficial. Further research should be carried out in order to investigate this. Dynamic simulation would be a very efficient way of doing this.

ACKNOWLEDGEMENT

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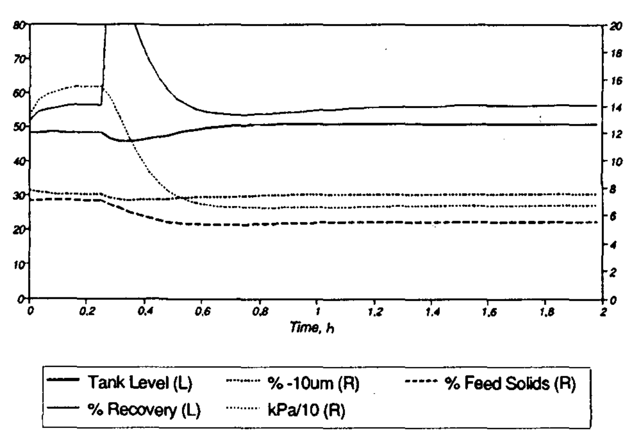

Fig. 12—Typical dynamic responses obtained from the single-variable model: A decrease in feed at t = 0,25 h, coarse distribution

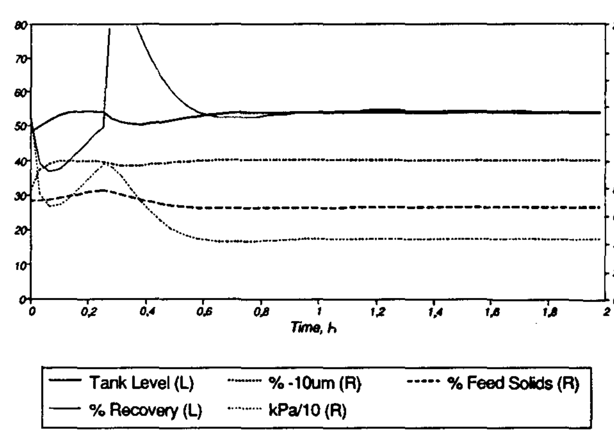

Fig. 13—Typical dynamic responses obtained from the two-variable model: A decrease in feed at t = 0,25 h, coarse distribution

REFERENCES

1. HINDE, A.L., and KRAMERS, C.P. The role of hydrocyclone technology in backfilling operations. *Innovations in mining backfill technology.* Proceedings of the 4th International Symposium on Mining with Backfill, Montreal, 1989. pp. 287–294.
2. HINDE, A.L., KRAMERS, C.P., KRUGER, F.J.A., LAMOS, A.W., and NAMI, M. The development of backfill technology for deep South African gold mines: Past, present and future. *Technical challenges in deep-level mining.* Proceedings of the International Deep Mining Conference, Johannesburg, South African Institute of Mining and Metallurgy, 1990. pp. 483–495.
3. JAGER, J., KRAMER, J.M., and DE JONG, E.J. On-line particle size measurement in dense slurries. *Powder Technol.*, vol. 62. 1990. pp. 155–162.
4. DE BEERS INDUSTRIAL DIAMONDS. Technology development—innovation in South African equipment: Particle-size monitor. *J. S. Afr. Inst. Min. Metall.*, vol. 90. no. 10. 1990. pp. 273–274.
5. DUBÉ, Y., LANTHIER, R., and HODOUIN, D. Computer-aided dynamic analysis and control design for grinding circuits. *CIM Bull.*, vol. 80, no. 905. 1987. pp. 65–70.
6. FEHLBERG, E. Klassiche Runge-Kutta-formeln vierter und niederigere ordnung mit schrittweiten-controlle und ihre anwendung auf warmeleitungsprobleme. *J. Computing*, vol. 6. 1970. pp. 61–71.
7. PLITT, L.R. A mathematical model of the hydrocyclone classifier. *CIM Bull.*, vol. 69, no. 776. 1976. pp. 114–123.
8. CILLIERS, J.J., and HINDE, A.L. An improved hydrocyclone model for backfill preparation. International Conference: Minerals Engineering '91, Singapore, 1991.
9. MACLEOD, I.M. Implementation of the three-term control algorithm in small computers. Symposium on Control Theory, CSIR, Pretoria, Jun. 1982.
10. STEPHANOPOULOS, G. *Chemical process control: An introduction to theory and practice.* Prentice-Hall, 1984.
11. HINDE, A.L. Classification and concentration of heavy minerals in grinding circuits. 114th AIME Annual Meeting, New York City, 1985.
12. GUPTA, A., and EREN, H. Mathematical modelling and on-line control of hydrocyclones. *Proc. Australas. Inst. Min. Metall.*, no. 1. 1990. pp. 31–41.
13. PLITT, L.R., and KAWATRA. Estimating the cut (d_{50}) size of classifiers without product particle-size measurement. *Int. J. Miner. Process.*, vol. 5. 1979. pp. 369–378.

Computerized production control

The Korean Institute of Metals and the The Institute of Metals, UK, are jointly planning an International Conference on Computerized Production Control in Steel Plant to be held in Seoul, Korea, 1st to 5th November, 1993. The event will have the support of societies in a number of other countries.

The purpose of this Conference is to contribute to the advancement of production-control systems in the steel industry and the direction of their computerization.

The scope of the Conference includes all areas within production planning and control systems, ranging from order receiving to shipping. However, computerized process control in individual plants is excluded.

The topics will cover the following areas:

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   - b. Production planning (yearly, quarterly)
   - c. Production information system
2. **Order entry system**
   - a. Order inquiry service
   - b. Order specification and coding system
   - c. Establishment of lead times
     1. Mill distribution
     2. Load control
3. **Production scheduling and control system**
   - a. Production scheduling (monthly, weekly, daily)
   - b. Shop-floor control (especially for materials)
4. **Quality Control**
   - a. Quality design
   - b. Quality tracking system
   - c. Inspection and quality assurance
5. **Storage, shipment, and customer delivery**
   - a. Warehouse management (including inventory management)
   - b. Physical distribution (including transportation and network)
   - c. VAN (Value Added Network) system for customers
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9. **Procurement system**

Those who are interested in presenting a paper in the above-mentioned areas are requested to submit an abstract of no more than 500 words in English by the end of September, 1992. The papers to be presented and discussed in this Conference can also be classified into the areas of Applied Optimization, Computer and Information Sciences, Engineering Statistics and Applied Probability, Engineering Economics, Facilities Design/Material Handling, and Simulation.

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