

SIMULATION OF

MULTIPLE

CLOSED LOOP

MILLING CIRCUITS

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SIMULATION OF MULTIPLE CLOSED LOOP MILLING CIRCUITS

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I hereby declare that this dissertation is my own work,
and has not been submitted to any other University for
a Degree.

ABSTRACT

The main subject of this dissertation is an investigation into the building of computer simulators which will portray the dynamics of milling circuits. The development of simulators for both the Blyvooruitzicht Gold Mine milling circuit and the Buffelsfontein Gold Mine milling circuit is described. The Blyvooruitzicht circuit can be considered as a "small" circuit, while the Buffelsfontein circuit can be considered as a "large" circuit. In addition to the main subject a secondary subject is dealt with: namely, an investigation into the feasibility of improved control on the Buffelsfontein circuit.

Chapter 1 outlines the role which computer simulators can play in the analysis of milling circuits. The objectives for improved milling circuit control are stated and the concept of pebble mill power control is described. Attention is given to the underlying principles on which the simulation models are based and the methods with which the simulators are validated.

Chapter 2 contains a description of the closed loop milling process and an introduction to the fact that a single size parameter has been chosen to describe the dynamic behaviour of the circuit over its normal operating range. This lack of definition does not detract from the practical utility of the simulator output. A detailed description of the Blyvooruitzicht simulator is given and the results of dynamic simulations, using both linear and non-linear versions of the Blyvooruitzicht simulator, are

presented.

Chapter 3 describes how the models for the Buffelsfontein circuit were determined. A comparison of the steady state values of the actual and the simulated Buffelsfontein circuit is given and the results of dynamic simulations of the Buffelsfontein circuit are presented.

In Chapter 4 attention is given to aspects of the modelling relating to the trade off between complexity and definition in the simulators. Reasons are advanced for the use of single size parameter modelling and for the use of constant water underflow from the hydrocyclones. A model is developed on the Blyvooruitzicht simulator which realistically describes the power characteristics of a pebble mill whose power signal is corrupted by noise and the use of this model on the Buffelsfontein circuit is described.

Chapter 5 deals with the validity of the simulators. The validity of the Blyvooruitzicht simulator is tested by means of comparing the simulated dynamic responses of the circuit with the actual dynamic responses of the circuit. The level of accuracy intended in the Buffelsfontein simulator and the factors influencing this accuracy are stated. The overall validity of the Buffelsfontein simulator is ascertained by comparing the simulated dynamic responses of the Buffelsfontein circuit with the actual responses of milling circuits cited in the literature. Future work aimed at improving the detailed accuracy of the Buffelsfontein simulator is outlined.

Chapter 6 investigates the feasibility of improved control of the Buffelsfontein circuit. The ability of a controller to maintain the steady state product size of the Buffelsfontein circuit under dynamic conditions is presented. Set point control to a value of product size finer than the steady state value is shown to be possible, while the feasibility of a controller to reduce product size variations caused by random disturbances is established. Two pebble mill control strategies are compared with each other with the aim of determining which strategy causes the pebble mills to run more efficiently.

Appendix 1 and Appendix 5 contain computer listings and a list of figures respectively, while the other appendices amplify certain aspects of the main text.

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CHAPTER 1INTRODUCTION

In recent years interest has been aroused in the ability of computer simulation to contribute towards the better understanding of milling circuits, and the use of this technique is steadily becoming an important tool in the design of milling circuit controllers.

The main objective of computer simulators is to enable control strategies - the intention of which is to improve the efficiency of the milling process - to be tested out and to be improved upon on a simulator of a milling plant rather than on the plant itself.

The rationale for this is the fact that it would be prohibitively expensive both in terms of capital expenditure and lost production to "optimise" a control strategy directly on a plant itself, whereas with a simulator of the plant, a vast number of control strategies can be analysed to find an "optimum" for the plant.

Computer simulation is especially attractive in the analysis of milling circuits under the following circumstances:

- (a) When the mathematical modelling of a milling circuit results in a set of non-linear differential equations, which, in general, do not lend themselves to be dealt with analytically. In order to deal with them analytically, one must linearise about some operating point and derive a set of linear differential equations which are

valid for small perturbations about that operating point only. If one is prepared, however, to simulate one can take the non-linear equations and use them to build a simulator which is valid over the entire operating range.

- (b) When the mathematical modelling of the milling circuit results in a large-scale system, the analytic handling of the system becomes extremely cumbersome and time consuming.

The control objective for a milling circuit is not uniquely defined and can be classified broadly under one of the following three categories:

- (1) The design of a control strategy which will ensure that a fixed feed of solids is ground to a specified size.
- (2) The design of a control strategy which will ensure that a maximum feed of solids will be ground to a specified size.
- (3) The design of a control strategy which will ensure that a fixed feed of solids is ground as fine as possible.

Implicit in the above three objectives is the fact that the pebble mills are grinding at full potential. In order to effect this, pebbles are added to the pebble mill with the aim of keeping the pebble mill at the half full level where maximum power is drawn by the pebble mill, and, consequently, maximum grinding occurs⁽¹⁾.

One way in which the addition of pebbles to the pebble mill has been controlled is through the use of a "Digicon"

controller which monitors mill power and adds pebbles to the pebble mill in an attempt to keep the mill power as close to its peak as possible.

In this dissertation, a mill power model has been developed on the Blyvooruitzicht Gold Mine simulator ("Digicon" control has been incorporated). This model has been adapted to form part of the larger Buffelsfontein Gold Mine simulator, which also incorporates "Digicon" control.

In order to build the Blyvooruitzicht and Buffelsfontein simulators which are dealt with in this dissertation, it has been necessary to model each element in the milling loop - such as the mills, the hydrocyclone and the pump - and then link all these models into one overall model which describes the operation of the entire circuit. The main principle behind the modelling of each element in the milling circuit is the setting up of mass balances for the material passing through each element.

The simulators which have been built are dynamic simulators in the sense that they reflect, with time, how a milling circuit responds dynamically to a given set of inputs. This is in contrast to a steady state simulator of which the outputs will only reflect the final or steady state of a milling circuit to a given set of inputs. Clearly, for the design of milling circuit controllers one needs dynamic simulators because of their ability to mimic continuously the state of the plant.

Results of dynamic tests on the Blyvooruitzicht plant were available for testing the validity of the

controller which monitors mill power and adds pebbles to the pebble mill in an attempt to keep the mill power as close to its peak as possible.

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Results of dynamic tests on the Blyvooruitzicht plant were available for testing the validity of the

Blyvooruitzicht simulator, while important steady state values of the Buffelsfontein plant were available for testing the validity of the Buffelsfontein simulator under steady state conditions. Data for testing the Buffelsfontein simulator under dynamic conditions were not available. However, the general forms of the dynamic responses of the simulator were compared with the general forms of dynamic responses of milling circuits cited in the literature, in order to determine the macroscopic validity of the simulator under dynamic conditions.

In the chapters that follow, the following questions concerning closed loop milling circuits have been looked at:

- (1) Can dynamic simulators be built for "small" milling circuits?
- (2) Can dynamic simulators be built for "large" milling circuits?
- (3) What level of definition is required in the simulators?
- (4) Once the simulators have been built, how valid are they?
- (5) Once one has built up confidence in the simulators, can they be used for the study of the dynamics of milling circuits and the assessment of control strategies?

All the simulations were written in C.S.M.P. (Continuous System Modelling Program)⁽²⁾ and were run on the University of the Witwatersrand's I.B.M. 370/158 computer. The integration routine employed to solve the differential equations was a fourth order variable step Runge-Kutta.

CHAPTER 2

THE BUILDING OF A SIMULATOR FOR A "SMALL" MILLING CIRCUIT

2.1 General

Work done⁽³⁾ at the Chamber of Mines of South Africa has resulted in the modelling of the milling circuit of the Blyvooruitzicht Gold Mining Co. Limited shown in Fig. 1. This circuit can be regarded as a "small" milling circuit.

The structure of the model, which has been well documented^(3, 4), is given in section 2.2. A very important feature of this model is that a single size parameter has been chosen to model the dynamic behaviour of the circuit over its normal operating range. To be specific, particle size distributions were measured as a fraction of solids less than $75\mu\text{m}$.

This is in line with South African gold milling practice where a fraction less than $75\mu\text{m}$ is taken as the indicator of fineness of grind, with experiments at the Blyvooruitzicht and other mines being based on an Automatic Particle Size Monitor (P.S.M.) set at the $75\mu\text{m}$ size.

Clearly, to completely specify particle size distribution one would require a large number of size parameters resulting in very complex models which, in turn, would cause correspondingly complex simulators and controllers designed on the basis of these simulators. Bearing this in mind it is desirable to use an indicator of fineness of grind which is as simple as possible,

SCHMATIC DIAGRAM OF THE BLYGORUITZICHT GOLD MINING CO. LIMITED'S MILLING CIRCUIT

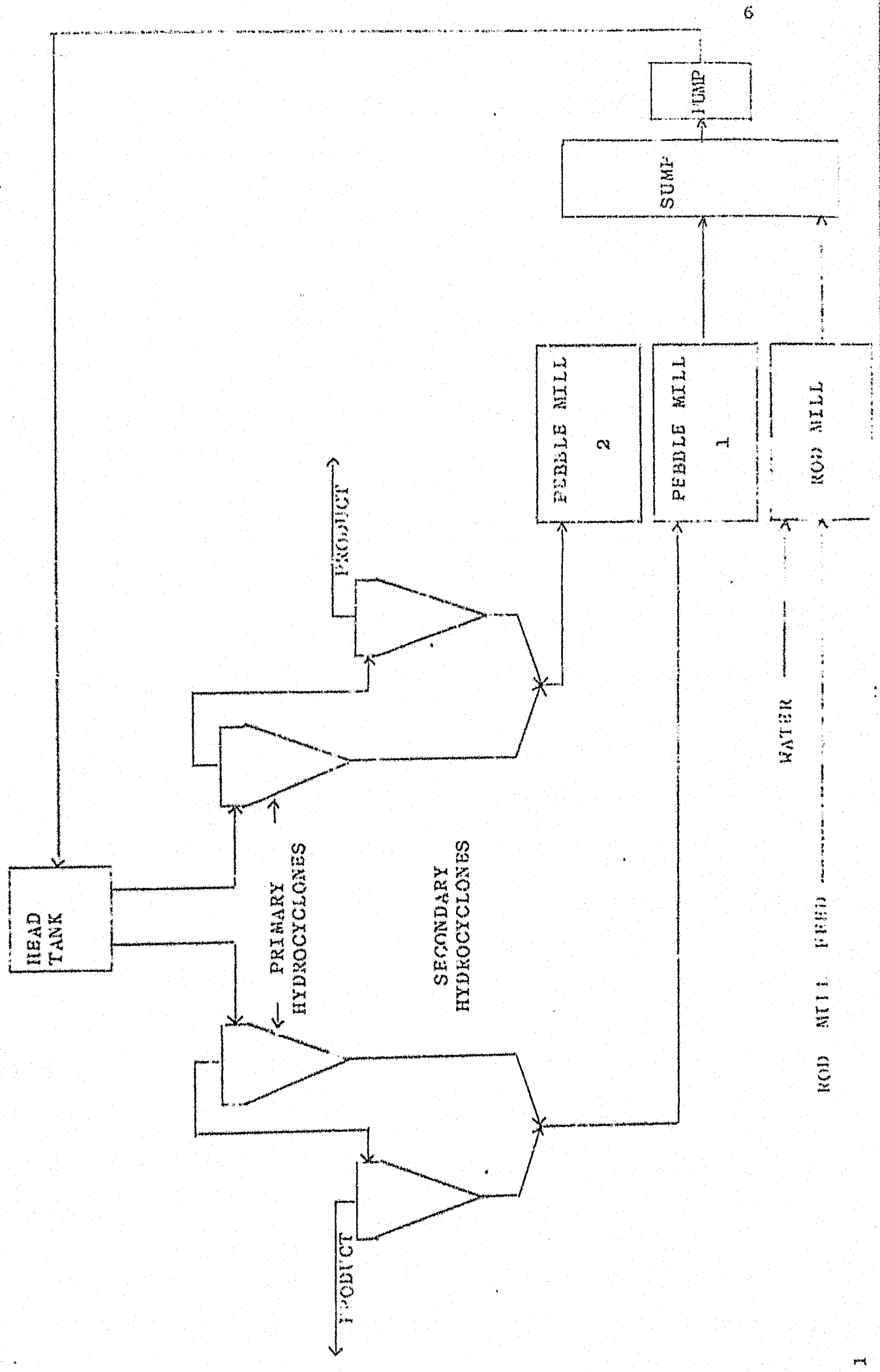


FIG. 1

while, at the same time, yielding enough information to portray size distribution satisfactorily. It is shown in section 4.2 that single size parameter modelling can be used satisfactorily for building milling simulators.

In order to obtain an appreciation of the workings of a closed loop milling circuit, consider Fig. 1. Initially the ore enters the circuit by passing through a rod mill where the ore is ground by means of the tumbling action of rods in the mill. The mixture of water and fines (ore), known as pulp, now passes from the rod mill into the sump. The pulp is then pumped from the sump up to a head tank. At this stage the pulp is distributed to the hydrocyclones under the influence of gravity. The action of the hydrocyclones is to separate the fine material from the coarse material. The fine material goes to the overflow of the hydrocyclone and is known as the product of the circuit, while the coarse material goes via the hydrocyclones' underflow into one of the pebble mills for further grinding. After this grinding has taken place, the pulp flows into the sump and the entire process is repeated.

Bearing the above in mind, one can appreciate that any simulator, attempting to portray the workings of such a milling circuit, must be able to reflect the flow rates of material through each element in a milling circuit. In addition to this, the simulator must portray the densities and size distributions in all parts of the circuit.

In section 2.2, the components of a dynamic simulator for the Blyvooruitzicht plant are discussed. This simulator is dynamic in that it is able to give continuous

information about the state of the plant for all operating conditions.

2.2 Model Structures

2.2.1 Pebble Mill Model Structure

It was postulated that the volume flow of pulp from the mill would be represented by an equation of the form:

$$P_1 = K_1 (X_1 + X_2/w)^n$$

where:

P_1 = pulp flow from the mill (m^3 /hour)

X_1 = mass of water in the mill (tons)

X_2 = mass of solids in the mill (tons)
(excluding the grinding media of pebbles)

w = specific gravity of the solids

K_1 = constant

From this equation it is clear that the volume flow of water from the mill will be:

$$\frac{X_1 K_1}{X_1 + X_2/w} (X_1 + X_2/w)^n = K_1 X_1 (X_1 + X_2/w)^{n-1}$$

(The mass flow of water will also be given by this expression since the specific gravity of water is unity).

Similarly, the volume flow of solids from the mill will be:

$$\frac{(X_2/w) K_1}{X_1 + X_2/w} (X_1 + X_2/w)^n = \frac{K_1 X_2}{w} (X_1 + X_2/w)^{n-1}$$

or, since the specific gravity of the solids is w , the mass flow of solids out of the mill is given by the following expression:

$$K_1 X_2 (X_1 + X_2/w)^{n-1}$$

Thus, by using a mass balance, it can be shown that:

$$dX_1/dt = Y_1 - K_1 X_1 (X_1 + X_2/w)^{n-1}$$

$$dX_2/dt = Y_2 - K_1 X_2 (X_1 + X_2/w)^{n-1}$$

where:

Y_1 = mass flow of water into the pebble mill (tons/hour)
(Y_1 equals the water reporting to the underflows of the primary and secondary hydrocyclones)

Y_2 = mass flow of solids into the pebble mill (tons/hour)
(Y_2 equals the solids reporting to the underflows of the primary and secondary hydrocyclones. Solids can report to the underflows either by being short circuited with the water reporting to the underflows or by being classified. See section 2.2.3)

Complete mixing was assumed to take place in the mill and the mass fraction of solids less than 75 μ m in the mill was represented by X_3 in an equation of the form:

$$dX_3/dt = Y_2(Y_3 - X_3)/X_2 + K_2(1 - X_3)$$

where:

Y_3 = mass fraction of solids less than 75 μ m in the solids feed into the pebble mill (fraction less than 75 μ m)
(Y_3 equals the fraction of solids less than 75 μ m in the underflows of the primary and secondary hydrocyclones)

K_2 = grinding rate constant (hour⁻¹)

To explain this equation, consider the following mass balance of - 75 μ m material:

$$d(X_3 X_2)/dt = Y_2 Y_3 - P_2 X_3 + K_2 X_2 (1 - X_3)$$

where:

P_2 = mass flow rate of solids out of the mill (tons/hour)

Differentiating the above equation, the following results:

$$\begin{aligned}
 d(X_3 X_2)/dt &= Y_2 Y_3 - P_2 X_3 + K_2 X_2 (1 - X_3) \\
 X_3 dX_2/dt + X_2 dX_3/dt &= Y_2 Y_3 - P_2 X_3 + K_2 X_2 (1 - X_3) \\
 X_3 (Y_2 - P_2) + X_2 dX_3/dt &= Y_2 Y_3 - P_2 X_3 + K_2 X_2 (1 - X_3) \\
 Y_2 X_3 + X_2 dX_3/dt &= Y_2 Y_3 + K_2 X_2 (1 - X_3) \\
 dX_3/dt &= Y_2 (Y_3 - X_3)/X_2 + K_2 (1 - X_3)
 \end{aligned}$$

The breakage rate constant is assumed to be independent of mill moisture and fines (ore) loading. No obvious correlations could be found between breakage rates, moisture and fines loading from the normal operating data⁽³⁾. Section 4.4.3.2 outlines how the model can be adapted to include a pebble loading dependence, while section 4.2 demonstrates that grinding can be accurately modelled with one cut size.

The actual equations defining the Blyvooruitzicht circuit are given below:

$$\begin{aligned}
 dX_1/dt &= Y_1 - 4.582X_1(X_1 + X_2/2.72)^{0.5} \\
 dX_2/dt &= Y_2 - 4.582X_2(X_1 + X_2/2.72)^{0.5} \\
 dX_3/dt &= Y_3(Y_3 - X_3)/X_2 + 1.65(1 - X_3)
 \end{aligned}$$

2.2.2 Rod Mill Model Structure

Complete mixing was assumed to take place in the rod mill and the mass fraction of solids less than 75 μ m in the rod mill was represented by X_4 in an equation of the form:

$$dX_4/dt = Y_4(Y_5 - X_4)/M + K_3(1 - X_4)$$

(The underlying principles of this equation are identical to the equation representing X_3),

where:

Y_4 = mass flow of solids to the mill (tons/hour)

M = hold-up mass of solids in the mill (tons)

Y_5 = mass fraction less than 75 μ m in the solids feed
(fraction less than 75 μ m)

K_3 = grinding rate constant

Using a mass balance, the flow rate of material out of the rod mill can be given by equations of the form:

Water flow rate out of the mill = constant (rod mill feed)
(tons/hour)

Solid flow rate out of the mill = rod mill feed
(tons/hour)

The actual equations defining the Blyvooruitzicht circuit are given below:

$$dX_4/dt = (70(0.03 - X_4))/6.03 + 2.4668(1 - X_4)$$

Water flow rate = 0.3(rod mill feed) (tons/hour)

2.2.3 Hydrocyclone Model Structure

In the modelling of the Blyvooruitzicht circuit, the conventional⁽⁵⁾ approach for the evaluation of the hydrocyclone cut size, d_{50c} , has been discarded in favour of an empirical approach which treats the primary and secondary cyclones as one unit.

The equation defining the cut size is given below:

$$\text{Log}_{10} d_{50c} = K_4 G_1 + K_5 V_1 + K_6$$

where:

G_1 = mass fraction of solids in the feed pulp to the hydrocyclone
(G_1 equals the mass fraction of solids in the flow from the head tank)

V_1 = volume flow of the feed pulp to the hydrocyclone
(m^3/hour)

(V_1 is calculated by splitting the volume flow of pulp from the head tank between the two sets of hydrocyclones. See section 2.2.4)

$K_4, K_5, K_6 = \text{constants}$

The equation for the reduced efficiency curve is the Plitt⁽⁶⁾ equation of the following form:

$$RE_c = (1 - \exp(-0.6931(d/d_{50c})^m))$$

where:

RE_c = Fraction of solids reporting to the underflow of size d (corrected for water split)

The water reporting to the underflow has been assumed constant. (This assumption will be dealt with in section 4.3).

2.2.4 Head Tank and Sump Model Structures

Both the head tank and sump were assumed to be perfect mixers. The volume flow from the sump was taken to be equal to the sump pump capacity. (See section 2.3 for a description of sump volume control). The volume flow from the head tank was taken to be a linear equation of the following form:

$$V_2 = K_7 H_1 + K_8$$

where:

V_2 = volume flow of pulp from the head tank (m^3/hour)

H_1 = volume of pulp in the head tank (m^3)

$K_7, K_8 = \text{constants}$

The constants which have been used⁽³⁾ are:

$$K_7 = 78.46$$

$$K_8 = 446.36$$

2.3 The Use of the Models in Simulation Studies of the Blyvooruitzicht Circuit

The models have been used directly in their non-linear state to form a simulator. (A listing of the program is

given in Listing 1).

During the course of these simulation studies, it was demonstrated that one of the requirements for overall stability of the Blyvooruitzicht circuit under dynamic conditions is that the sump volume has to be controlled.

The reason for this is the fact that under dynamic conditions the circulating load will fluctuate. If the circulating load decreases, the volume of material in the sump will decrease, and a possibility exists that the sump will dry up. On the other hand, if the circulating load increases, the volume of material in the sump will increase, and a possibility exists that the sump will overflow. Each of the above cases represents an instability that can be controlled by means of a proportional integral controller which adds water to the sump depending on the sump level.

Fig. 2 shows the results of non-linear and linear simulations of the Blyvooruitzicht circuit subjected to a step change in water addition to the head tank (60 tons/hour to 120 tons/hour), while Fig. 3 shows the results of non-linear and linear simulations of the Blyvooruitzicht circuit subjected to a step change in rod mill feed (70 tons/hour to 50 tons/hour). Both these figures and subsequent figures show a variable tabled "circulating load". The definition of this variable is the sum of the mass flow rates of all the solids reporting to the underflows of the hydrocyclones.

From these figures it is clear that simulators can be built for small systems which are at least numerically

RESPONSE OF THE LINEAR AND NON-LINEAR BLYVOGRUITZICHT SIMULATORS TO A STEP CHANGE IN WATER ADDITION TO THE HEAD TANK (60 TONS/HOUR TO 120 TONS/HOUR)

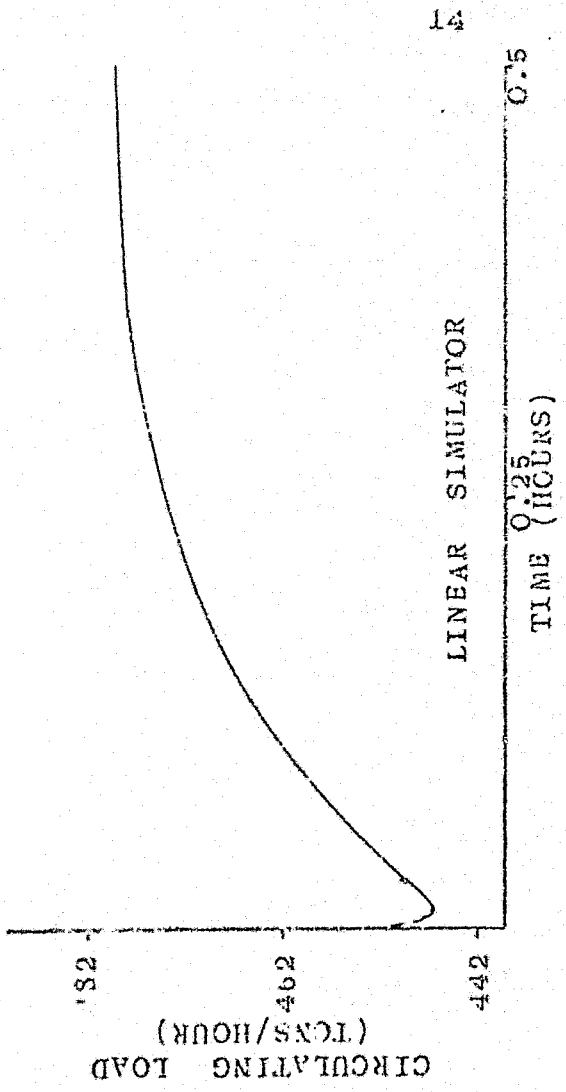
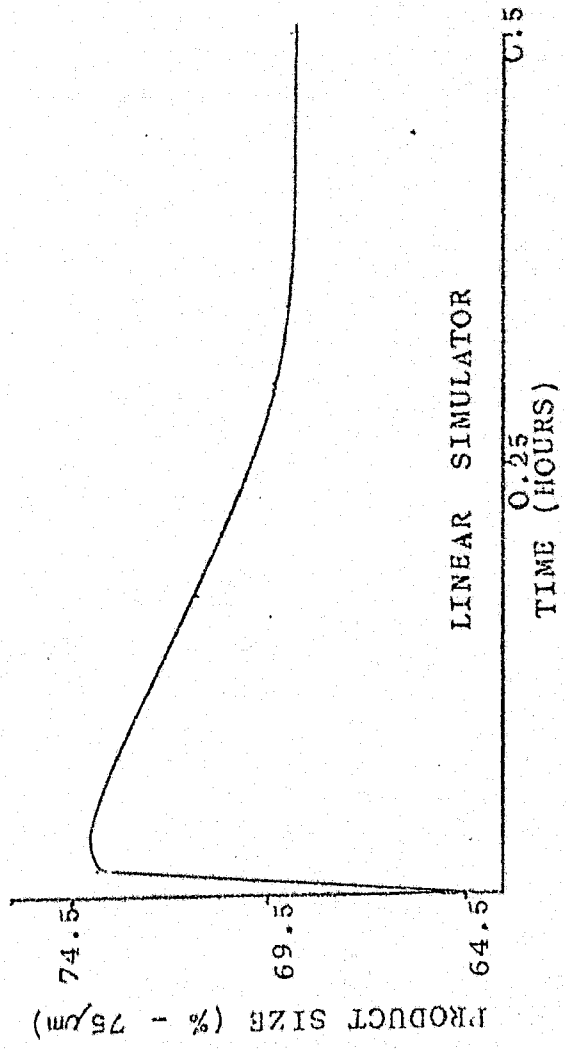
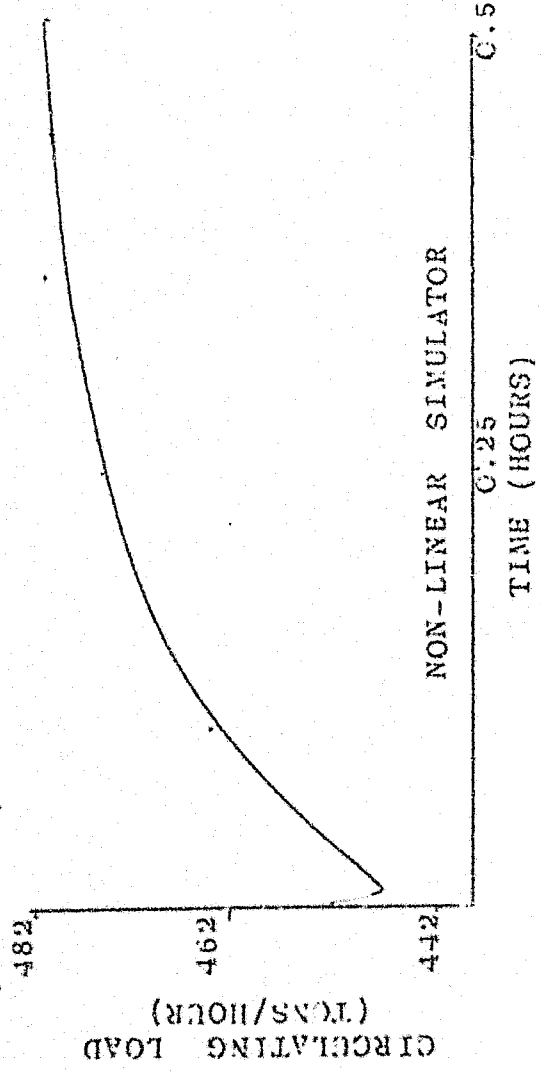
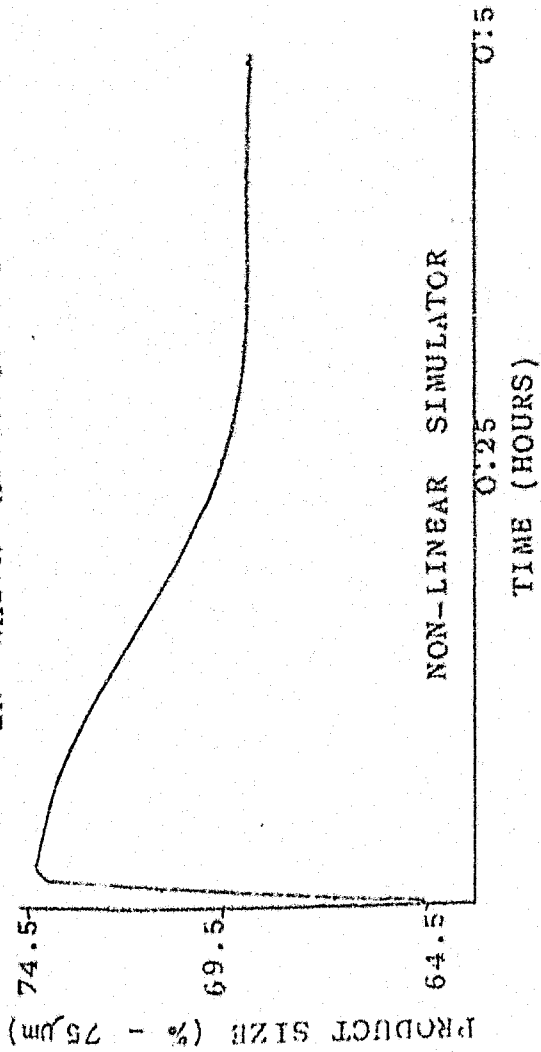


Fig. 2

RESPONSE OF THE LINEAR AND NON-LINEAR BLYVOORITZICHT SIMULATORS TO A STEP CHANGE IN ROD MILL FEED (70 TONS/HOUR TO 50 TONS/HOUR)

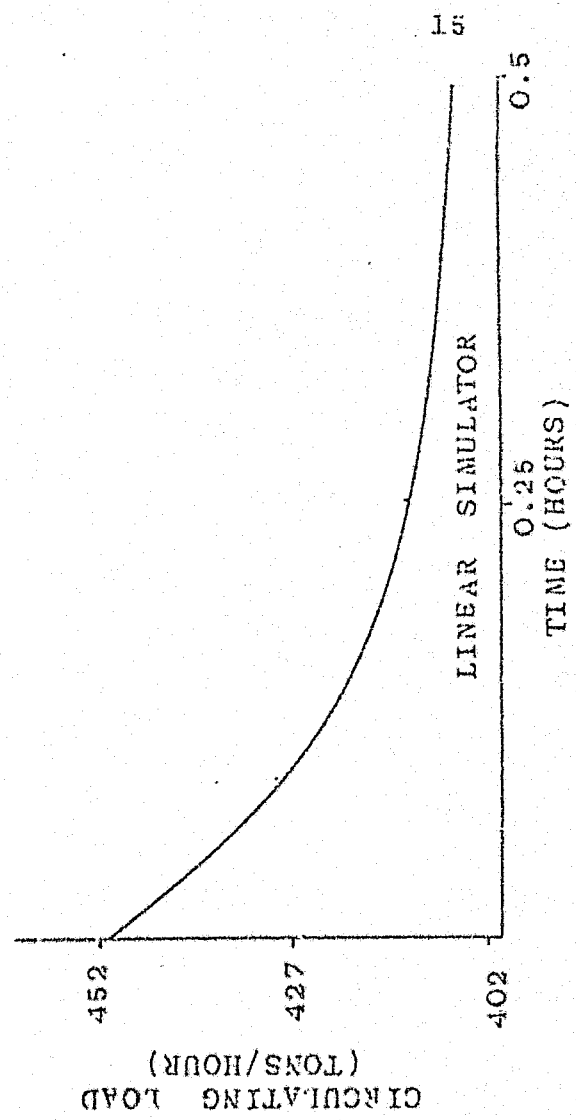
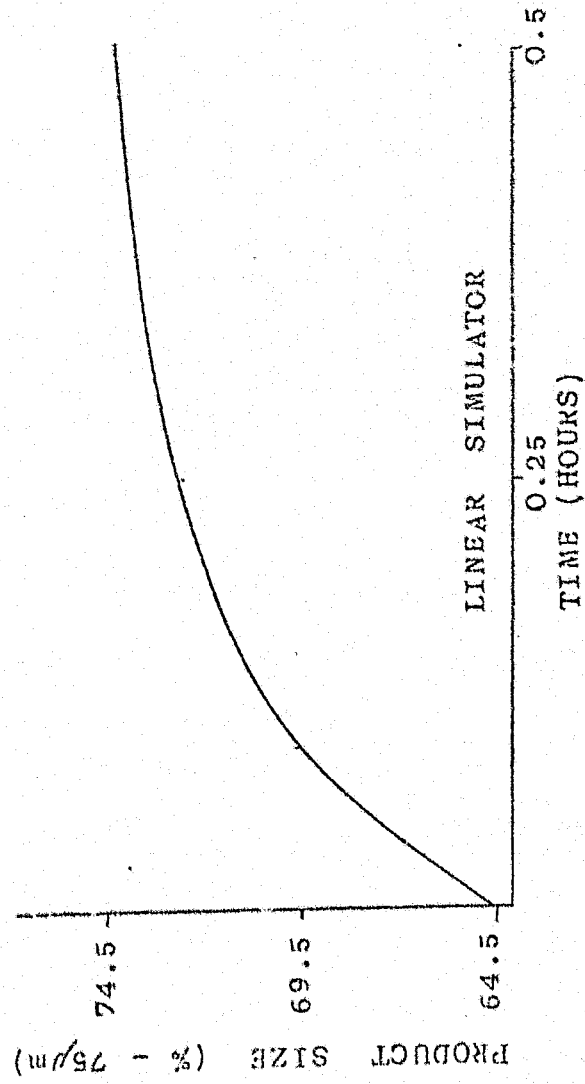
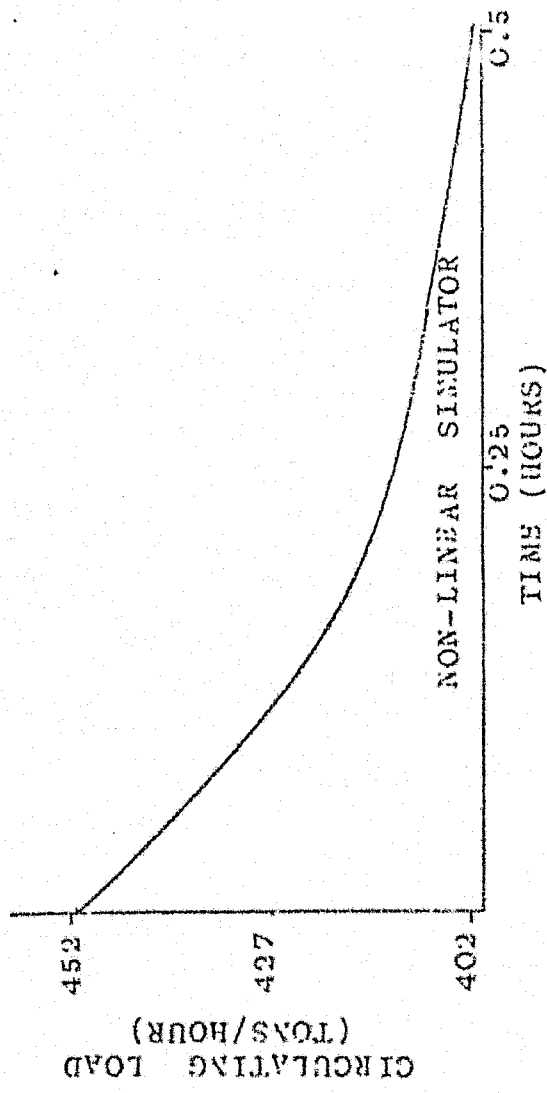
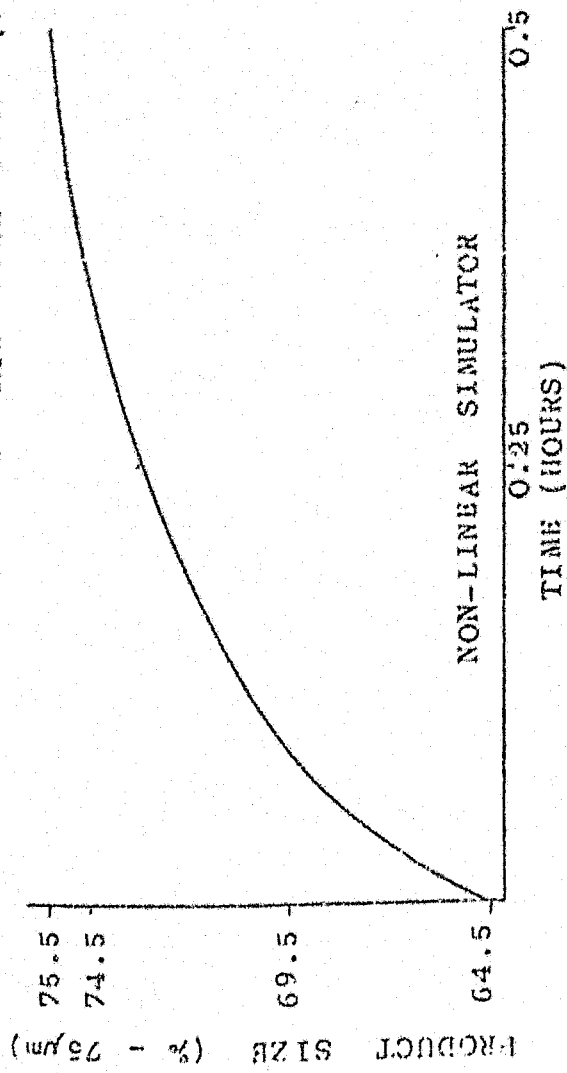


Fig. 3

stable. The accuracy of these simulations will be discussed in Chapter 5.

At this stage, however the linear simulator can be compared with the non-linear simulator. The results of this comparison are summarised in Tables 1, 2, 3 and 4.

Table 1

Step in Rod Mill Feed (70-50 tons/hour). 28.5% Deviation from Steady State			
Time (minutes)	Product Size (fraction less than 75 μ m)		
	Linear Model	Non-Linear Model	% Difference between the Models' Deviations from Steady State
0.0	64.5	64.5	0.0
3.0	68.1	68.5	0.62
6.0	69.9	70.2	0.47
9.0	71.1	71.5	0.62
12.0	72.1	72.6	0.78
15.0	72.8	73.3	0.78
18.0	73.3	74.0	1.09
21.0	73.7	74.5	1.24
24.0	73.9	74.9	1.55
27.0	74.1	75.2	1.71
30.0	74.3	75.5	1.86

Table 2

Step in Rod Mill Feed (70-50 tons/hour). 28.5% Deviation from Steady State			
Time (minutes)	Circulating Load (tons/hour)		
	Linear Model	Non-Linear Model	% Difference between the Models' Deviations from Steady State
0.0	451.6	451.6	0.0
3.0	434.8	433.1	0.38
6.0	427.7	426.1	0.36
9.0	422.2	420.5	0.38
12.0	417.9	415.9	0.44
15.0	414.7	412.2	0.55
18.0	412.3	409.3	0.66
21.0	410.4	406.9	0.78
24.0	409.1	405.0	0.91
27.0	408.1	403.5	1.01
30.0	407.4	402.2	1.15

Table 3

Step in Water Addition to the Head Tank (60-120 tons/hour). 100% Deviation from Steady State			
Time (minutes)	Product Size (fraction less than 75 μ m)		
	Linear Model	Non-linear Model	% Difference between the Models' Deviations from Steady State
0.0	64.5	64.5	0.0
3.0	74.0	73.6	0.62
6.0	72.5	72.4	0.16
9.0	71.2	71.4	0.31
12.0	70.4	70.5	0.16
15.0	69.7	69.9	0.31
18.0	69.2	69.4	0.31
21.0	68.8	69.0	0.31
24.0	68.6	68.8	0.31
27.0	68.4	68.6	0.31
30.0	68.2	68.4	0.31

Table 4

Step in Water Addition to the Head Tank (60-120 tons/hour). 100% Deviation from Steady State			
Time (minutes)	Circulating Load (tons/hour)		
	Linear Model	Non-linear Model	% Difference between the Models' Deviations from Steady State
0.0	451.6	451.6	0.0
3.0	457.1	458.0	0.20
6.0	463.3	463.6	0.07
9.0	467.9	468.1	0.04
12.0	471.5	471.7	0.04
15.0	474.4	474.6	0.04
18.0	476.6	476.9	0.07
21.0	478.3	478.7	0.09
24.0	479.5	480.0	0.11
27.0	480.5	481.1	0.13
30.0	481.2	482.0	0.18

From the preceding tables it is clear that the linear model is in very good agreement with the non-linear model. It can therefore be concluded that for analytic studies the linear model can be used, while for simulation studies the non-linear model will be that much more accurate.

Note: The simulations using the linear model were run by Hinde⁽⁷⁾ of the Chamber of Mines of South Africa.

CHAPTER 3

THE BUILDING OF A SIMULATOR FOR A "LARGE" MILLING CIRCUIT

3.1 General

It was demonstrated in Chapter 2 that, in principle, it is possible to build a dynamic simulator for a "small" circuit.

The next stage is to look at the building of simulators for a "large" milling circuit. The circuit which was considered is the milling circuit of the Buffelsfontein Gold Mining Co. Limited. Fig. 4 illustrates the circuit.

The philosophy adopted for building this simulator was to take the models which had been developed for the Blyvooruitzicht circuit and adapt them to fit the Buffelsfontein circuit. This adaptation⁽⁸⁾ was done by means of getting the steady state response of the simulated circuit to accord with the steady state response of the actual circuit.

Tests were then carried out to test the validity of the simulator as a dynamic simulator. These will be discussed in section 5.3.

Section 3.2 describes how the models for the Buffelsfontein circuit were arrived at.

3.2 Model Structures

3.2.1 Pebble Mill Model Structure

The basic structure of the model was taken to be of the same form as the Blyvooruitzicht pebble mill model. For

SCHEMATIC DIAGRAM OF THE BUFFELSFONTEIN GOLD MINING CO. LIMITED'S MILLING CIRCUIT

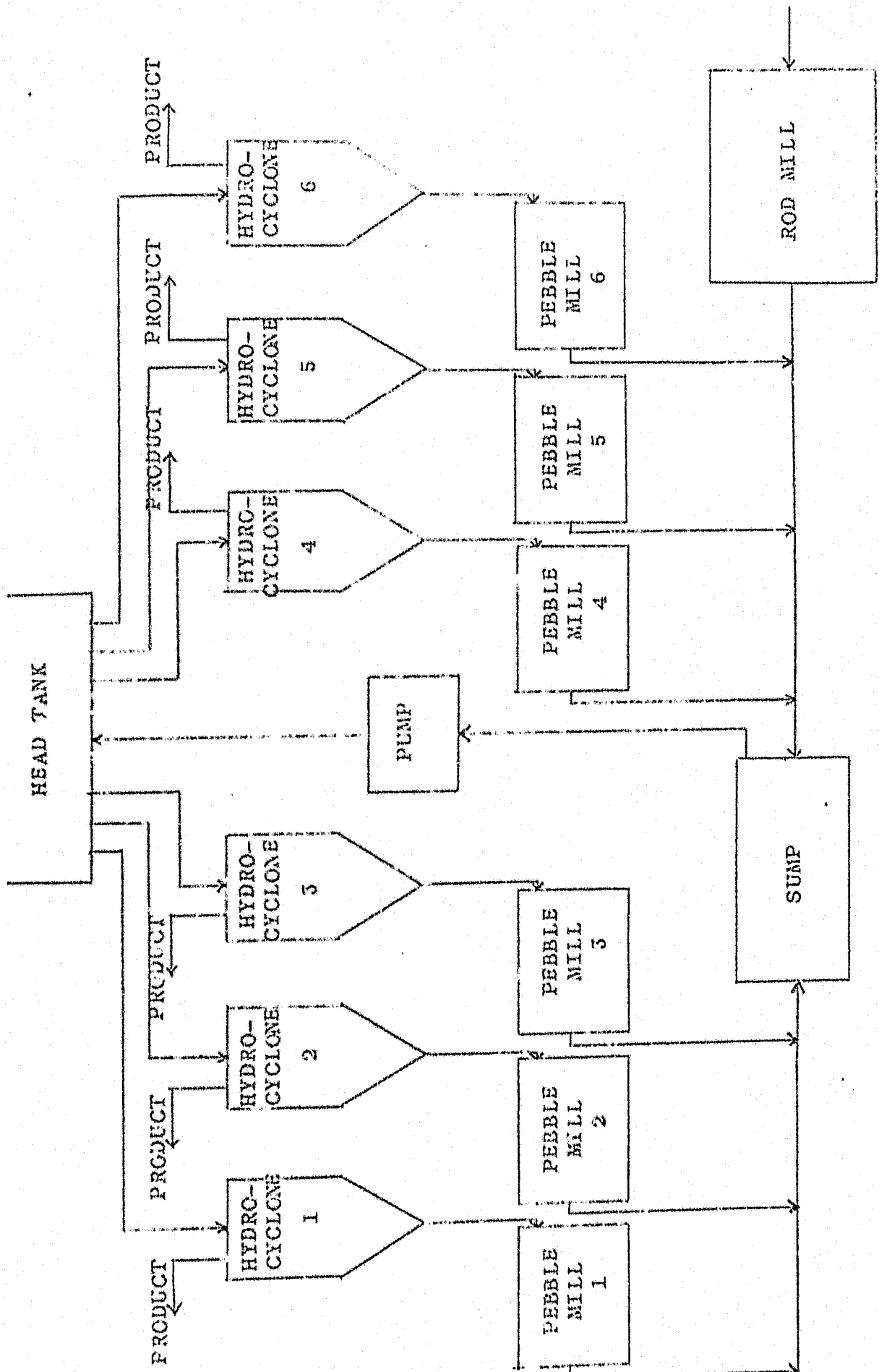


Fig. 4

convenience this structure is repeated below:

$$dX_1/dt = Y_1 - K_1 X_1 (X_1 + X_2/w)^{n-1}$$

$$dX_2/dt = Y_2 - K_1 X_2 (X_1 + X_2/w)^{n-1}$$

$$dX_3/dt = Y_2(Y_3 - X_3)/X_2 + K_2(1 - X_3)$$

where the symbols are defined in Chapter 2.

In order to determine the values of K_1 , K_2 and n , simulations were run in which the following steady state objectives - which correspond with data for the Buffelsfontein circuit - were aimed for:

Mass of water plus mass of solids in the pebble mill
 $(X_1 + X_2) = 8.99$ (tons)

Mass fraction of solids less than $75\mu\text{m}$ in the pebble mill
 $(X_3) = 0.183$

Specific gravity of mill contents = 1.84

Values of K_1 , K_2 and n which gave the closest accord with the real system were determined from these simulations and the resultant models are listed below:

$$dX_1/dt = Y_1 - 10.99X_1(X_1 + X_2/2.72)^{0.5}$$

$$dX_2/dt = Y_2 - 10.99X_2(X_1 + X_2/2.72)^{0.5}$$

$$dX_3/dt = Y_2(Y_3 - X_3)/X_2 + 2.650(1 - X_3)$$

The steady state values that the computer model ran up to were:

$$X_1 + X_2 = 9.17$$

$$X_3 = 0.208$$

Specific gravity
of mill contents = 1.96

3.2.2. Rod Mill Model Structure

As in the case of the pebble mill model, the model of the

Buffelsfontein rod mill is based on the Blyvooruitzicht model. This model structure is given below:

$$dX_4/dt = Y_4(Y_5 - X_4)/M + K_4(1 - X_4)$$

Water flow rate out of the mill = constant (rod mill feed)
(tons/hour)

Solid flow rate out of the mill = rod mill feed rate
(tons/hour)

Simulations were run in which the following objectives, which correspond with data for the Buffelsfontein circuit, were aimed for:

Mass fraction of solids less than 75 μ m in the rod mill
(X_4) = 0.149

Rod mill specific gravity = 2.02

As a result of these simulations, equations were determined which gave the best correspondence with the data. The equations are listed below:

$$dX_4/dt = Y_4(Y_5 - X_4)/6.03 + (1 - X_4)2.467$$

Water flow rate = 0.25 (rod mill feed rate)

The steady state values that the computer ran up to were:

X_4 = 0.155

Rod mill specific gravity = 2.02

3.2.3 Hydrocyclone Model Structure

A conventional mechanistic⁽⁵⁾ approach has been used for evaluating the hydrocyclone cut size. The reason for this decision is the fact that the Lynch⁽⁵⁾ equation can easily be applied to the Buffelsfontein circuit because the classification is done by primary hydrocyclones rather than by primary and secondary hydrocyclones as is the case on the

Blyvooruitzicht circuit.

Note was taken of the most recent work done in the field of hydrocyclone modelling by Plitt⁽⁹⁾. This work, however, offers models which are no more accurate, in the operating range of Buffelsfontein classifiers, than the Lynch⁽⁵⁾ models.

The structure of the Lynch model used is given below:

$$\text{Log}_{10} d_{50c} = 0.0400(\text{VF}) - 0.0576(\text{SPIG}) + 0.0366(\text{INLET}) + 0.0299(\text{FPS}) - 0.0001(\text{LPM})$$

where:

- d_{50c} = size of particle in the feed pulp which is equally distributed between the overflow and underflow streams due to centrifugal action only
- VF = vortex finder diameter (cm)
- SPIG = spigot diameter (cm)
- INLET = inlet diameter (cm)
- FPS = per cent solids in feed to the hydrocyclone by weight (%)
- LPM = volume feed rate to the hydrocyclone (litres/minute)

The Plitt⁽⁶⁾ equation has again been used for defining the reduced efficiency curve, and is of the following form:

$$\text{RE}_c = (1 - \exp(-0.6931)(d/d_{50c})^m)$$

where:

- RE_c = fraction of solids reporting to the underflow of size d (corrected for water split)

The water reporting to the underflow has been assumed constant. (This assumption is dealt with in section 4.3).

Simulations were run in order to evaluate the unknown

parameters. The following objectives, which correspond with data for the Buffelsfontein circuit were aimed for:

Mass fraction less than $75\mu\text{m}$ in hydrocyclone underflow	= 0.125
Specific gravity of hydrocyclone underflow	= 1.93
Specific gravity of hydrocyclone overflow	= 1.09
Mass fraction less than $75\mu\text{m}$ in hydrocyclone overflow	= 0.69

As a result of these simulations, equations were determined which gave the best correspondence with the data.

The equations are listed below:

$$G_u = (1 - \exp(-0.6931(166/d_{50c})^2))$$

$$L_u = (1 - \exp(-0.6931(71.66/d_{50c})^2))$$

where:

G_u = fraction of solids greater than $75\mu\text{m}$ in the feed that report to the underflow

L_u = fraction of solids less than $75\mu\text{m}$ in the feed that report to the underflow

The values 166 and 71.66 account for all the coarse and fine materials respectively and ensure that the desired objectives are met.

The constant volume of water reporting to the underflow was calculated by considering that the overall steady state circulating load is 960(tons/hour) and that the steady state specific gravity of the hydrocyclone underflow is 1.93.

3.2.4 Head Tank and Sump Model Structures

As in the case of the Blyvooruitzicht circuit, the volume flow from the sump was taken to be a function of the sump pump capacity, while the volume flow from the head tank

was taken to be a linear function of head tank level.

3.3 Steady State Response of the Buffelsfontein Circuit Models

Once all the parameters in the Buffelsfontein models had been decided upon, a steady state simulation was run. (See Listing 2).

A comparison of the outputs of this simulator with the actual Buffelsfontein steady state values is given in Table 5. This table relates to a feed to the rod mill of 100(tons/hour).

Table 5

	Simulator	Actual
Specific gravity of rod mill discharge	2.02	2.02
Specific gravity of hydrocyclone feed	1.44	1.41
Specific gravity of hydrocyclone overflow	1.10	1.09
Specific gravity of hydrocyclone underflow	1.94	1.93
Specific gravity of pebble mill discharge	1.96	1.84
Particle size distribution of rod mill discharge (% - 75 μ m)	14.84	15.56
Particle size distribution of hydrocyclone overflow (% - 75 μ m)	68.30	69.00
Particle size distribution of hydrocyclone underflow (% - 75 μ m)	12.70	12.50
Particle size distribution of pebble mill discharge (% - 75 μ m)	20.80	18.30
Circulating load (tons/hour)	960.70	960.00

3.4 Dynamic Response of the Buffelsfontein Circuit Models

Figs. 5 and 6 show the response of the Buffelsfontein simulator to step changes in water addition (112 tons/hour to 224 tons/hour) to the head tank and in the rod mill feed (100 tons/hour to 75 tons/hour) respectively.

The accuracy of these simulations will be discussed in section 5.3.

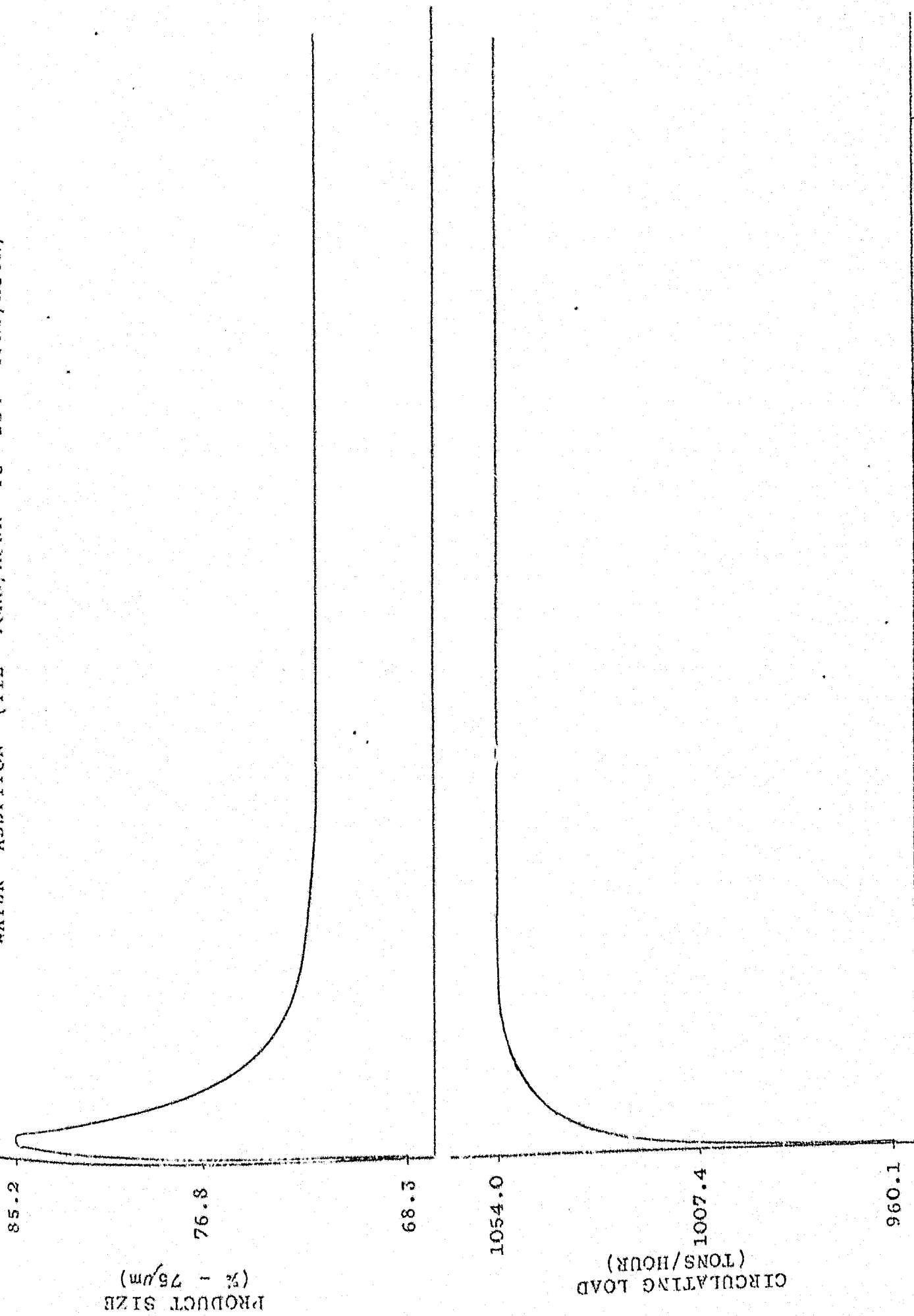
3.5 Concluding Remarks

It has been shown that it is possible to build a simulator for a large-scale milling system which is numerically stable and which is in good agreement with the system operating in steady state.

The validity of the simulator as a dynamic simulator will be discussed in section 5.3.

Note: Each element in this simulator has been modelled separately to allow for simulations wherein some of the pebble mills or hydrocyclones may operate differently from the remaining pebble mills or hydrocyclones; however, in this dissertation, all simulations have been run with all pebble mills and hydrocyclones operating uniformly.

WATER ADDITION (112 TONS/HOUR TO 224 TONS/HOUR) A STEP CHANGE IN HEAD TANK



1.0

0.5
TIME (HOURS)

Fig. 5

RESPONSE OF THE BUEHLSFONTEIN SIMULATOR TO A STEP CHANGE IN ROD MILL FEED (100 TONS/HOUR TO 75 TONS/HOUR)

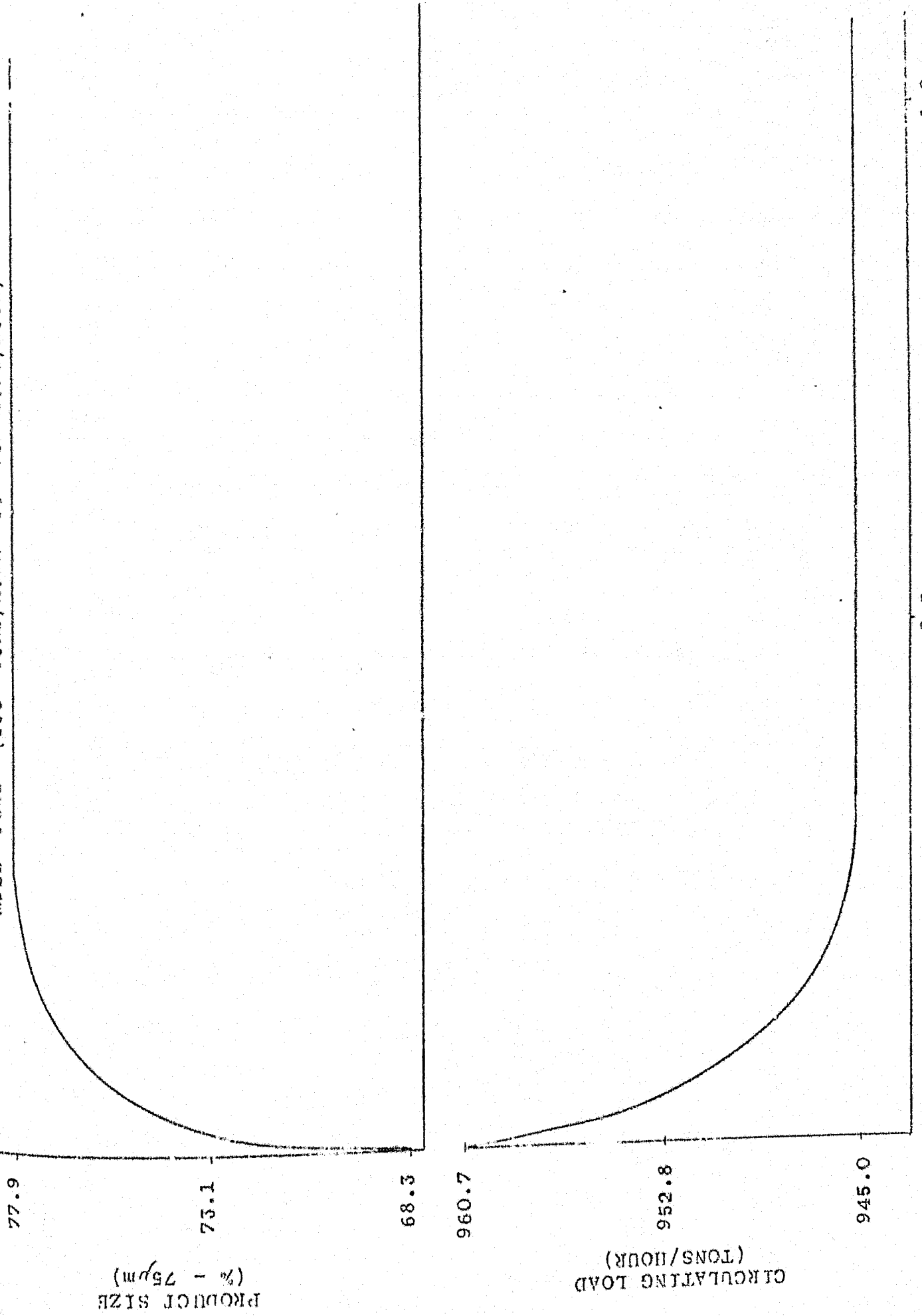


Fig. 6

CHAPTER 4THE LEVEL OF DEFINITION REQUIRED IN THE SIMULATORS4.1 General

When one is building simulators it is important to keep one's models as simple as possible within the overall framework of not losing definition of the system which one is attempting to portray. Alternatively, one must know what level of definition is required in a model to ensure that the resultant simulator does not give a distorted picture of the system which is being simulated. Bearing this in mind, there are four aspects of the modelling described in Chapters 2 and 3 which require attention.

These are:

- (1) The use of a discrete size model for grinding consisting of one cut size.
- (2) The use of a constant water underflow from the hydrocyclones as opposed to a variable water underflow.
- (3) The development of a model, which will interact with the rest of the simulator, reflecting the power drawn by the pebble mill as a function of pebble addition and wear.
- (4) The use of this model in a "large" milling circuit.

4.2 Discrete Size Modelling with one Cut Size

The most convincing argument for the use of a discrete

size model with one cut size is that it simplifies the models extremely, and the results obtained from such models by the Chamber of Mines of South Africa have been encouraging, i.e. experimental responses and simulated responses have a high degree of correlation.

The initial decision by Hinde of the Chamber of Mines to use a single cut size is based on observations from the Blyvooruitzicht circuit that the weight fraction less than some given size uniquely defines the whole size distribution to within tolerable limits⁽³⁾.

Further empirical justification pointing towards the use of a discrete size model with one cut size is the fact that a successful control system has been implemented at Craigmont Mines⁽¹⁰⁾ where particle size description is based on a single size measurement. In addition to this, Dart and Sand⁽¹¹⁾, after studying particle size distributions on fifteen different plants, have concluded that "a single read out can be used to identify an entire distribution with more than adequate accuracy for control purposes".

In analysing the effects the choice of one cut size have on the modelling of grinding, consider the following:

According to Austin⁽¹²⁾, in general:

$$S_j = Ax_j^\alpha$$

$$j = 1, 2, \dots, n-1$$

$$B_{i,j} = B(x_i/x_j)^\delta + (1 - B)(x_i/x_j)^\beta$$

$$\beta \gg \delta \gg 0, \quad 0 < B < 1$$

where:

- S_j = selection function of material in the j th size interval
 $B_{i,j}$ = breakage function of material from the j th size interval into the i th size interval (size i being the top size of interval i)
 x_i, x_j = size of material in size intervals i and j respectively
 $A, B, \alpha, \beta, \gamma$ = constants

According to Taut δ ⁽¹³⁾, $\gamma \approx \alpha$ for gold ore, thus

$$B_{i,j} = B(x_i/x_j)^\alpha + (1 - B)(x_i/x_j)^\beta$$

The fact that the experimental results fit the actual results tends to indicate that:

$$S_j = Ax_j^\alpha$$

$$B_{i,j} = B(x_i/x_j)^\alpha + (1 - B)(x_i/x_j)^\beta$$

But for small sizes of x_i/x_j the first term on the right hand side is dominant⁽¹²⁾, thus:

$$B_{i,j} = B(x_i/x_j)^\alpha$$

thus:

$$B_{i,j} S_j = ABx_i^\alpha = \text{function of } i \text{ only}$$

Physically this means that the rate of breakage to less than size i depends only on the fractional amount of material greater than size i ⁽¹⁴⁾.

The importance of this fact is that it demonstrates that even though the grinding models used are coarse, they are nevertheless accurate. Care must be taken when choosing the cut size to ensure that the cut size is such that x_i/x_j is small enough to allow the first term in the breakage equation to be dominant; e.g. if a cut size of $400\mu\text{m}$ had been chosen instead of $75\mu\text{m}$, $B_{i,j} S_j$ would not be a function of i only.

The significance of single cut size modelling is that it allows reasonably simple and accurate simulators (see sections 5.2 and 5.3) to be built for complex systems.

4.3 The Use of Constant Water Underflow from the Hydrocyclone

The assumption that has been made is that the amount of water reporting to the hydrocyclone underflow is constant. It is necessary to consider how seriously this assumption affects the definition and the accuracy of the hydrocyclone model.

Consider the following equation, which is the Lynch⁽⁵⁾ equation for water reporting to the underflow:

$$WUF = WF(193.SPIG/WF - 271.6/WF - 1.61)/100$$

where:

WUF = flow rate of water in the underflow (tons/hour)

WF = flow rate of water in the feed (tons/hour)

SPIG = spigot diameter (cm)

Taking SPIG to be 10.16 cm, Table 6 can be derived.

Table 6

Water Flow Rate into the Hydrocyclone (tons/hour)	Water Flow Rate to the Hydrocyclone Underflow (tons/hour)
120.0	14.96
130.0	14.80
140.0	14.64
150.0	14.48
160.0	14.32
170.0	14.16
180.0	13.99
190.0	13.83
200.0	13.67
210.0	13.51
220.0	13.35

From this table it is clear that no significant loss of definition or accuracy will occur as a result of assuming the underflow water flow rate to be constant.

4.4 The Development of a Model reflecting the Power Characteristics of a Pebble Mill

In the simulators of the Blyvooruitzicht and Buffelsfontein circuits described in Chapters 2 and 3 respectively, an average value for feed rate of pebbles to the pebble mills has been used and the pebble mills have been assumed to draw constant power.

In order to design controllers that ensure that the pebble mills grind at Full potential it is necessary to

develop a model which will accurately portray the way in which mill power varies as a function of pebble feed and which will interact with the rest of the circuit. The significance of the power drawn by a pebble mill is that maximum power drawn by the mill corresponds with maximum energy available for breakage, resulting in a finer product⁽¹⁾. Consequently, it is desirable to control the addition of pebbles to the mill to ensure that the mill is driven as close to the maximum power point as possible. Studies have shown that this maximum power point corresponds with the pebble mill being half full.

In this section, the Blyvooruitzicht simulator has been used for the development of a model reflecting pebble mill power. In this development work, the mills have been controlled by a "Digicon" controller. (See section 4.4.1). In section 4.5, "Digicon" control of the pebble mills has been included in the Buffelsfontein simulator.

Chapter 6 deals with the Buffelsfontein simulator in which "Digicon" control of the pebble mills has been included, while section 6.6 contrasts "Digicon" mill power control of the Buffelsfontein pebble mills with an alternative mill power control strategy.

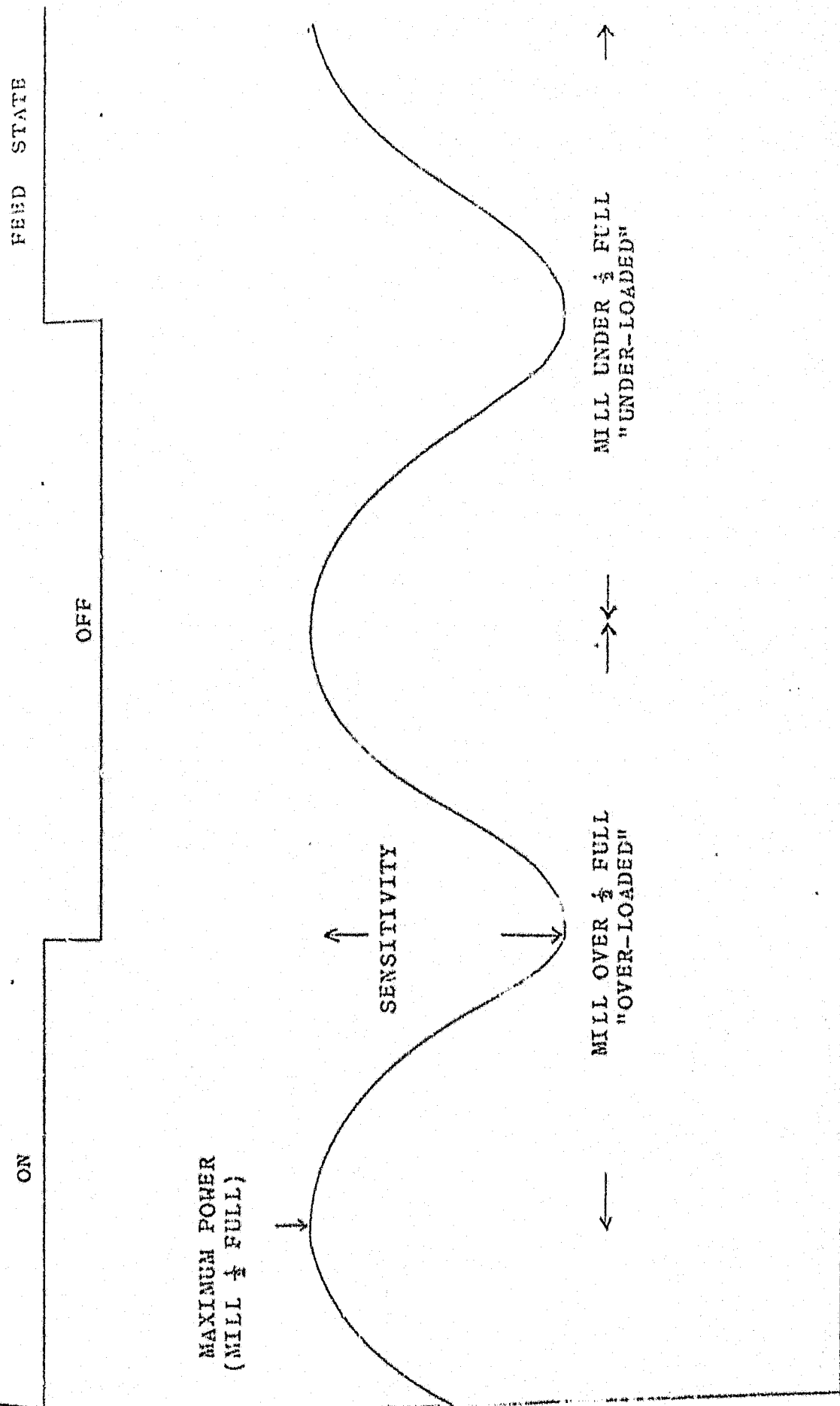
4.4.1 Description of the "Digicon" Operation

The ideal operation of the "Digicon" can best be described by considering Fig. 7.

Fig. 8 gives a schematic lay-out of the "Digicon".

In practice⁽¹⁵⁾, the following was observed, and it was set as an objective to build a model with these characteristics:

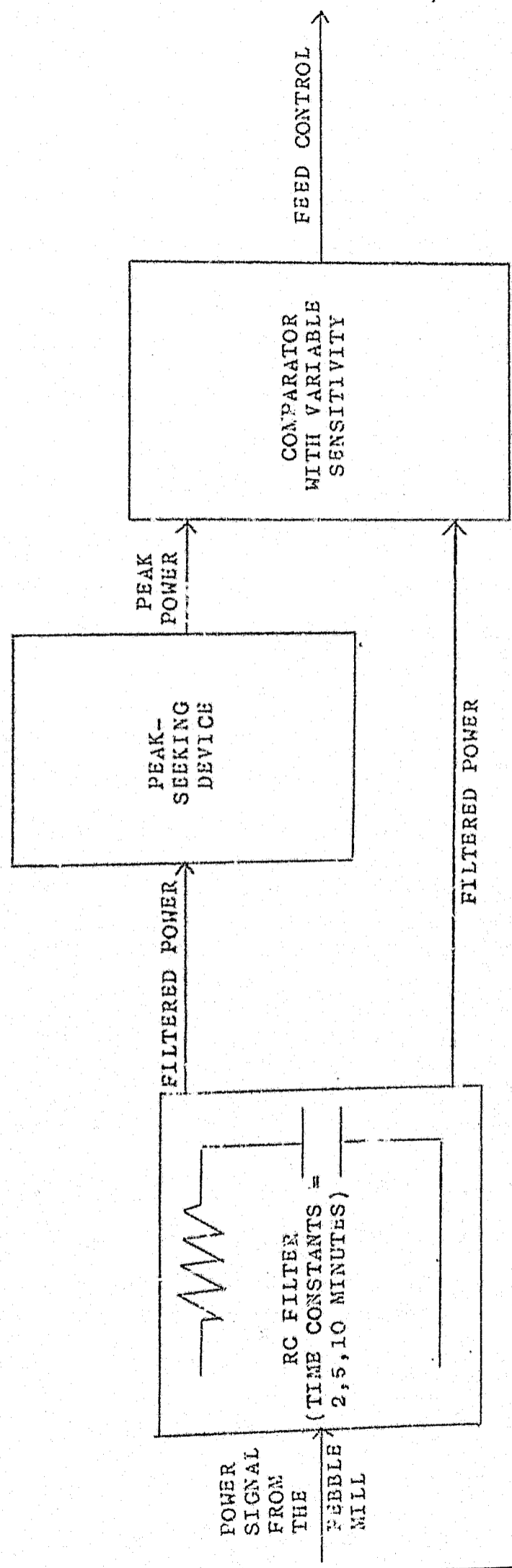
IDEAL OPERATION OF THE "DIGICON"



MILL POWER

When the power has dropped by an amount equal to the sensitivity, the feed state is changed and the power rises

SCHEMATIC LAYOUT OF THE "DIGICON"



When the filtered power has dropped by a certain percentage (sensitivity) from the peak power the feed state is changed.

Fig. 8

- (1) The power continued to fall for a period of time, after the feed state had been changed, before rising. As a result of this, a delay was incorporated into the "Digicon" which prevented the "Digicon" from looking at the power until the power had begun to rise.
- (2) The power curve was a-symmetric about power peaks, and the power peaks differed depending on whether the mill was coming out of an overloaded or underloaded state.
- (3) The "Digicon" often switched spuriously. This was due to the fact that, in spite of the filter, the filtered power signal still contained surges, due to random fluctuations, which caused the peak-seeking device to lock onto peaks other than the real power peaks.

4.4.2 Power Equation

Geuerro and Arbiter⁽¹⁶⁾ and Hogg and Fuerstenau⁽¹⁾ have proposed power equations for tumbling mills. The Geuerro and Arbiter equation exhibits asymmetric characteristics about a specific mill filling of one half. The Hogg and Fuerstenau equation, however, has been used for the following reasons:

- (i) It is the most modern power equation and it is not subject to the criticisms which have been levelled at the Geuerro and Arbiter equation.
- (ii) In spite of the fact that the Geuerro and Arbiter equation has a-symmetric properties, when simulations comparing it to the Hogg and

Fuerstennau equations were run, little difference could be found. Thus no discernible gain was to be had by using the more complex Geuerro and Arbiter equation in preference to the Hogg and Fuerstenau equation.

In the operating region of the mill, where Θ is small (see Appendix 3), the Hogg and Fuerstenau equation can be expressed in the form shown below:

$$P = C(BD)(\sin(\pi s))^3(\sin\alpha)$$

where:

P = power drawn by the mill

C = a constant

BD = bulk density

α = dynamic angle of repose of material in the mill

s = specific filling of the mill

Θ = filling angle (see Appendix 3)

Sections 4.4.2.1 and 4.4.2.2 deal with the bulk density and angle of repose terms required in the Hogg and Fuerstenau equation.

4.4.2.1 Bulk Density Calculation

The equation used is:

$$BD = W/1.4 + W(X_1 + X_2)/MM(1.4)$$

where:

W = specific gravity of the solids

X_1 = hold-up weight of water in the mill (tons)

X_2 = hold-up weight of fines (solids) in the mill (tons)

BD = bulk density

MM = mass of pebbles in the mill (tons)

The derivation of this equation, which is based on 40%

voids, is given in Appendix 4.

The bulk density term serves to link the power required by the mill to the dynamics of the rest of the circuit.

4.4.2.2 Investigation into the Behaviour of α

Tests were run at the University of the Witwatersrand on small-scale mills (approximately 40 cm long and 23 cm in diameter) to investigate the following:

- (1) α as a function of rotational speed;
- (2) α as a function of specific mill filling;
- (3) α as a function of bulk density of the material in the mill.

The results of these tests are shown in Tables 7 and 8. It is clear from these tables that, within the accuracy of measurement, α is not functionally dependent on rotational speed, specific mill filling, or bulk density. It is important to note that the results obtained do not necessarily hold for large-scale industrial mills. In consequence of this investigation, $\sin \alpha$ was taken to be a constant in the Hogg and Fuerstenau equation and it was incorporated in the constant term.

Table 7

Results of experiments to determine α as a function of bulk density and rotational speed		
(± 0.01) BD	$\frac{n}{N1}$	($\pm 5^\circ$) α
3.0	1.0	45
2.8	1.0	45
2.6	1.0	45
2.4	1.0	45
2.2	1.0	45
2.0	1.0	45
3.0	0.75	45
2.8	0.75	45
2.6	0.75	45
2.4	0.75	45
2.2	0.75	45
2.0	0.75	45
3.0	0.5	45
2.8	0.5	45
2.6	0.5	45
2.4	0.5	45
2.2	0.5	45
2.0	0.5	45
2.5	0.0	45

N1 = normalising factor

n = rotational speed

BD = bulk density

Table 8

Results of experiments to determine α as a function of bulk density and specific mill filling		
(± 0.01) BD	(± 0.01) s	($\pm 5^\circ$) α
3.0	0.7	45
3.0	0.6	45
3.0	0.5	45
3.0	0.4	45
3.0	0.3	45
2.8	0.7	45
2.8	0.6	45
2.8	0.5	45
2.8	0.4	45
2.8	0.3	45
2.6	0.7	45
2.6	0.6	45
2.6	0.5	45
2.6	0.4	45
2.6	0.3	45
2.4	0.7	45
2.4	0.6	45
2.4	0.5	45
2.4	0.4	45
2.4	0.3	45
2.2	0.7	45
2.2	0.6	45
2.2	0.5	45
2.2	0.4	45
2.2	0.3	45

$\frac{n}{N1} = 1.0$. The same results were obtained for $\frac{n}{N1} = 0.7$

4.4.3 Interaction with the Rest of the Circuit

One of the requirements for a mill power model is that there exists interaction between the mill power model and the dynamic model of the grinding circuit as a whole. The link from the grinding circuit to the mill power model is via the bulk density function which has been discussed in section 4.4.2.1. The link from the mill power model to the grinding circuit is achieved by including a dynamic pebble wear rate and by including a factor which modifies the rate of production of 75 μ m material in the pebble mill. These two links will be discussed in sections 4.4.3.1 and 4.4.3.2 respectively.

4.4.3.1 Pebble Wear Rate

In order for a mass balance of material going through the pebble mill to exist, the pebble wear rate must be known dynamically rather than on an hourly average basis.

Stanley⁽¹⁷⁾ has determined that the wear rate of pebbles in a pebble mill can be expressed in the following form:

$$WR = (M_{\text{nominal}}/MM)^{0.71}$$

where:

WR = wear rate (tons/hour)

M_{nominal} = a standard dry load weight to which the wear rate is corrected (tons)

MM = mass of pebbles in the mill (tons)

The average pebble wear rate for the Blyvooruitzicht circuit is 7 tons/hour, and, assuming that this corresponds with the mill being one half full on average, the following equation can be derived for the Blyvooruitzicht

Author Rabins R

Name of thesis Simulation of Multiple closed loop milling circuits 1977

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