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SPOC
Simulated Processing of Ore and Coal

Chapter 5 Unit Models (Part A)

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The SPOC Manual

Chapter 5 Unit Models (Part A)

Unit Models and FORTRAN Simulators of Ore and Coal Process Equipment: Comminution and Flotation

A. Mular

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THE SPOC MANUAL

The **SPOC*** manual consists of eighteen chapters, published separately. Their numbers and short titles are as follows:

1. Summary
2. Sampling Methodology
2.1 SAMBA Computer Program
2.2 Grinding Circuit Sampling
3. Material Balance
3.1 BILMAT Computer Program
3.2 MATBAL Computer Program
4. Modelling and Simulation
4.1 Industrial Ball Mill Modelling
5. Unit Models: Part A
5.1 Unit Models: Part B
5.2 Unit Models: Part C
6. Flowsheet Simulators
7. Model Calibration
7.1 STAMP Computer Program
7.2 FINDBS Computer Program
7.3 RTD and MIXERS Computer Programs
8. Miscellaneous Computer Programs

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*Simulated Processing of Ore and Coal

FOREWORD

High energy costs and depleting ore reserves combine to make process evaluation and optimization a challenging goal in the 80's. The spectacular growth of computer technology in the same period has resulted in widely available computing power that can be distributed to the most remote mineral processing operations. The SPOC project, initiated at CANMET in 1980, has undertaken to provide Canadian industry with a coherent methodology for process evaluation and optimization assisted by computers. The SPOC Manual constitutes the written base of this methodology and covers most aspects of steady-state process evaluation and simulation. It is expected to facilitate industrial initiatives in data collection and model upgrading.

Creating a manual covering multidisciplinary topics and involving contributions from groups in universities, industry and government is a complex endeavour. The reader will undoubtedly notice some heterogeneities resulting from the necessary compromise between ideals and realistic objectives or, more simply, from oversight. Critiques to improve future editions are welcomed.

D. Laguitton
SPOC Project Leader
Canada Centre for Mineral and Energy Technology

AVANT-PROPOS

La croissance des coûts de l'énergie et l'appauvrissement des gisements ont fait de l'évaluation et de l'optimisation des procédés un défi des années 80 au moment même où s'effectuait la dissémination de l'informatique jusqu'aux concentrateurs les plus isolés. Le projet SPOC, a été lancé en 1980 au CANMET, en vue de développer pour l'industrie canadienne, une méthodologie d'application de l'informatique à l'évaluation et à l'optimisation des procédés minéralurgiques. Le Manuel SPOC constitue la documentation écrite de cette méthodologie et en couvre les différents éléments. Les retombées devraient en être une vague nouvelle d'échantillonnages et d'amélioration de modèles.

La rédaction d'un ouvrage couvrant différentes disciplines et rassemblant des contributions de groupes aussi divers que les universités, l'industrie et le gouvernement est une tâche complexe. Le lecteur notera sans aucun doute des ambiguïtés ou contradictions qui ont pu résulter de la diversité des sources, de la traduction ou tout simplement d'erreurs. La critique constructive est encouragée afin de parvenir au format et au contenu de la meilleure qualité possible.

D. Laguitton
Chef du projet SPOC,
Centre canadien de la technologie des minéraux et de l'énergie

ABSTRACT

Specific mathematical models of comminution and flotation equipment are described and the need for quantifying equipment constraints is discussed along with the limitations of each model.

The mathematical descriptions of a primary gyratory crusher, a primary jaw crusher, a secondary cone crusher, a tertiary cone crusher, a crushing rolls, an autogeneous grinding mill and a flotation cell have been converted to FORTRAN programs for subsequent use as subroutines in an executive steady state simulator.

Documentation should permit potential users to install subroutines in different computers or to translate them into languages other than FORTRAN.

RÉSUMÉ

Ce chapitre décrit les modèles mathématiques d'unités de comminution et de flottation. Le domaine de validité de chaque modèle et les limites physiques des unités y sont aussi discutés.

Les modèles mathématiques des unités suivantes ont été programmés en FORTRAN en vue de leur utilisation dans un simulateur de circuit: concasseur giratoire primaire, concasseur primaire à mâchoires, concasseur secondaire à cône, concasseur tertiaire à cône, broyeur à cylindres, broyeur autogène et cellule de flottation.

Le format utilisé devrait permettre le transfert des programmes à d'autres ordinateurs ou leur traduction en langages autres que le FORTRAN.

ACKNOWLEDGEMENTS

The SPOC project has benefited from such a wide range of contributions throughout the industry, the university, and the government sectors that a nominal acknowledgement would be bound to make unfair omissions. The main groups that contributed are: the various contractors who completed project elements; the Industrial Steering Committee members who met seven times to provide advice to the project leader; the various users of project documents and software who provided feedback on their experience; the CANMET Mineral Sciences Laboratories staff members who handled the considerable in-house task of software development, maintenance, and documentation; the EMR Computer Science Centre staff who were instrumental in some software development; and the CANMET Publications Section. Inasmuch as in a snow storm, every flake is responsible, their contributions are acknowledged.

CONTENTS

FIGURES

1. PROGRAM IDENTIFICATION

Program Titles:

Primary **G**yratory **CRUS**her
Primary **J**aw **CRUS**her
Secondary **C**one **CRUS**her
Tertiary **C**one **CRUS**her
CRu**SH**ing **RO**lls
AUT**O**genous **MILL**
FLoTation **CeL**l**S**

Program Code Names:

PGCRUS
PJCRUS
SCCRUS
TCCRUS
CRSHRO
ATMILL
FLTCLS

Program Writers:

A.L. Mular, J.S. Forsyth and J.C. Leighton, Department of Mining and Mineral Process Engineering, University of British Columbia, Vancouver, B.C., Canada, V6T 1W5.

Date:

March 1981.

Basis For Models:

PGCRUS: Proposed and fitted to plant data by A.L. Mular but based upon the mathematical description of CRSHRO and modified.
PJCRUS: A special case of PGCRUS.
SCCRUS: Modified version of the Whiten cone crusher model (1) proposed by C. Hatch (2) and C. Hatch and A.L. Mular (3).
TCCRUS: A modification of SCCRUS.
CRSHRO: Version proposed by Austin et al., (4) and slightly modified by A.L. Mular.
ATMILL: Version proposed by Gault (5) and Lynch (6).
FLTCLS: Version proposed by Bull (7) and modified slightly by J.S. Forsyth and A.L. Mular.

Updates:

All subroutines are based upon mathematical descriptions found in the literature. Modifications to original mathematical descriptions are noted in the section entitled ENGINEERING DOCUMENTATION.

Source Language:

FORTRAN Extended 4.6, complying with American National Standards Institute FORTRAN language as described in X3.9 — 1966. Versions have been implemented on the CANMET computer.

Availability:

Complete source listings are available from:
Technology Information Division,
CANMET,
Energy, Mines and Resources,
555 Booth Street,
Ottawa, Ontario,
K1A 0G1.

2. ENGINEERING DOCUMENTATION

2.1 NARRATIVE DESCRIPTION

2.1.1 Introduction

Since the advent of the digital computer, process engineers have launched ambitious projects to develop mathematical models of mineral processing equipment for various purposes with reasonable success (8). Models may be converted to computer programs which become subroutines in a flexible "mathematical flowsheet" (executive structure). The resulting simulator may be employed for many purposes (8). For example, simulators may be useful to increase process knowledge, assess circuit performance, investigate flowsheet modifications, evaluate the feasibility of a proposed flowsheet, perform off-line optimization and compare alternative control strategies.

This chapter describes the mathematical basis for specific models of comminution and flotation equipment and provides the reader with the documentation essential for understanding and transferring FORTRAN versions of corresponding models. The models will be used with the SPOC simulator (9).

2.1.2 General Basis For Comminution Models

In 1948, Epstein (10) proposed that a breakage process depends on two basic functions:

- the probability of the breakage by a machine of particles of size x;
- the size distribution of the finer fragments produced as a result of the breakage step.

Using these concepts, Broadbent and Callcott (11,12,13,14,15) developed a matrix algebra approach to describe size reduction in comminution machines. They introduced the idea of selection followed by breakage, where a comminution device is considered to select portions of narrow-size fractions of particles for breakage. Selected portions are broken according to a breakage function, such as Epstein's, while the remainder is unbroken. Thus broken fragments may leave the size range, while other fragments enter it after breakage of coarser-size fractions.

Various modifications to the above concepts have arisen over the years. For example, Gardner and Austin (16), and Meloy and Bergstrom (17), employed a time-dependent selection function (sometimes referred to as breakage rate coefficients) and considered comminution processes in a dynamic context. Lynch and Callcott (18) introduced the idea of internal classification (or "bypassing") of fragments during stages of breakage. Whiten (19) derived a comminution model which accounts for the "discharge rate" of narrow-size fractions from a comminution machine. The text by Lynch (6) and the review by Herbst et al. (20) serve as excellent summaries of progress since the pioneering efforts of Broadbent and Callcott.

In general the comminution models employed here, use the concepts of selection-followed-by-breakage. Classification and/or discharge rate arrays are introduced as necessary.

2.1.3 Basis For Flotation Cell Models

In 1942, Schuhmann (21) studied a small continuous flotation cell and established that the rate of flotation of a given pure mineral is proportional to the amount of the mineral in the cell. This observation is consistent with a first-order rate process at steady state, when conditions of perfect mixing exist. Since 1942, flotation has been viewed as a rate phenomenon (22). In 1965, Bull (23) showed that particles of different sizes have different flotation rates that depend upon cell mixing characteristics and the extent to which corresponding particles have been liberated. In other words, there is a distribution of flotation rates for a given mineral, depending upon particle size, degree of liberation and degree of hydrophobicity. Imaizumi and Inoue (24) and Loveday (25) chose functional forms that continuously distribute such properties over all particles, whereas King (26) chose discrete distributions. Furthermore, King isolated the effects of particle size and available bubble surface area in the model. A review of progress over the years is given by Woodburn et al. and by Huber-Panu et al. (27).

Flotation cell models employed here, assume that flotation is a first-order rate process. Thus, the rate of flotation of a mineral component is proportional to the amount of the component present in the cell. The constant of proportionality is a "rate coefficient" which depends on operating variables.

2.1.4 Importance of Model Constraints

A constraint is a restriction of some sort (28) and realistic models of mineral processing equipment should incorporate them. For example, the feed rate of solids to a given tertiary cone crusher must not exceed a certain value that depends on the properties of the feed and the close side set. Otherwise, either the motor overloads or the rock in the crushing chamber overflows the feed opening. A crusher model should incorporate mathematical expressions which relate the "overload" tonnage to the properties which caused the overload. These serve to warn of conditions that cannot be tolerated in actual operations. Constraint equations can be devel-

oped from empirical model building procedures (29). However, direct experimentation with industrial process units is necessary in most cases.

2.1.5 Terminology

Common terms relevant to comminution and flotation models used throughout this chapter are defined as follows:

Feed Classification Matrix: An nxn diagonal array, where elements represent the proportion of a narrow-size fraction retained for further transformation such as breakage.

Selection Function:* An nxn diagonal array, where elements represent the proportion of a narrow-size fraction selected for breakage or the proportion of a narrow-size fraction broken into finer size ranges per unit time.

Breakage Function:** An nxn lower triangular array, where elements represent the proportion of fragments appearing in size range i (row) from the instantaneous breakage of coarser-size fractions j. An array of "instantaneous" size distributions.

Size Distribution: The weight fraction or per cent of solids retained on screen size x_i.

Geometric Mean Size:** The square root of the product of two screen sizes, where screen sizes vary according to a screen ratio.

Screen Ratio: A constant that defines the variations in the linear dimension of square screen openings. Thus $xi+1 = x_i/A$, where x_i is the ith screen size and A is the screen ratio such as the square root of 2.

Mineral Species: (or component) A narrow-size fraction of particles of a given mineral such as chalcopyrite.

Flotation Rate Coefficients: The ratio of the amount of component that floats per unit time to the amount of the component in flotation cell pulp excluding froth.

Bank of Cells: Flotation cells in series. The tailing from the first cell is the feed to the second and so on.

Recovery: (based on feed to cell) The percentage of a mineral species fed to a flotation cell that appears in the float product of the cell.

Recovery: (based on feed to bank) The percentage of a mineral species fed to the first cell of a bank of cells that appears in the float product of a cell of interest. Such values are added to determine the cumulative recovery of the first k cells in a bank.

Mineral Assay: The percentage of a mineral species present in a given stream based on the total solids flow in the stream.

Feed Fractions: The percentage of a mineral species in the feed based on the total feed solids flow. The assay of mineral species in the feed to the first cell of a bank of cells.

Terminology unique to a given model is defined in the appropriate section of this chapter (see under "Methods of Solution").

2.2 METHODS OF SOLUTION

2.2.1 Primary Gyratory Crusher (PGCRUS)

2.2.1.1 Equipment characteristics

Primary gyratory crushers break run-of-mine ore from as coarse as five feet in diameter to sizes finer than about six to ten inches. Figure 1 is a schematic of a typical primary gyratory crusher. A typical plant installation is shown in Figure 2.

Trucks dump ore into a crusher pocket (Figure 2). Below the crusher is a discharge or surge pocket that serves to protect the hydrastroke feeders underneath.

Primary crushers are relatively slow-speed devices so that the size of the discharge material is about 85 per cent finer than the open side setting of the crusher. Sets may be altered by raising the mantle either hydraulically (hydraset mechanism) or mechanically (mainshaft support nut).

**If elements are time dependent, their values are not restricted between 0 and 1.*

***For many cases, it is assumed that the jth fraction broken is of geometric mean size, but fragments are distributed onto screens of size x_j.*

****Flintoff (see Chapter 5.1 in SPOC Manual) has argued that arithmetic mean size should be employed, because bias errors will be smaller.*

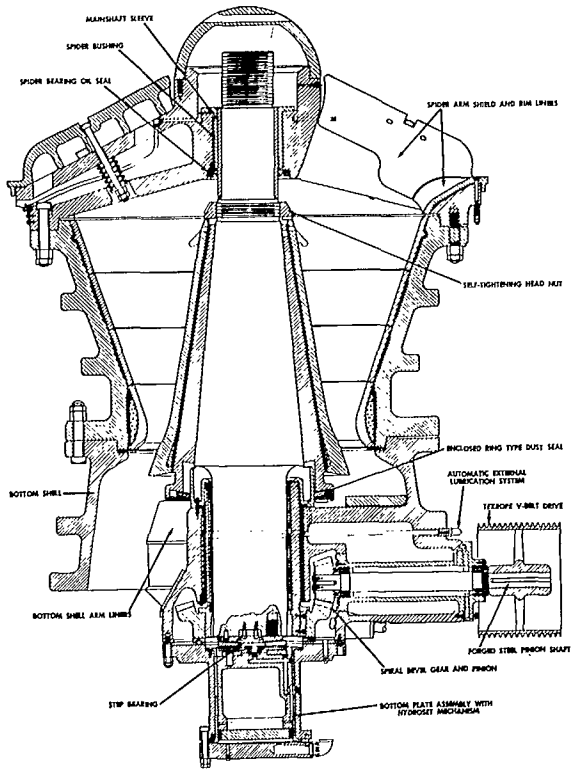


Fig. 1*— Primary gyratory crusher (30)

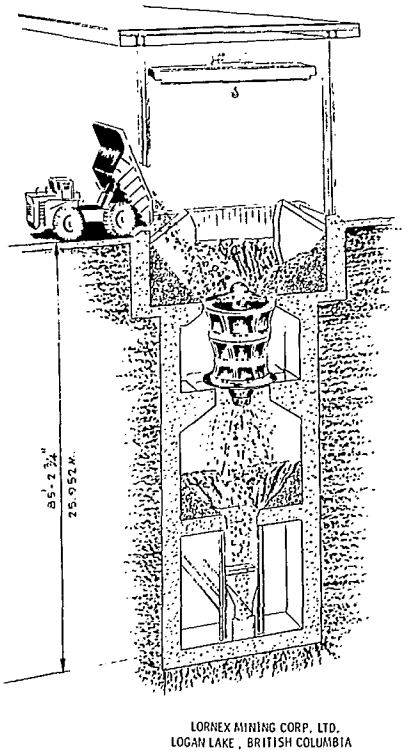


Fig. 2 — Typical installation (31)

Bond (32) maintains that the 80 per cent passing size P (in micrometres) of primary crusher discharge may be calculated from:

$$P = 25400\ S_o(.04\ W_i + .40) \qquad \text{Eq 1}$$

where S_o is the open side set (inch) and W_i (kWh/Ton) is the Bond Work Index as determined from a crushability test. Independent verification of Equation 1 would be useful.

Taggart (33) proposed that the capacity of a primary gyratory crusher is proportional to the discharge area. Thus:

$$T = k\ S_o\ (L - 3.1416\ G) \qquad \text{Eq 2}$$

where T is the average feed rate (STPH), k is a constant (about 0.75), S_o is the open side set (inch), L is the length of the outer periphery of the receiving opening (inch), and G is the gape (inch). The expression should be verified independently.

Power consumption of a primary gyratory crusher may be estimated from a combination of Equation 1 and the Bond Equation (32):

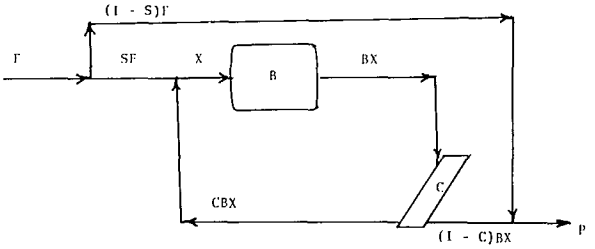
$$H = \frac{.0841\ W_i((\sqrt{R} - 1) / \sqrt{R})\ T}{\sqrt{S_o}\ \sqrt{(.04\ W_i - .4)}} \qquad \text{Eq 3}$$

where H is power consumption (HP), T is feed rate (STPH), W_i is the Bond Work Index (kWh/ton), S_o is the open side set (inch), R is the reduction ratio (F/P) and F is the 80 per cent passing size (μm) in the feed. The expression should be assessed against plant data.

2.2.1.2 Mathematical derivations

A literature search indicated that a primary gyratory crusher model had not been developed. On the basis of the concept of selection/breakage/classification, a model was formulated and fitted to data gleaned from the literature. The idea for the model was triggered by a paper on crushing rolls by Austin et al. (4).

To formulate the model, the following diagram is a useful aid.



*Courtesy of Allis Chalmers, Wisconsin

where:
- n = number of size fractions
- F = feed vector (nxl)
- S = feed classification matrix (diagonal, nxn)
- X = crusher contents vector (nxl)
- B = breakage function (lower triangular, nxn)
- C = classification after breakage matrix (diagonal, nxn)
- I = identity matrix (diagonal, nxn)
- P = product vector (nxl)

As visualized, fresh feed enters the crusher and some of it, (I − S)F, is bypassed directly to the product fraction — depending upon the open side set of the crusher. The portion not bypassed, SF, joins material CBX retained by the crusher for rebreakage to form the crusher contents X. The crusher contents are broken to form fragments BX. A portion, (I − C)BX, leaves with the bypassed fraction (I − S)F to provide product P, while an amount CBX is retained for rebreakage. The following mass balance relations can be constructed:

$$X = SF + CBX \quad (a)$$
$$P = (I-S)F + (I-C)BX \quad (b)$$

Convert (a) into $X = (I - CB)^{-1}SF$

and substitute into (b) to obtain:

$$P = (I-S)F + (I-C)B(I-CB)^{-1}SF \quad \text{Eq 4}$$

where Equation 4 is the basic primary gyratory model in matrix notation.

The elements of the breakage function matrix B are initially set to zero.

The first column of B is determined from a cumulative size distribution equation of the form:

$$y_i = 1 - (1 - (x_i/x_t)^a)^r$$

where y_i is the cumulative fraction finer than screen size x_i from the breakage of geometric mean size x_t, and a and r are constants. For example,

$$b_{11} = (1 - (x_1/x_t)^a)^r$$
$$b_{21} = (1 - (x_2/x_t)^a)^r - (1 - (x_1/x_t)^a)^r$$
. .
. .

$$b_{nl} = (1 - (x_n/x_t)^a)^r - (1 - (x_{n-1}/x_t)^a)^r$$

where b_{il} is the desired column element of B for the ith row and 1st column. Other columns of B are obtained by displacing the first column so that $b_{ij} = b_{i-1,j-1}$, j = 2,...n and i = j , j+1,..,n.

This is equivalent to the assumption that the fragments produced by breakage of a given size fraction follow the same size distribution equation after adjustment to the size of the fraction being broken. In other words, the B array has been "normalized".

Diagonal elements of S are determined from the expression $s_{ii} = 1/(1 + \exp((X_5 - X_i)/q))$, i = 1,2, ...,n; where X_5 and q are constants, $X_i = x_i/x_g$, x_i is the screen size and x_g is the open side set. Diagonal elements of C are found from a similar expression, except that X_5 and q have different values.

For computational convenience, Equation 4 was converted to a series of linear equations (linearized). The first step was to determine (I − CB) by setting (I − CB) = R, where R is nxn lower triangular. Elements of R can be determined from:

$$r_{jj} = 1 - c_{jj}b_{11} \qquad j = 1,2,..,n;\ j = i$$
$$r_{ij} = -c_{ii}b_{i-j+1,1} \qquad j = 1,2,..,n;$$
$$i = j+1, j+2,..,n;$$
$$i \neq j \neq n+1$$

For example, $r_{11} = 1 - c_{11}b_{11}$, $r_{21} = -c_{22}b_{21}$, $r_{32} = -c_{33}b_{21}$ and so on. Once R is known, a vector G (nxl) can be defined by setting $G = (I - CB)^{-1}SF$ so that (I − CB)G = SF. Use R such that RG = SF which, in linear notation, is:

$$g_1 = (s_{11}f_1)/r_{11}$$
$$g_2 = (s_{22}f_2 - r_{21}g_1)/r_{22}$$
$$g_3 = (s_{33}f_3 - r_{31}g_1 - r_{32}g_2)/r_{33}$$
. . . . . .
. . . . . .

$$g_i = (s_{ii}f_i - \sum_{j=1}^{i-1} r_{ij}g_j)/r_{ii} \qquad i = 2,3,...,n;\ j = 1,2,...,i-1$$

At this stage the product size distribution is found from the matrix expression P = (I − S)F + (I − C)BG. This is linearized to:

$$p_i = (1 - s_{ii})f_i + (1 - c_{ii}) \sum_{j=1}^{i} b_{i+1-j,1}g_j \qquad i = 1,2,...n;\ j = 1,2,...i$$

Thus:

$$p_1 = (1 - s_{11})f_1 + (1 - c_{11})b_{11}g_1$$
$$p_2 = (1 - s_{22})f_2 + (1 - c_{22})(b_{21}g_1 + b_{11}g_2)$$
$$p_3 = (1 - s_{33})f_3 + (1 - c_{33})(b_{31}g_1 + b_{21}g_2 + b_{11}g_3)$$
. . . .
. . . .

where p_i represents the weight per cent retained on size x_i in the product. Alternative methods to linearize Equation 4 were explored, but in each case an array had to be inverted. Consequently, the above forms were judged acceptable.

2.2.1.3 Constraints

Constraints on capacity, open side set and power consumption could not be developed with the limited data

available. Obviously, there is an upper limit on power consumed relative to that drawn by an empty crusher. Likewise, an upper limit must exist on throughput. In the absence of more quantitative information, caution must be exercised during a simulation not to exceed nominal power and capacity quoted by equipment suppliers. Power may be estimated from Equation 3, while capacities are available from tables supplied by manufacturers. Both power draw and throughput must be heavily dependent upon open side set, chamber design, speed, throw and the hardness and size distribution of the feed.

There must be a lower limit on open side set, because suppliers stress that the mechanical reduction ratio of a primary crusher should not exceed about 7. Hence, if x_f is the crusher gape, the open side set should not be less than around 1/7 of x_f. Capacity tables usually show the nominal capacity of a given crusher at various open side settings. When a capacity is not shown for a given set, the corresponding set is not recommended.

2.2.1.4 Limitations

The primary gyratory crusher model is severely limited, for it does not incorporate either design variables (other than open side set) or variables associated with the feed (e.g., ore hardness and feed rate). Moreover, constraints have not been incorporated into the model.

Ore hardness may influence the product size distribution, because the breakage function, the feed classification array and the classification after breakage array may be affected. Changes in feed rate may have similar influences. To resolve the problem, experiments on plant units should be conducted.

Presumably, these factors have been "optimized" by suppliers.

The assumptions that (a) the breakage function can be normalized and that (b) s-elements and c-elements can be calculated as discussed in the mathematical derivation must be verified experimentally.

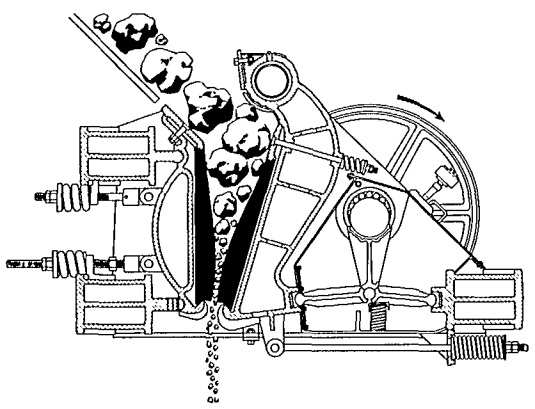


Fig. 3 — Primary jaw crusher (30)

2.2.2 Primary Jaw Crusher (PJCRUS)

2.2.2.1 Equipment characteristics

Primary jaw crushers are employed in situations where relatively low tonnages are to be treated. Their head room is less, and their ability to handle awkward lumps is an advantage. Of course, feed must be scalped for proper operation, thereby avoiding such problems as chamber packing. Figure 3 is a section of a typical double toggle jaw crusher, and Figure 4 shows a typical installation. Sets are normally altered by insertion of shims between the rear toggle and a support plate.

Bond (32) suggests that Equation 1 may be used to estimate the 80 per cent passing size for primary jaw crushers. This should be verified experimentally.

Rose and English (34) have proposed that the capacity of a jaw crusher can be determined from the expression:

$$T = 285(N/N_c)bw\ \sqrt{t}(S+t/2)\ \sqrt{(R/R-1)}\ d(1+10.9\ \exp(-90(t/G)))\phi(a) \qquad \text{Eq 5}$$

where T is capacity* (LTPH), N is speed (r/min), N_c is the speed (r/min) above which throughput decreases, S is close side set (ft), t is throw (ft), R is mechanical reduction ratio (gape/close side set), G is gape (ft), ø(a) is a function of [(maximum feed size — minimum feed size)/mean feed size], and b is a constant with a value of 1.05 for trap rock, 0.95 for granite and 0.55 for coal. ø(a) values are obtained from a table and vary between 0.4 for coarse feeds and 0.88 for finer feeds. Crusher widths w were not reported.

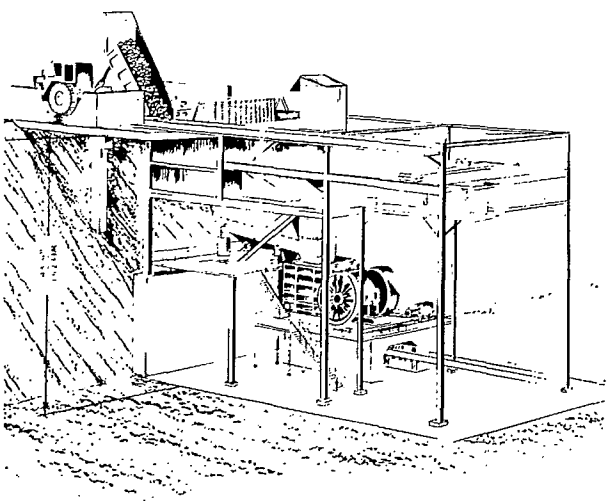


Fig. 4 — Typical installation (31)

*Long tons per hour = 2200 lb/h.

**Courtesy of Pennsylvania Crusher Corp., Broomall, PA.

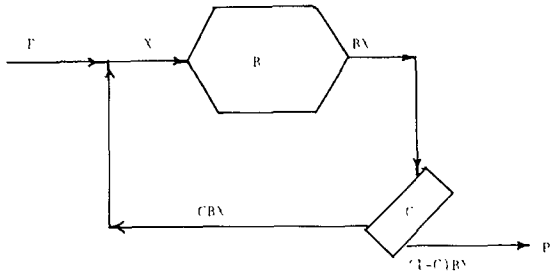
The power to install on a jaw crusher may be calculated from (34):

$$H = .0281W_iT((\sqrt{G} - 1.07\sqrt{(S+t)})/(\sqrt{G}\sqrt{(S+t)})) \quad \text{Eq 6}$$

where W_i is the Bond Work Index (HpHr/LT) and H is the motor horsepower.

2.2.2.2 Mathematical derivations

Although a primary jaw crusher model has been developed for coal (35), it seemed more reasonable to consider a jaw crusher as a special case of the primary gyratory crusher. The feed to a jaw crusher must be scalped for effective operation. Consequently, the following diagram was modified to accommodate the idea of a screened feed.



Because X = F + CBX and P = (I − C)BX, the product may be predicted from the expression:

$$P = (I - C)B(I - CB)^{-1}F \quad \text{Eq 7}$$

(See Section 2.2.1.2 for a definition of all terms.)

Note that this is equivalent to Equation 4 when S is an identity matrix.

To calculate b-elements in B and c-elements in C, the procedure shown in Section 2.2.1.2 was used, although the values of the constants a, r, X_5 and q were not the same. Likewise, the technique to linearize Equation 7 follows that employed for the primary gyratory crusher but with s-elements equal to 1. Accordingly, the product size distribution is determined from:

$$p_i = (1 - c_{ii}) \sum_{j=1}^{i} b_{i+1-j,1}g_j \qquad \begin{matrix} i = 1,2,...,n \\ j = 1,2,...,i \end{matrix}$$

$$p_1 = (1 - c_{11})b_{11}g_1$$

$$p_2 = (1 - c_{22})(b_{21}g_1 + b_{11}g_2)$$

$$p_3 = (1 - c_{33})(b_{31}g_1 + b_{21}g_2 + b_{11}g_3)$$

. . . .

. . . .

The primary jaw crusher model was fitted with reasonable success to data obtained from literature.

2.2.2.3 Constraints

Jaw crusher constraints on power consumption, capacity and open side set have not been formulated from experimental data. However, Rose and English (34) argue that below a critical speed (above this speed the capacity varies inversely with speed), the maximum theoretical volume flow rate of feed V depends on:

$$V = 120Nwt(S + t/2)(R/(R - 1))$$

where V has the units ft^3/stroke; other symbols have been defined. The expression might serve as an upper limit on capacity. Alternatively, Equation 5 may be adequate for this purpose.

Equations 5 and 6 may be combined to express power as a function of speed, design variables and feed characteristics. The resulting expression might well serve as an upper limit on power consumption.

In the absence of a quantitative expression, the open side set should not be much less than 1/7 of the crusher gape. This conforms with rough rules employed by manufacturers.

2.2.2.4 Limitations

The jaw crusher model is limited, because design variables (other than open side set), operating variables and constraints have not been incorporated into the model. How these influence the breakage function and the classification matrix is uncertain. In particular, the effects of scalping screen size, feed rate and ore hardness on the predicted product size distribution should be determined. Although the study by Rose and English (34) provides some clues, considerable experimental effort must be expended to develop a better model.

2.2.3 Secondary Cone Crusher (SCCRUS)

2.2.3.1 Equipment characteristics

Secondary cone crushers are fed with primary crusher discharge for reduction to sizes less than about 2 or 3 inches. Figure 5 shows a typical cone crusher, where the close side set is adjusted by means of an air hammer or manually (Nordberg cone crusher). Alternatively, the set may be adjusted hydraulically (Allis-Chalmers hydrocone crusher). A typical installation is shown in Figure 6.

According to Bond (32), the 80 per cent passing size P (in μm) in cone crusher discharge may be determined from:

$$P = (25400S(7t)(.02W_i + .7))/(7t - 2S) \quad \text{Eq 8}$$

where S is close side set (inch), t is throw (inch), and W_i is the Bond Work Index (kWh/ton). This relationship should be verified.

A capacity relationship for a secondary cone crusher could not be formulated with certainty. However, Nordberg capacity tables (36) were evaluated for a 2-ft standard cone crusher in open circuit. The data were fitted to:

$$T = 20 - 10\,(S_m/S_o) + 2.6(S_m/S_o)S(D/2 + S) \qquad \text{Eq 9}$$

where T is feed rate (STPH), S_m is the recommended minimum discharge setting (inch) that is listed for the type of cavity, S_o is the recommended minimum discharge setting (inch) for the fine cavity, S is close side set (inch) and D is the diameter (inch) of the mantle at the discharge annulus. It is not known whether this expression will fit data shown for other crusher sizes; the constants may differ.

The Bond Equation (32) may be combined with Equation 8 so that:

$$H = .0318TW_i((\sqrt{R-1})/\sqrt{R})(\sqrt{7t\text{-}2S})/(\sqrt{St(.02W_i + .7)}) \qquad \text{Eq 10}$$

where H is the power consumption (Hp). Equation 10 should be independently verified.

An alternative expression that relates current draw to operating parameters is of the form (2,3):

$$A = b_o + b_1T + b_2G \qquad \text{Eq 11}$$

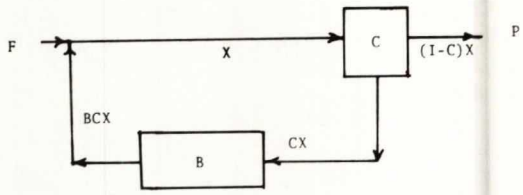
where A is current draw (A) at approximately 4.16 kV, T is feed rate (STPH), and G is close side set (cm).

2.2.3.2 Mathematical derivations

Two models were available in the literature, one developed by Whiten (1) and a modification of the Whiten model proposed by Hatch and Mular (2,3) that is currently under revision (38).

The Whiten model could not be fitted to data acquired in a crushing plant (2) so it was modified. The modified version has been used for this chapter, although a greatly simplified model (38) will be incorporated in a future update.

The Whiten model is best described by referring to the following diagram.



where:
- F = feed size distribution vector (nxl)
- X = crusher contents vector (nxl)
- P = product size distribution vector (nxl)
- C = classification (before breakage) array (diagonal, nxn)
- B = breakage function (lower triangular, nxn)

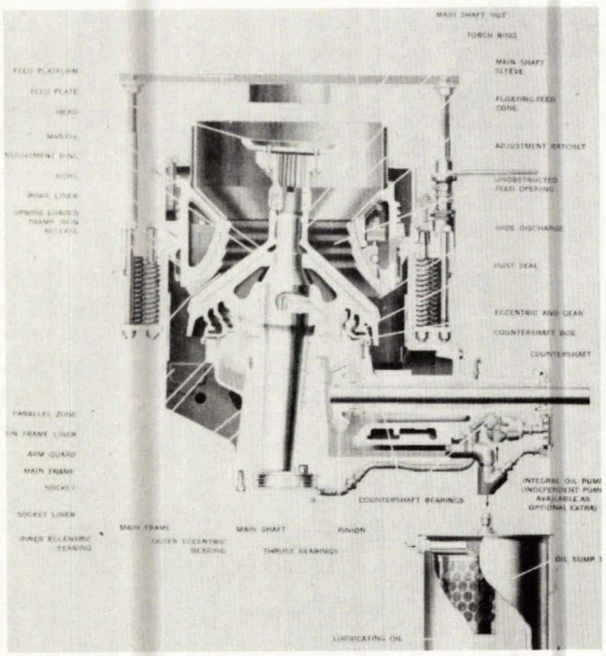


***Fig. 5**— Secondary cone crusher (36)*

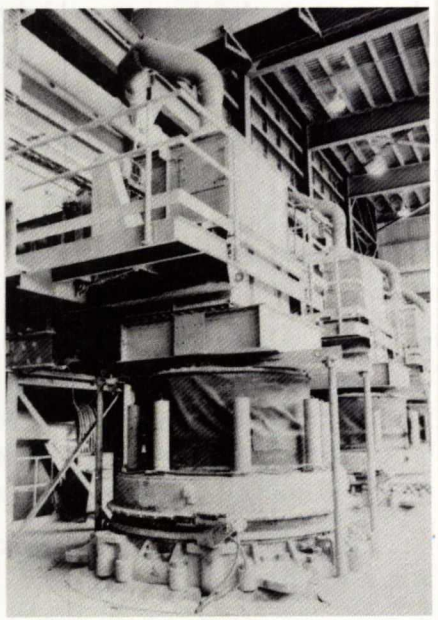


Fig. 6 — Typical installation (37)

*Courtesy of Nordberg Manufacturing

From this diagram the following mass balance relationships are obtainable: $F + BCX = X$ and $X = CX + P$. Combining these provides the basic cone crusher model written:

$$P = (I - C)(I - BC)^{-1}F \qquad \text{Eq 12}$$

To calculate B, Whiten (1) assumed that both compression (impact) and abrasion breakage events take place in a crushing chamber. If B_1 is the impact breakage array (lower triangular, nxn) and B_2 is the abrasion breakage array (lower triangular, nxn), then B can be assumed to be a linear combination of the two so that:

$$B = \alpha B_1 + (1 - \alpha)B_2$$

The term α is empirically related to operating variables (2,3) such that:

$$\alpha = d_o + d_1G + d_2T + d_3S,$$

where d_o, d_1, d_2 and d_3 are constants, G is close side set (cm), T is feed rate (STPH) and S is the per cent +2.72 cm material in the feed. Elements of B_1 are determined (2,3) from a size distribution equation of the form:

$$y_i = 1 - (1 - (X_i/X_t)^a)^r$$

in a manner identical with that already described in Section 2.2.1.2; of course, constants a and r will be different. First column elements of B_2 are found (2,3) from a Rosin-Rammler type size distribution (Y_i is cumulative fraction coarser)*:

$$Y_i = \exp(-X_i/u)^v)$$

For example, $_2b_{11} = \exp(-(X_1/u)^v)$

$_2b_{21} = \exp(-(X_2/u)^v) - \exp(-(X_1/u)^v)$

$_2b_{31} = \exp(-(X_3/u)^v) - \exp(-(X_2/u)^v)$

and so on.

Once $_2b_{il}$ values have been calculated, the other columns may be determined as follows:

$$B_2 = \begin{bmatrix} {}_2b_{11} & 0 & 0 & \cdots & 0 \\ {}_2b_{21} & {}_2b_{11} + {}_2b_{21} & 0 & \cdots & 0 \\ {}_2b_{31} & {}_2b_{31} & {}_2b_{11} + {}_2b_{21} + {}_2b_{31} & \cdots & 0 \\ {}_2b_{41} & {}_2b_{41} & {}_2b_{41} & \cdots & 0 \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & \cdot & & \cdot \\ {}_2b_{nl} & {}_2b_{nl} & {}_2b_{nl} & & {}_2b_{11} + {}_2b_{21} + \ldots + {}_2b_{nl} \end{bmatrix}$$

Elements of B are then calculated as:

$b_{11} = \alpha(_1b_{11}) + (1 - \alpha)_2b_{11}$

$b_{21} = \alpha(_1b_{21}) + (1 - \alpha)_2b_{21}$

$b_{31} = \alpha(_1b_{31}) + (1 - \alpha)_2b_{31}$

$b_{nl} = \alpha(_1b_{nl}) + (1 - \alpha)_2b_{nl}$

$b_{12} = 0$

$b_{22} = \alpha(_1b_{11}) + (1 - \alpha)(_2b_{11} + {}_2b_{21})$

$b_{32} = \alpha(_1b_{21}) + (1 - \alpha)_2b_{31}$

$b_{n2} = \alpha(_1b_{n-1,1}) + (1 - \alpha)_2b_{nl}$

$b_{13} = 0$

$b_{23} = 0$

$b_{33} = \alpha(_1b_{11}) + (1 - \alpha)(_2b_{11} + {}_2b_{21} + {}_2b_{31})$

$b_{43} = \alpha(_1b_{21}) + (1 - \alpha)_2b_{41}$

$b_{n3} = \alpha(_1b_{n-2,1}) + (1 - \alpha)_2b_{nl}$

and so on.

To calculate c-elements, Whiten (1) argues that below a certain size k_1, $c_{ii} = 0$ for $X_i < k_1$; above a certain size k_2, $c_{ii} = 1$ for $X_i > k_2$. For $k_1 \leq X_i \leq k_2$, the assumption was made that c_{ii} could be determined from:

$$c_{ii} = \frac{\int_{X_{i+1}}^{X_i} (1 - (X - k_2)^2/(k_1 - k_2)^2)dX}{X_i - X_{i+1}}$$

Note that u and v are constants in the equation.

Upon rearranging and integrating by parts:

$$c_{ii} = \frac{(X_i - (X_i - k_2)^3/(3(k_1 - k_2)^2)) - (X_{i+1} - (X_{i+1} - k_2)^3/(3(k_1 - k_2)^2))}{X_i - X_{i+1}}$$

which is used to determine c_{ii} for $k_1 \leq X_i \leq k_2$ with k_1 and k_2 being functions of operating variables such that (2,3):

$$k_1 = m_o + m_1 G + m_2 G^2 + m_3 S$$

$$k_2 = n_o + n_1 G + n_2 G^2 + n_3 S$$

The symbols m_o, m_1, m_2, m_3, n_o, n_1, n_2 and n_3 are constants for the particular crusher.

Crusher current is calculated from Equation 11, although alternative forms are available (3).

For convenience, Equation 12 has been linearized in parts that were finally combined to calculate P, the product size distribution vector. Thus, the linear form of $X = F + BCX$ is:

$$x_1(1 - b_{11}c_{11}) = f_1$$

$$x_i(1 - b_{ii}c_{ii}) = f_i + \sum_{j=1}^{i-1} b_{ij}c_{jj}x_j \qquad \begin{matrix} i = 2,3,...,n \\ j = 1,2,...,i-1 \end{matrix}$$

(Note that small x denotes elements of X.)

For example:

$$x_2(1 - b_{22}c_{22}) = f_2 + b_{21}c_{11}x_1$$

$$x_3(1 - b_{33}c_{33}) = f_3 + b_{31}c_{11}x_1 + b_{32}c_{22}x_2$$

...and so on.

Since b-elements are a linear combination of B_1 and B_2, they can be calculated from:

$$b_{ij} = \alpha({}_1b_{i+1-j,1}) + (1 - \alpha)_2 b_{ii} \qquad 1 \neq j$$

$$b_{ii} = \alpha({}_1b_{11}) + (1 - \alpha) \sum_{j=1}^{i} {}_2b_{j1} \qquad i = j$$

Using the above formations,

$$x_1 = \frac{f_1}{1 - (\alpha({}_1b_{11}) + (1-\alpha)_2 b_{11})c_{11}}$$

.

.

.

$$x_i = \frac{f_i + \sum_{j=1}^{i-1} (\alpha({}_1b_{i+1-j,1}) + (1 - \alpha)_2 b_{ii})c_{jj}x_j}{1 - (\alpha({}_1b_{11}) + (1 - \alpha) \sum_{j=1}^{i} {}_2b_{j1})c_{ii}} \qquad i = 2,3,...,n$$

The above expression can save computation time, since matrix inversion is not involved.

The linear form of $P = (I - C)X$ is written:

$$p_i = (1 - c_{ii})x_i \qquad i = 1,2,...,n$$

which is used to predict the weight per cent retained, p_i, on each size X_i.

2.2.3.3 Constraints

Constraints on power consumption, capacity and close side set have not been clearly formulated, although Equations 9 and 10 may be useful in this regard. However, most crusher motors are equipped with thermal overloads so that the current draw expression (Equation 11) may be used as a warning that the feed rate at a given close side set has caused the predicted current draw to exceed the overload setpoint. For a 7-ft standard cone crusher driven by a 300-HP motor, a typical overload current (if sustained) is around 70 A at 4.16 kV. An alternative expression for current draw (3) incorporates an "operating" work index and thus serves to warn that either feed rate or ore hardness has changed such that the predicted current draw exceeds the overload setpoint.

Crusher manufacturers have stressed that the mechanical reduction ratio of a secondary cone crusher should not exceed about 5. However, this depends heavily upon chamber design, so that capacity tables which show recommended close side sets should be consulted.

A capacity constraint to warn that the crushing chamber is overflowing (despite low current draw) is highly desirable. This requires experimental study in an operating plant.

2.2.3.4 Limitations

The secondary cone crusher model does not incorporate design variables such as cavity type, speed, throw and mantle diameter. Moreover, a capacity constraint is not available. The model was developed for a 7-ft standard cone crusher. Extrapolation to other sizes is hazardous. Approximate ranges for operating variables incorporated in the model are as follows: crusher close side set between 2.5 and 3.8 cm, feed rate between 635 and 789 STPH, per cent +2.72 cm in crusher feed between 75% and 94% and current draw between 18 and 32 A.

2.2.4 Tertiary Cone Crusher (TCCRUS)

2.2.4.1 Equipment characteristics

Tertiary cone crushers are used to reduce secondary crusher discharge to sizes less than about 0.5 to 0.75 inch. Usually, a tertiary crusher resembles a sec-

ondary crusher, but is different in speed, throw and type of cavity. Figure 7 shows the difference in cavity designs for Nordberg secondary and tertiary crushers.

Bond (32) suggests that the 80 per cent passing size may be calculated from Equation 8. However, this should be independently verified.

A capacity equation for tertiary crushers is not available, although an empirical expression, such as Equation 9, may be obtainable from manufacturers' tables.

Power consumption may be estimated from Equation 10; the expression, however, should be verified independently.

Current draw is related to feed rate and close side set in accordance with Equation 11, although the constants in the equation are different.

2.2.4.2 Mathematical derivations

The tertiary cone crusher model is similar to that developed for the secondary cone crusher shown in Section 2.2.3 with the following differences:

- The value of α in $B = \alpha B_1 + (1 - \alpha)B_2$ is found from:

$$\alpha = a_o + a_1 T + a_2/(1 + a_3(T - a_4)^2)$$

where a_o, a_1, a_2, a_3 and a_4 are constants.

- The value of r in $y_i = 1 - (1 - (X_i/X_t)^a)^r$ is determined from:

$$r = c_o + c_1 \exp(-c_2 \alpha^c)$$

where c, c_o, c_1 and c_2 are constants. Also, the value of a is different.

- The values of k_1 and k_2 are calculated from:

$$k_1 = u_o + u_1 S$$
$$k_2 = v_o + v_1 G + (v_2/(1 + v_3(G - v_4)^2))^v$$

where u_o, u_1, v, v_o, v_1, v_2, v_3 and v_4 are constants.

The complex relationships between constants of the model and operating variables will be greatly simplified in a future update of this model (38).

2.2.4.3 Constraints

Constraints on power consumption, capacity and close side set are not well formulated. However, Equation 11 may serve to warn that the feed rate is such that the thermal overload setpoint (related to current draw) is being exceeded. The setpoint is about 60 A at 4.16 kV for a 7-ft short head cone crusher (300 HP). An alternative current draw expression (3) can warn that a combination of feed rate and "ore hardness" is creating excessive current draw.

A capacity constraint is currently under development (38) and may be incorporated in a subsequent update of the model.

Equations 9 and 10 are useful for estimating nominal power draw and capacity. Alternatively, tables provided by manufacturers may be consulted. Capacity should not greatly exceed table values for a given close side set and crusher size.

2.2.4.4 Limitations

Important design variables which include cavity type, speed, throw and mantle diameter have not been incorporated into the model. The model was developed for a 7-ft short head cone crusher equipped with a 300-HP motor at 4.16 kV. Ranges for operating variables are: close side set from 0.5 to 1.1 cm, feed rate from 221 to 421 STPH and per cent +2.72 cm material in the feed from 44% to 77%.

Complex relationships between model constants and operating variables will be eliminated in a future update.

2.2.5 Crushing Rolls (CRSHRO)

2.2.5.1 Equipment characteristics

Crushing rolls are best considered to be either tertiary or quaternary crushers in the base metals industries, and

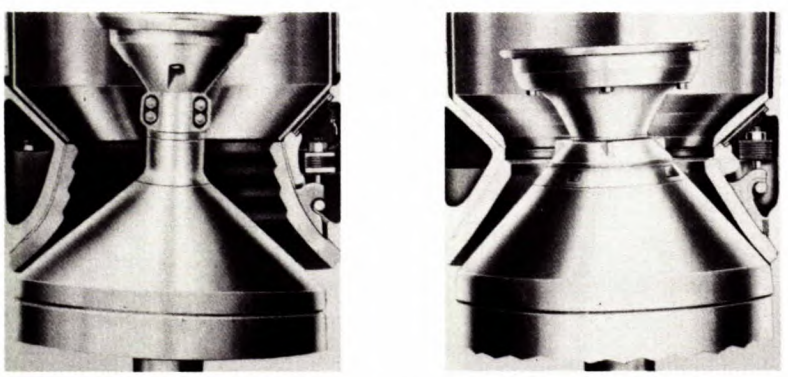
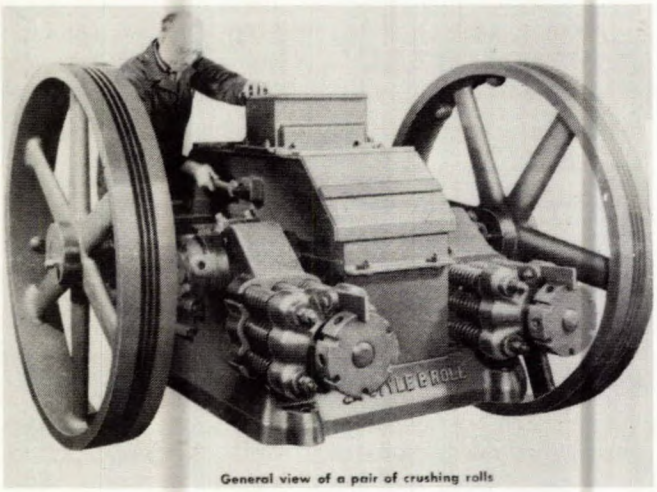


Fig. 7*— Gravity differences between secondary and tertiary crusher (36)

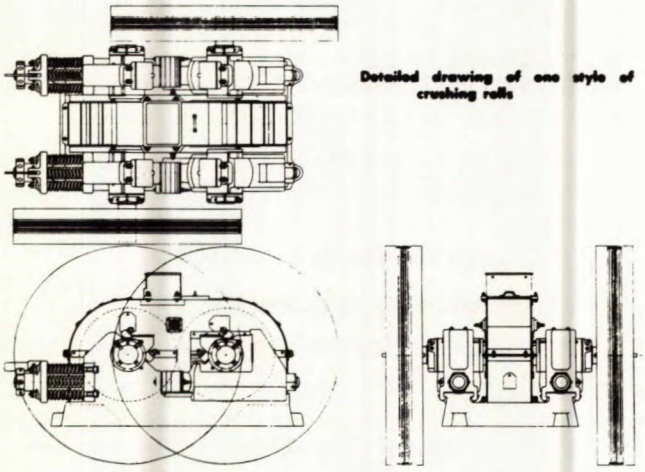
*Courtesy of Nordberg Manufacturing

will not serve as primary crushers. Figure 8 shows both a plan drawing and a photograph of a crushing rolls. Feed may be as coarse as 10 cm and products as fine as 0.2 cm may be produced. Sets are adjusted by insertion of shims which cause movable bearings on one of the rolls to slide horizontally closer to the other rolls.

A relationship between product 80 per cent passing size and mechanical design variables of crushing rolls could not be found in a literature search. Such a relationship should depend upon crusher set, packing and feed size distribution.



General view of a pair of crushing rolls



Detailed drawing of one style of crushing rolls

Fig. 8*— Crushing rolls with plan view (30)

The capacity of a crushing roll that has been properly sized for the feed to it is given by (39,30):

$$T = KNDwSd \qquad \text{Eq 13}$$

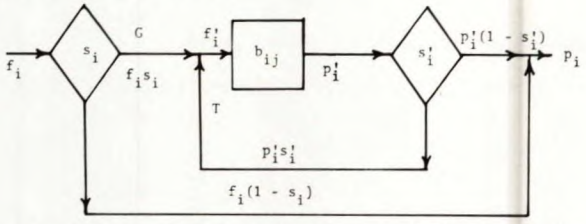
where K = .00131 (heavy duty) or K = .00111 (light/medium duty), N = speed (r/min), D = roll diameter (inch), w = roll length (inch), S = set (inch) and d = specific gravity of the feed. In the above, T is in STPH. It should be noted that if x_t is the top size of feed, the recommended roll diameter that causes particles to be nipped must be such that:

$$(D/(x_t - S)) \geq 40$$

A relationship between power consumption and design variables was not found in literature. However, approximately 1 HP is drawn per unit of throughput (STPH) for hard material (30). For soft material this is reduced by as much as 50 per cent. Roughly, the power consumption is proportional to the reduction ratio.

2.2.5.2 Mathematical derivations

Austin et al. (4) have formulated a crushing rolls model that appears reasonable. The following diagram shows the essential features.



The symbols used in this diagram are defined as follows (4):

- f_i = feed fraction in size i
- s_i = fraction of f_i broken
- f_i' = effective feed fraction in size i to breakage process
- p_i' = product fraction in size i after breakage
- s_i' = fraction of p_i' broken
- p_i = final product fraction in size i
- b_{ij} = ij element of the breakage function

Austin et al. (4) argue that breakage leads to material smaller than the particular size range of interest. Material that remains within the size range after passing through the rolls is considered material that is unbroken (bypassed). Fragments produced from breakage but larger than the crusher gap can, in turn, be either bypassed or retained for rebreakage.

Based on unit mass of feed, the mass of size i from the breakage process is p_i^*,

where:

$$p_1^* = 0$$
$$p_2^* = b_{21}(p_1^* s_1' + f_1 s_1)$$
$$p_3^* = b_{31}(p_1^* s_1' + f_1 s_1) + b_{32}(p_2^* s_2' + f_2 s_2)$$
$$p_4^* = b_{41}(p_1^* s_1' + f_1 s_1) + b_{42}(p_2^* s_2' + f_2 s_2) + b_{43}(p_3^* s_3' + f_3 s_3)$$
$$\vdots$$
$$p_i^* = \sum_{j=1}^{i-1} b_{ij}(p_j^* s_j' + f_j s_j) \qquad i = 2,3,\ldots,n; \quad i > j$$

*Courtesy of Allis Chalmers, Wisconsin

Note that each p_i^* is evaluated sequentially starting with p_1^* to determine p_2^*. Both are employed to determine p_3^* and so on. When feed mass is unity, a mass balance around the final product node is written (4):

$$p_i = f_i (1 - s_i) + p_i^*(1 - s_i') \qquad i = 1,2,...,n$$

where p_i is the weight fraction of final product of size i. An alternative to the expression is written (4):

$$p_i = f_i (1 - s_i) + p_i'(1 - s_i') \sum_{j=1}^{n} p_j^*$$

where $p_i' = p_i^*/(\sum_{j=i}^{n} p_j^*)$

in which the sum over n of the p_j^* represents the total mass of material that enters the breakage process.

To determine b_{i1} elements**, the following expressions were used (4):

$$b_{11} = 0$$

$$b_{il} = (m(x_{i-1}/x_1)^v + (1\text{-}m)(x_{i-1}/x_1)^r) - (m(x_i/x_1)^v + (1\text{-}m)(x_i/x_1)^r)$$

for i = 2,3,...,n.

Once b_{i1} elements are known, all others can be determined from $b_{ij} = b_{i-1,j-1}$ for j = 2,...,n and i = j,j+1,...,n.

This *normalization* technique means that:

$$p_1^* = 0$$

.

.

$$p_i^* = \sum_{j=1}^{i-1} b_{i-j+1,1}(p_j^* s_j' + f_j s_j) \qquad i = 2,3,...,n \quad i > j$$

Hence, only b_{i1} elements are used in the calculation.

Austin et al. (4) experimentally measured s_i elements and fitted them to a log-normal equation as a function of x_i/x_g, where x_i represents size range i, and x_g is the crusher gap (set). As an alternative, s_i values were fitted to the equation:

$$s_i = 1/(1 + \exp((x_5 - (x_i/x_g))/k))$$

where x_5 and k are constants. The fit was judged to be satisfactory.

Values of s_i' were calculated as $s_1' = 1$, $s_i' = s_{i-1}$ for i = 2,3,...,n based on Austin's experimental observation that this is a good approximation.

2.2.5.3 Constraints

Constraints on throughput, power consumption and set are not experimentally available. However, when N, D, w, S and d are known, Equation 13 can be useful for estimating a nominal capacity which should not be exceeded to any great extent.

Given the top size of feed x_t and the roll diameter D, crushing rolls will not nip the particle x_t, if the set S is much less than (x_t – D/40). Hence, this defines a minimum value for the set.

A power constraint must be determined by direct experimentation. Presumably, most crushing rolls have adequately sized motors, so that power draw may depend primarily on set, feed rate, ore hardness and speed.

2.2.5.4 Limitations

The crushing rolls model does not incorporate the influence of operating variables (other than set) and design variables on model constants such as b_{ij}, s_i and s_i'. Such factors as feed rate, ore hardness and speed may or may not affect the product size distribution.

A relationship between power consumption and design variables would be useful when a simulator is employed for design purposes. Most likely, the expression will bear some similarity to a constraint on power consumption.

Clearly, considerable experimental effort is still necessary to develop an adequate crushing rolls model. Data used here were taken from Austin et al. (4).

2.2.6 Autogenous Mill (ATMILL)

2.2.6.1 Equipment characteristics

Autogenous mills are cylindrically shaped grinding machines that rotate at speeds of up to 79 per cent of the critical speed. They reduce primary crusher discharge to sizes smaller than about 2 inches or finer. The mill does not contain artificial grinding media such as steel balls or rods. Rather, the feed degrades by itself because of the tumbling action imparted to the mill load by inside lifters. Pebble mills resemble ball and rod mills in appearance with diameter-to-length ratios of 1 or less, while cascade mills have diameter-to-length ratios of 2 to 3. Figure 9 shows a typical autogenous mill installation of the cascade type with a diameter of 9.75 m and a length of 4.72 m. The mill is driven by two motors, each of 4000 HP; it has a grate discharge.

***It should be noted that m, v and r are constants for a given material.*

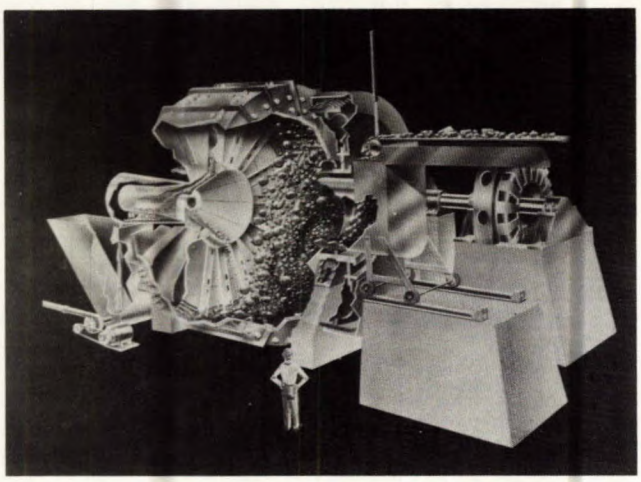


Fig. 9*— Autogenous mill illustration (40)

Bond (32) suggests that the 80 per cent passing size P (in μm) in autogenous mill discharge can be estimated from the Bond Equation when written as:

$$P = (13.4W_iT\sqrt{F}/(1 + H\sqrt{F}))^2 \qquad \text{Eq 14}$$

where W_i is the Bond work index (kWh/ton), $\sqrt{F}$ is the 80 per cent passing size (μm) in the feed, H is the power draw (HP), and T is the throughput (STPH). It is known that this is a crude approximation for autogenous mills.

MacPherson and Turner (41) recommend that the 80 per cent passing size of primary crusher discharge fed to an autogenous mill be calculated from:

$$F = 0.95D^{.667}$$

where D is the mill diameter (inside the shell) in feet.

The gross power, P_c (kW), required to drive the mill may be estimated from the Bond Equation (32) or from:

$$P_c = 1.05P_t(L_c/L_t)(D_c/D_t)^{2.65} \qquad \text{Eq 15}$$

where P_t is the net power (kW) drawn by a test mill, L_c and D_c are the length and diameter of a commercial mill, and L_t and D_t are the length and diameter of a test mill (41). Charge levels should be between 25 and 30 per cent of mill volume.

Nominal capacity, T_c (STPH), can be estimated from (41):

$$T_c = 0.9P_cT_c/P_t \qquad \text{Eq 16}$$

where T_c (STPH), is the capacity of a test mill at a net power draw of P_t (kW).

2.2.6.2 Mathematical derivations

Whiten (19) proposed a model of a comminution machine which is ideal for perfectly mixed grate discharge mills of the cascade type. The basic model was used by Gault (5) and Lynch (6).

Whiten showed that the change in the mill contents size distribution vector M with respect to time could be expressed as:

$$\frac{dM}{dt} = BKM + F - KM - DM \qquad \text{Eq 17}$$

where:
- M = mill contents size distribution vector (nxl)
- F = feed size distribution vector (includes recycle streams) (nxl)
- P = product size distribution vector (nxl)
- K = diagonal, selection function array (nxn)
- B = lower triangular, breakage function array (nxn)
- D = diagonal, discharge rate array (nxn)

In Equation 17, BKM is the rate at which material appears after breakage, KM is the rate at which fragments are broken out of size ranges, and DM = P is the rate at which corresponding weight fractions are discharged from the mill.

Equation 17 was placed at steady state and the relationship P = DM was used. Thus:

$$\frac{dM}{dt} = 0 = BKM + F - KM - P$$

or
$$F - P = KM - BKM = (I - B)KM$$

But $M = D^{-1}P$ so that $F - P = (I - B)KD^{-1}P$, which can be rearranged to:

$$P = DK^{-1}(I - B)^{-1}(F - P) \qquad \text{Eq 18}$$

Now define $Q = (I - B)^{-1}(F - P)$, which means that Equation 18 can be rewritten as:

$$P = DK^{-1}Q \qquad \text{Eq 19}$$

and

$$(I - B)Q = (F - P) \qquad \text{Eq 20}$$

Equations 19 and 20 represent the basic autogenous mill model employed in this chapter. An alternative has been studied on a laboratory scale by Austin et al. (42).

*Courtesy of MINERAL PROCESSING SYSTEMS, INC.

Equations 19 and 20 were converted to a series of linear equations (i.e., linearized) that permit the calculation of q-elements and the product size distribution. The linearized form of Equation 20 is:

$$
\begin{aligned}
f_1 - p_1 &= (1-b_{11})q_1 \\
f_2 - p_2 &= (1-b_{22})q_2 - b_{21}q_1 \\
f_3 - p_3 &= (1-b_{33})q_3 - b_{31}q_1 - b_{32}q_2 \\
f_4 - p_4 &= (1-b_{44})q_4 - b_{41}q_1 - b_{42}q_2 - b_{43}q_3 \\
&\ \ \vdots \qquad\qquad \vdots \qquad\qquad \vdots \qquad\qquad \vdots \\
f_i - p_i &= (1-b_{ii})q_i - \sum_{j=1}^{i-1} b_{ij}q_j \qquad \begin{matrix} i = 2,3,\ldots,n \\ j = 1,2,\ldots,i-1 \end{matrix}
\end{aligned}
$$

Eq 21

In linear equation form, final product elements p_i are found from the expression $p_i = (d_i/k_i)q_i = r_iq_i$, where d_i and k_i are the ii elements of D and K respectively, and $r_i = (d_i/k_i)$.

Since $q_i = p_i/r_i$ and $q_j = p_j/r_j$, Equation 21 may be rearranged and solved for p_i so that:

$$
\begin{aligned}
p_1 &= r_1f_1/(1 + r_1 - b_{11}) \\
p_2 &= (r_2f_2 + (r_2/r_1)b_{21}p_1)/(1 + r_2 - b_{22}) \\
&\ \ \vdots \qquad\qquad \vdots \qquad\qquad \vdots \\
p_i &= (r_if_i + \sum_{j=1}^{i-1} (r_i/r_j)b_{ij}p_j)/(1 + r_i + b_{ii}) \qquad \begin{matrix} i = 2,3,\ldots,n \\ j = 1,2,\ldots,i-1 \end{matrix}
\end{aligned}
$$

Eq 22

Equation 22 may be used to predict the weight per cent of size i in the mill discharge when f_i, b_{ij}, and r_i are known.

Gault (5) sampled a 9.75 m diameter by 3.7 m length cascade mill with 16-mm grate openings and driven by two 2250-HP motors at 75 per cent of critical speed. He observed that $r_i = gr_{io}$, where each r_{io} is a reference value that remains constant for a given mill, and g is a multiplier.

To a reasonable approximation, $g = a_o + a_1(T/H)$, where a_0 and a_1 are constants, T is the feed rate* (t/h) of $+x_o$ μm solids fed to the autogenous mill, H is the power draw (kW), and x_o is a reference size (53882 μm in this chapter). Consequently, values of r_i are found from the expression:

$$r_i = (a_o + a_1(T/H))r_{io}$$

for each screen size x_i, when r_{io} values have been determined for a given mill. If T1 is the metric tons per hour of new solids fed to the mill and if f_{xo} is the per cent of $+x_o$ solids in the the new feed, $T = (T1)f_{xo}/100$.

The elements of B, namely b_{ij}, are comprised of components that are associated with chipping/abrasion and with impact/compression breakage (43). Stanley (44) and Austin** et al. (42) proposed complex functions to calculate or determine b_{ij} values, whereas Gault (5) used a more practical approach based on a suggestion by Wickham (45). Wickham postulated that, if the particles in a single size interval lose a proportion w of their weight as the result of an abrasion breakage event, then $(1/A)^3w$ appears in the next smaller A interval, and the remaining $1 - (1/A)^3w$ forms the "detritus" that spreads over a number of considerably smaller size intervals. Assuming that 90 per cent of the parent size fraction remains after an abrasion event, elements for 25 size intervals of an abrasion breakage function, with a screen ratio of $A = \sqrt{2}$, were determined (5). These are used in the model described here.

The physical appearance of the mill load (5) suggested that mainly abrasion/chipping events occur for material coarser than a size x_k (about 13470 μm). Below this size, mainly impact/compression breakage was assumed to occur according to a modified Rosin-Rammler cumulative breakage function written:

$$y_{ij'} = (1 - \exp(-(x_i/x_{j'})^p)/(1 - \exp(-1))$$

where $y_{ij'}$ is the cumulative weight fraction finer than screen size x_i from breakage of geometric mean size $x_{j'}$, and p is a constant. If abrasion occurs primarily for particles of sizes x_k and coarser, then particles of size $\sqrt{x_kx_{k+1}} = x_{j'}$ and finer are broken by impact primarily. This idea is used to compute the breakage function matrix B. The first column comprises abrasion elements b'_{i1}, which are "normalized" to form columns 2,3,...k, where k represents the screen size at which an abrupt transition to impact breakage occurs.

Impact breakage elements b'_{ij} for $i = k+1, k+2,\ldots,n$ are calculated at geometric mean size $x_j' = \sqrt{x_kx_{k+1}}$ from the expressions:

$$
\begin{aligned}
b''_{k+1,j'} &= (\exp(-(x_{k+1}/x_{j'})^p) - \exp(-1))/(1 - \exp(-1)) \\
b''_{ij'} &= (\exp(-(x_{i+1}/x_{j'})^p) - \exp(-(x_i/x_{j'})^p))/(1 - \exp(-1))
\end{aligned}
$$

for $i = k+2, k+3,\ldots,n$. Impact breakage elements are then normalized for successive columns of B in the usual manner.

Recycle streams are not included when calculating T.
***Austin's mechanism appears to be more meaningful.*

The elements of the final breakage function array thus appear as:

Row	Column							
	(1)	(2)	. . .	(k)	(k+1)	(k+2)	. . .	(n)
1	b'_{11}	0	. . .	0	0	0	. . .	0
2	b'_{21}	b'_{11}	. . .	0	0	0	. . .	0
3	b'_{31}	b'_{21}	. . .	0	0	0	. . .	0
4	b'_{41}	b'_{31}	. . .	0	0	0	. . .	0
.	.	.	. . .	.	.	.	. . .	0
.	.	.	. . .	.	.	.	. . .	0
k	b'_{k1}	$b'_{k-1,1}$	. . .	b'_{11}	0	0	. . .	0
k+1	$b'_{k+1,1}$	b'_{k1}	. . .	b'_{21}	$b''_{k+1,j'}$	0	. . .	0
k+2	$b'_{k+2,1}$	$b'_{k+1,1}$	. . .	b'_{31}	$b''_{k+2,j'}$	$b''_{k+1,j'}$	. . .	0
.	.	.	. . .	.	.	.	. . .	0
.	.	.	. . .	.	.	.	. . .	0
.	.	.	. . .	.	.	.	. . .	0
n	b'_{n1}	$b'_{n+1,1}$	. . .	b'_{n-k-1}	$b''_{nj'}$	$b''_{n-1,j'}$	. . .	$b''_{k+1,j'}$

The breakage function, the vector of r_{io} values, the feed size distribution vector, T and H are then used in Equation 21 to predict the product size distribution. Note that the value of x_k and x_o must be found experimentally for a given mill.

2.2.6.3 Constraints

Constraints that involve throughput, power draw and mill bearing pressure are not available. It is known that autogenous mills operate to maintain a power setpoint that is subject to an upper limit on mill bearing pressure. Feed size may influence constraint expressions which must be developed by direct experimentation in an operating environment.

In the interim, Equations 15 and 16 could serve as constraints, where user-selected power draw and throughput should not exceed gross power and nominal capacity.

2.2.6.4 Limitations

The autogenous mill model used here does not incorporate design variables such as diameter, length, speed, grate opening size and lifter configuration. Constraints which are necessary have not been developed. Moreover, the assumption that the load is perfectly mixed should be established experimentally and the exact nature of breakage mechanisms (hence the characteristics of the breakage function) inside the mill should be examined further.

The values of k_i (selection function elements) and d_i (discharge rate elements) should be determined experimentally to assess the merits of the Gault model.

Ranges for operating variables involved in the development of the Gault autogenous mill model (5) are: total feed rate of solids between 381 and 912 mth, new feed rate of solids between 275 and 608 mth, per cent of +53 882 μm solids in new feed approximately between 14 and 56 per cent, mill power draw between 2820 and 4770 kW, value of x_k equal to 13 470 μm approximately.

2.2.7 Flotation Cells (FLTCLS)

2.2.7.1 Equipment characteristics

Flotation is a selective process commonly used to separate minerals from each other. It is preceded by comminution that economically liberates minerals locked together in run-of-mine ore. Liberated minerals are suspended in water, and the mixture is fed continuously to a flotation cell where separation takes place. The cell mixes the contents by such means as an impeller mechanism. Reagents are added to impart hydrophobicity to minerals of interest, to depress undesirable minerals and to create a stable froth. Hydrophobic minerals attach themselves to air bubbles that are introduced into the cell. The resulting froth (called concentrate) overflows the cell lip, while the bulk of the material that does not overflow (called tailing) enters the next cell in series. The theory and technology of flotation is well documented in the text, *Flotation, A.M. Gaudin Memorial Volumes*, Ed., M.C. Fuerstenau (27).

Flotation cells perform six major functions:

- Maintain particles in suspension during the residence time of the pulp in the cell.
- Keep the pulp adequately aerated.
- Promote particle-bubble collisions.
- Reduce turbulence in the froth column.
- Provide for efficient transport of feed into the cell and transfer of concentrate and tailing out of the cell.
- Incorporate methodology to control pulp depth and froth level.

Figure 10 shows a typical flotation cell along with a schematic of a bank of cells in series.

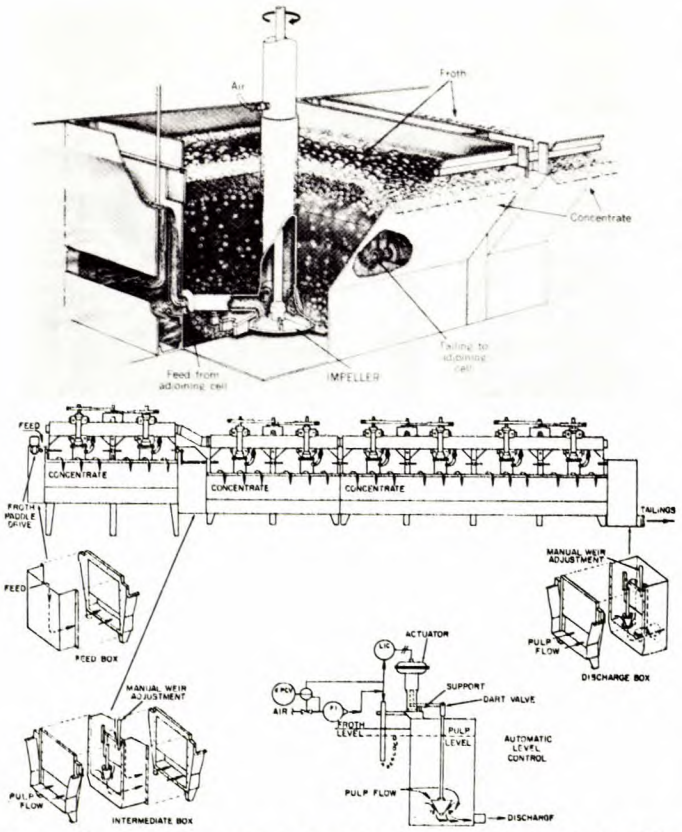


***Fig. 10**— Flotation cell and bank of cells schematic (46,47)*

Depending upon the design, cells draw from 70 to 1200 cfm of air where cell volumes vary from 50 to 2000 ft^3.

Power draw ranges from .02 to .14 HP per ft^3 of cell volume and again is dependent upon the particular design. Impeller speeds vary and may be adjusted to ensure that cells do not sand out and/or to ensure adequate mixing.

Capacities can range between 0.1 to 0.3 STPH of solids per ft^3 of cell volume and higher, depending on the characteristics of the minerals present ("fast" floating versus "slow" floating). Feed per cent solids can be as low as 20 per cent and as high as 55 per cent.

Liquid reagent addition rates vary from as little as 10 mL/min to several hundred mL/min, depending upon initial concentration and purpose. Solid reagents are often added to the primary grinding circuit.

2.2.7.2 Mathematical derivations

The flotation cell model used in this chapter is based on the assumptions that a steady-state flotation cell is perfectly mixed and that the rate of floatable mineral type i of size fraction j, r_{ij}, is a first-order rate phenomenon (20,23). Thus $r_{ij} = k_{ij}M_{ij}$, where k_{ij} is the flotation rate coefficient of mineral type i and size fraction j, and M_{ij} is the mass of i and size fraction j of the pulp in the cell. At steady state, the recovery of mineral i size fraction j, R_{ij} (based on the total mass flow of mineral type i in the feed to the cell) is:

$$R_{ij} = k_{ij}\lambda/(1 + k_{ij}\lambda) \qquad \text{Eq 23}$$

where λ is V/V_t, V is the effective volume of pulp in the cell and V_t is the volume flow rate of pulp in the tailing. The "constant", k_{ij}, is dependent upon design variables, operating variables and the degree of liberation. Because of the lack of real plant data, the degree of liberation is taken as 100 per cent. An alternative model (26) accounts for such factors as liberation, bubble loading and froth overflow rate, but realistic information relevant to the base metals industry is unavailable. Moreover, most flotation operations can place an upper limit on recovery, $R_{ij}max$, which would be a multiplier to Equation 23. In this chapter, $R_{ij}max$ is taken to be unity.

The mass flow rate of feed mineral type i, F_i, can be determined from:

$$F_i = \sum_{j=1}^{n} F(F_{ij})$$

where F_{ij} is the mass fraction of mineral type i size fraction j in the feed, F is the mass flow rate of feed solids and n is the number of size fractions. Note that for m species, $F = F_1 + F_2 + F_3 \ldots + F_m$. It follows that if C_{ij} is the mass flow rate of mineral i size fraction j in the concentrate,

$$C_{ij} = F_iR_{ij} = F_ik_{ij}\lambda/(1 + k_{ij}\lambda) \qquad \text{Eq 24}$$

so that the total mass C_i of mineral type i floated per unit time is:

$$C_i = \sum_{j=1}^{n} C_{ij}$$

for all size fractions (including the pan size fraction) 1,2,...,n. Consequently, the mass flow rate of mineral type i in the tailing is $T_i = F_i - C_i$.

The total mass flow rate of concentrate solids C is given by $C = C_1 + C_2 + C_3 + \ldots + C_m$, where m is the number of mineral types, and the total mass flow rate of tailing solids T is:

$$T = \sum_{j=1}^{m} F_i - \sum_{j=1}^{m} C_i$$

Note that C_{ij} can be calculated from Equation 24 when F_i, k_{ij}, V and V_t are known. To find F_i, F is required and, in general, the effective volume V of the pulp in the cell can be estimated with reasonable accuracy. To determine V_t, the amount of water present in the feed and concentrate must be calculated and the specific gravities of each mineral type i given.

*Courtesy of Inco Limited

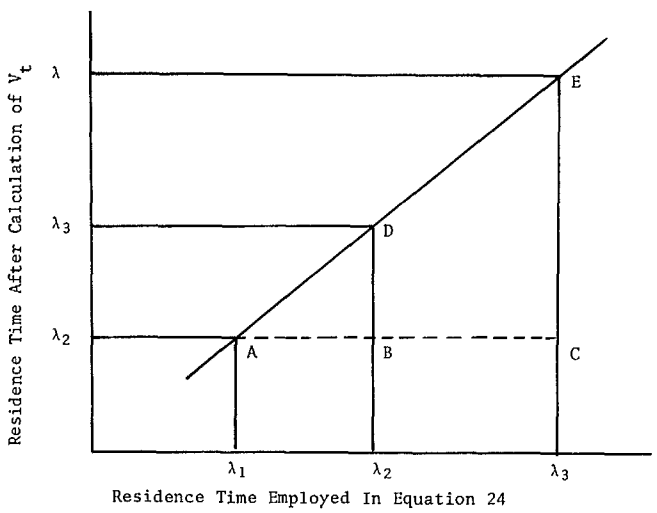
Cheng and Mular (48) observed that the mass of water floated per unit time was proportional to the mass of pan size gangue present in the float per unit time, or:

$$W_c = qC_{mn} = qF_i k_{mn}\lambda/(1 + k_{mn}\lambda)$$

where q is a constant for a given type of bank (i.e., rougher, scavenger, cleaner), m is the gangue mineral and n is the pan size fraction. If the feed per cent solids P_f is measured, then the flow rate of feed water W_f to the cell must be: $W_f = F(100 - P_f)/P_f$. The tailing flow rate of water W_t is then $W_t = W_f - W_c$ at steady state. The value of V_t can then be determined when d_i, the specific gravities of each mineral i, are given. Thus:

$$V_t = (L)(W_t + \sum_{i=1}^{m} (T_i/d_i)) \qquad \text{Eq 25}$$

where L is a conversion factor (2000/62.4, if W_t and T_i are STPH and V_t is to be ft^3). Clearly, both T_i and W_t depend on λ and on flotation rate coefficients. The exact value of λ is not known, unless V_t is measured in some manner. This is difficult at best. However, λ can be estimated with high precision by classical linear interpolation. The following diagram describes the essential features of the procedure.



λ_1 is a first estimate of residence time from the ratio of V/V_f, where V_f is the volume of feed pulp determined in a manner analogous to Equation 25. Next, Equation 24 is used to calculate C_{ij} values which finally lead to the determination of the first estimate of tailing volume flow rate from Equation 25. The estimated V_{t1} is then used to determine λ_2. In turn, λ_2 leads to a second estimate of volume flow rate of tailing V_{t2}, which is used to calculate λ_3. But λ_3 is then assumed to be "close" to the correct answer λ. From similarity of triangles:

$$\frac{BA}{DB} = \frac{CA}{EC}$$

so that:

$$A = \frac{\lambda_2 - \lambda_1}{\lambda_3 - \lambda_2} = \frac{\lambda_3 - \lambda_1}{\lambda - \lambda_2}$$

A test is conducted to determine whether λ_3 is a suitable estimate of residence time. Thus, if the absolute value of $(\lambda_3 - \lambda_2)/\lambda_2$ is less than some small value (.000001 for example), λ_3 is an acceptable answer. If not, assume that $\lambda \simeq \lambda_3$ (where λ is closer to the "correct" answer) in Equation 25 which becomes:

$$\lambda \simeq (\lambda_1 - A\lambda_2)/(1 - A)$$

and is used to obtain a better estimate of λ for determining a better estimate of V_t. Then old λ_2 becomes new λ_1, old λ_3 becomes new λ_2, a new λ_3 is calculated from new V_t, and the test is repeated until convergence. Usually one or two iterations are sufficient.

Once the correct value of λ is known for a given cell, various parameters may be calculated. Thus, the mineral assays c_i and t_i of species i in the concentrate and tailing respectively are found from:

$$c_i = 100C_i/C \qquad t_i = 100T_i/T$$

and the recovery of mineral type i in the float is $R_i = 100C_i/F_i$.

Since flotation cells are always placed in series to form a bank of cells, it is useful to simulate p cells in series rather than a single cell. The tailing from the first is the feed to the second and so on. Each cell has a different residence time, because material is lost to the concentrate as slurry progresses through the bank. When the calculation of recovery is based on the feed to the first cell, then the recovery R_{iq} of mineral i from cell q is:

$$R_{iq} = (\sum_{j=1}^{n} k_{ij}\lambda_q/(1 + k_{ij}\lambda_q))(1 - \sum_{g=1}^{q-1} R_{ig})$$

The cumulative recovery of mineral i from p cells is then:

$$R_{icum} = \sum_{g=1}^{p} R_{ig}$$

while the cumulative grade c_{icum} is:

$$c_{icum} = 100\,(\sum_{g=1}^{p} C_{ig})/(\sum_{g=1}^{p} C_g)$$

where C_{ig} is the mass flow rate of concentrate mineral i in cell g, and C_g the mass flow rate of total concentrate solids in cell g.

2.2.7.3 Constraints

The flotation cell model described here is rather crude, because the influence of important operating and design variables on constraints is unknown. In fact, important constraints have not been formulated. For example, there must be an upper limit to the size of particles fed to a flotation cell, but this depends on feed flow rate, pulp density, viscosity, aeration intensity and impeller speed. Rate coefficients measured for one size range may not match with respect to size range under different conditions. The expression k_{ij} should include the maximum size of floatable material under conditions of permissible operation.

If the aeration intensity is too low, power climbs at a given speed, and damage to the motor may result. If aeration intensity is too high, cell efficiency is reduced. Such constraints must be formulated by direct experimentation.

The minimum/maximum types and amounts of reagents to add must be determined for a given processing plant. Composition and type of minerals, degree of oxidation, degree of liberation, and froth character are influencing factors.

2.2.7.4 Limitations

The flotation cell model is severely limited, since the effects of important design and operating variables have not been incorporated into the model. Constraints are unavailable as well.

Many factors are expected to influence rate coefficients k_{ij}. These include degree of oxidation, degree of liberation, reagent types, reagent addition rates (collectors, modifiers, frothers), pulp density, pulp viscosity, mineralogical composition, aeration intensity, froth level, froth depth, impeller speed and cell geometry. Data should be acquired to:

1. test the King model (26);
2. evaluate the effects of the many factors;
3. develop constraints. (Empiricism will certainly be necessary to develop a more practical model.)

Data to develop the model described here were gathered around a bulk flotation circuit, where $CuFeS_2$ and MoS_2 were the major valuable minerals in the concentrate. Reagents used were xanthate collector (added to the grinding circuit), fuel oil collector (added to the conditioning tank) and MIBC frother (added to the conditioning tank). Flotation rate coefficients were determined experimentally. During the data acquisition phase, deliberate changes in operating variables were not permitted by operators, so that the data apply to one set of conditions only.

2.3 PROGRAM CAPABILITIES

Each unit simulator is a subroutine called within a short main program by a standard argument list. This list has been chosen to be as close as possible to that used in the MODSIM simulator (49):

(NS,NG,NC,SOL1,WAT1,CH1,SOL2,WAT2,CH2,
SOL3,WAT3,CH3,SOL4,WAT4,CH4,DER1,DER2,
DER3,PARAM,OPT)

where:
- NS – Number of size fractions.
- NG – Number of specific gravity intervals.
- NC – Number of characteristics. (A characteristic is any physical assay by which the solid is characterized: weight, % Cu, % ash, BTU, etc. By convention, the first characteristic must be the solid weight.)
- SOLi – Flow rate of solids in stream i (i = 1 to 4).
- WATi – Flow rate of water in stream i (i = 1 to 4).
- CHi – Three-dimensional array of dimensions NS, NG, NC containing the solid characteristics for stream i (i = 1 to 4).
- DERi – Numerical derivative of characteristic CH(i + 1) (i = 1 to 3). Three-dimensional arrays provided to store the numerical derivatives of characteristic i + 1 with respect to its value in the feed (CH1). This option is unused but could be activated to study linearization of complex models.
- PARAM – A vector of model parameters specific to each model.
- OPT – A vector of options relative to each model.

The size vector XMU and the specific gravity vector SG are passed by labelled COMMON/SZSG with fixed dimensions of 20 and 10, respectively. Each module includes also a pool of memory transmitted by COMMON/POOL for local memory requirements of up to 1000 words. This pool is locally distributed to local variables by an EQUIVALENCE statement.

2.4 DATA INPUT

Each simulator reads a set of data in file number 5 through subroutine RDFILE. Subsequently, subroutine UDRIVR prints the data divided into six tables and the user is prompted to accept or modify interactively each of the six groups:

1. NS, NG, NC, SOL1, WAT1.
2. Three-dimensional feed characteristics entered as NC sets of NS records of NG values.
3. Vector PARAM.
4. Vector OPT.
5. Vector XMU.
6. Vector SG.

For the simulator FLTCLS, additional data are required. An initial interactive prompt asks the user to enter the type of flotation cell bank — either ROUGHER, SCAVENGER or CLEANER. A final prompt requests entry of the names of the mineral species, one for each specific gravity interval.

2.4.1 PGCRUS

```
NS      = NUMBER OF SIZE FRACTIONS
NG      = NUMBER OF SPECIFIC GRAVITY FRACTIONS
NC      = NUMBER OF CHARACTERISTICS
SOL     = SOL1 = SOLID FEED RATE (UNUSED)
WAT     = WAT1 = WATER FEED RATE (UNUSED)

FEED    = FEED SIZE DISTRIBUTION (% RETAINED ON SIZE
          INCLUDING PAN)

PARAM   = PARAMETER VALUES - 1 = X00
                             2 = GI
X00     = SMALLEST SIZE THROUGH WHICH ALL PARTICLES PASS
GI      = OPEN SIDE SET IN MICROMETRES

OPT     = OPTION VECTOR (UNUSED)

XMU     = X = SCREEN SIZE VECTOR (MICROMETRES)
```

2.4.2 PJCRUS

```
NS     = NUMBER OF SIZE FRACTIONS
NG     = NUMBER OF SPECIFIC GRAVITY FRACTIONS
NC     = NUMBER OF CHARACTERISTICS (WEIGHT,ASSAYS,ETC.)
WAT    = WAT1 = WATER FEED RATE (UNUSED)
SOL    = SOL1 = SOLID FEED RATE (UNUSED)

FEED   = FEED SIZE DISTRIBUTIONS (% RETAINED ON SIZE
         INCLUDING PAN)

PARAM = PARAMETER VECTOR - 1 = X00
                           2 = GI
X00    = SMALLEST SIZE THROUGH WHICH ALL PARTICLES PASS
GI     = OPEN SIDE SET IN MICROMETRES

OPT    = OPTION VECTOR (UNUSED)

XMU    = X = SCREEN SIZE VECTOR (MICROMETRES)
```

2.4.3 SCCRUS

```
NS      = NUMBER OF SIEVES INCLUDING THE PAN
NG      = NUMBER OF SPECIFIC GRAVITY FRACTIONS
NC      = NUMBER OF CHARACTERISTICS
SOL     = THRUPT = SOLID FEED RATE (STPH)
WAT     = WAT1   = WATER FEED RATE (UNUSED)

FEED    = FEED SIZE DISTRIBUTION (% RETAINED ON SIZE)

PARAM   = PARAMETER VALUES - 1 = SIZZER
                             2 = SETCS
SIZZER  = APERTURE OF LARGEST SIEVE WHICH RETAINS NO SOLIDS
SETCS   = CLOSE SIDE SET (CM)

OPT     = OPTION VECTOR (UNUSED)

XMU     = SIZE = SCREEN SIZE VECTOR (CM)
```

2.4.4 TCCRUS

```
NS      = NUMBER OF SIZE FRACTIONS (PAN INCLUDED)
NG      = NUMBER OF SPECIFIC GRAVITY FRACTIONS
NC      = NUMBER OF CHARACTERISTICS
SOL     = THRUPT = SOLID FEED RATE (STPH)
WAT     = WAT1   = WATER FEED RATE (UNUSED)

FEED    = FEED SIZE DISTRIBUTION (% RETAINED ON SIZE(I))

PARAM   = PARAMETER VECTORS - 1= SIZZER
                              2= SETCS
SIZZER  = APERTURE OF LARGEST SIEVE WHICH NEVER RETAINS SOLIDS
SETCS   = CLOSE SIDE SET (CM)

OPT     = OPTION VECTOR (UNUSED)

XMU     = SIZE = SCREEN SIZE VECTOR (CM)
```

2.4.5 CRSHRO

```
 NS      = NUMBER OF SIZE FRACTIONS (PAN INCLUDED)
 NG      = NUMBER OF SPECIFIC GRAVITY FRACTIONS
 NC      = NUMBER OF CHARACTERISTICS
 SOL     = THRUPT = MASS FLOW RATE OF SOLIDS IN FEED (STPH)
 WAT     = WAT1   = MASS FLOW RATE OF WATER IN FEED (STPH)

 FEED    = SOLDIN = FEED SIZE DISTRIBUTION =% RETAINED
           SIEVE INCLUDING PAN MATERIAL

PARAM    = PARAMETER VECTOR - 1 = RHOORE
                              2 = SIZMAX
                              3 = DIA
                              4 = REVS
                              5 = LENGTH
                              6 = SET
                              7 = BETA
                              8 = GAMMA
                              9 = PHI
 RHOORE = SPECIFIC GRAVITY OF ORE
 SIZMAX = SIZE OF LARGEST SIEVE WHICH RETAINS NO SOLIDS (MM)
 DIA    = DIAMETER OF ROLLS (MM)
 REVS   = SPEED OF ROLLS (RPM)
 LENGTH = LENGTH OF ROLLS (MM)
 SET    = GAP BETWEEN ROLLS (MM)
 BETA )
 GAMMA) = CONSTANTS IN CUMULATIVE BREAKAGE FUNCTION EQUATION
 PHI  )

 OPT    = OPTION VECTOR    - 1 = NWARD
                             2 = DUTY
                             3 = ISTOUT
 NWARD  = FLAG TO DETERMINE WHETHER CALCULATION SHOULD PROCEED
          ( 0= NO ;  1 = YES )
 DUTY   = CALIBRE OF ROLLS
        = 1:  MEDIUM/LIGHT
          2:  HEAVY
 ISTOUT = FLAG TO PRINT OUT INPUT DATA
          (0 = NO ; 1 = YES)

 XMU    = SIZE = SCREEN SIZE VECTOR (MM)
```

2.4.6 ATMILL

```
NS      = NUMBER OF SIZE FRACTIONS (PAN INCLUDED)
NG      = NUMBER OF SPECIFIC GRAVITY FRACTIONS
NC      = NUMBER OF CHARACTERISTICS
SOL     = T     = MASS FLOW RATE OF SOLIDS IN FEED (TONNES/HR)
WAT     = WAT1 = MASS FLOW RATE OF WATER IN FEED (TONNES/HR)

FEED    = WEIGHT FRACTION OF SIZE(I) IN TOTAL
          FEED TO MILL (INCLUDES RECYCLE
          STEAM) (% RETAINED)

PARAM   = PARAMETER VECTOR  - 1 = T1
                              2 = W
                    3 TO (2+NS) = DKFNO
             (3+NS) TO (2+2*NS) = ABRKFN
T1      = % OF +53882 MICROMETRES MATERIAL IN NEW FEED TO
          CIRCUIT
W       = POWER DRAW (KILOWATTS)
DKFNO   = DIAGONAL ELEMENTS OF REFERENCE FUNCTION
ABRDFN  = FIRST COLUMN OF BREAKAGE FUNCTION WHICH
          REPRESENTS ABRASION BREAKAGE

OPT     = OPTION VECTOR (UNUSED)

XMU     = SIZE = SCREEN SIZE VECTOR (MICROMETRES)
```

2.4.7 FLTCLS

It should be noted that data input for FLTCLS has the same format regardless of the type of bank. However, numerical values of the data depend upon bank type (i.e. rougher, scavenger, first cleaner, second cleaner, third cleaner or fourth cleaner).

```
NS      = NUMBER OF SIZE FRACTIONS (PAN INCLUDED)
NG      = NUMBER OF SPECIFIC GRAVITY FRACTIONS
NC      = NUMBER OF CHARACTERISTICS
SOL     = FEEDS = MASS FLOW RATE OF SOLIDS IN FEED (STPH)
WAT     = FEEDW = MASS FLOW RATE OF WATER IN FEED (STPH)

FEED    = MASS DISTRIBUTION OF THE FEED STREAM

PARAM   = PARAMETER VECTOR      - 1 = CONS
                                  2 = VOLCEL
                                  3 = NCELL
                      4 TO (3+NG*NS) = FCOEF
CONS    = FROTH WATER FLOTATION RATE CONSTANT
VOLCEL  = CELL VOLUME (CU. FT.)
NCELL   = NUMBER OF FLOTATION CELLS IN BANK
FCOEF   = FLOTATION RATE COEFFICIENT ARRAY
          (SPECIES I, SIZE J)

OPT     = OPTION VECTOR         - 1 = IPRINT
IPRINT  = PRINT OPTION
          0 = RESULTS PRINTED
          1 = RESULTS NOT PRINTED

XMU     = VECTOR OF UPPER SIZES FOR THE INTERVALS (MICROMETRES)
SG      = VECTOR OF UPPER SPECIFIC GRAVITIES FOR THE
          INTERVALS

DER1    = TYPE = TYPE OF FLOTATION BANK
DER2    = NAME = ARRAY OF NG NAMES OF SPECIES
          FOR TYPE OF BANK
```

2.5 PRINTED OUTPUT

2.5.1 PGCRUS, PJCRUS, SCCRUS, TCCRUS, ATMILL

In order to fit CRT and hard-copy terminals as well as an 8½ by 11-in. standard page, output generated by PGCRUS, PJCRUS, SCCRUS, TCCRUS and ATMILL contains fewer than 80 columns. Corresponding subroutines, PGOUT, JCOUT, SCOUT, TCOUT, and MILOUT control the output which can be modified selectively to satisfy special output requirements without altering the overall program structure.

Each output subroutine prints the weight per cent retained on size of the feed and calculated product with the corresponding sieve size vector. In addition, SCOUT and TCOUT print the predicted current draw.

2.5.2 CRSHRO

In order to fit CRT and hard-copy terminals as well as an 8½ by 11-in. standard page, the output tables generated by CRSHRO contain fewer than 80 columns. Subroutines CROUT1 and CROUT2 control the output, and they can be selectively modified to satisfy special output requirements without altering the overall program structure. Two output options are available, depending on the value of the variable ISTOUT as read from the data file.

If ISTOUT is equal to 1, the starting conditions and parameters are printed. If ISTOUT is 0, starting data are not printed. The method is easily adapted to print starting conditions in PGCRUS, PJCRUS, SCCRUS, TCCRUS, and ATMILL.

Another variable, NWARD, controls the output depending on tests executed within subroutine ALARM1. If NWARD is 1, the derived output tables are printed. If NWARD is 0, warnings are printed to indicate that starting conditions do not satisfy normal crushing rolls specifications.

Starting conditions, which can be printed, are crusher duty, ore specific gravity, maximum size of feed particles and design/operating parameters such as length, diameter, speed, set and throughput.

Final output consists of the sieve number, screen aperture size, feed per cent retained on size, calculated product per cent retained on size and the cumulative per cent passing the sieve in the product.

2.5.3 FLTCLS

Subroutines FLOUT1 and FLOUT2 control the output, and these can be selectively modified to satisfy special output requirements without altering the overall program structure. Two output options are available, depending on the value of the variable ISTOUT read from the data file.

If ISTOUT is 1, the starting conditions and parameters are printed. If ISTOUT is 0, no starting data are printed.

During program execution, iterative calculations should converge to yield the final results. If more than four iterations are necessary, a warning is printed along with the results calculated at that point.

Starting conditions that may be printed are: bank type, number of cells, number of minerals, cell volume, per cent feed solids by weight, feed rate of solids to the bank, feed rate of water, froth constant, names of minerals, weight per cent of a mineral of a given size in the feed, specific gravities of each mineral and flotation rate coefficients.

Final output includes results for each individual cell and the cumulative results for the bank. Results include per cent of feed, froth and tailings solids, cell retention time, mass flow rate of froth and tailing solids, froth and tailings mineral assays, and recoveries based on either the feed to each cell or the feed to the bank.

3. SYSTEM DOCUMENTATION

3.1 COMPUTER EQUIPMENT

All programs were written in FORTRAN IV on a CDC CYBER 730 computer operating under NOS/BE and have been tested in both batch and interactive mode. The programs have also been converted to MS-FORTRAN on an IBM-PC/XT operating under MS-DOS 3.0 to duplicate the CYBER outputs.

3.2 SOURCE PROGRAMS

Enquiries regarding source programs should be directed to:

Technology Information Division
CANMET
Energy, Mines and Resources Canada
555 Booth Street
Ottawa, Ontario, Canada
K1A 0G1

3.3 MAIN PROGRAMS AND SUBROUTINES

As described in Sections 2.3 and 2.4, each unit simulator is driven by a short program allowing the entry of default data from a file, its optional modification and the actual simulation. The general list of arguments described in Section 2.3 is used for all the process units. The parameter list specific to each unit is given in Section 2.4 and repeated in the preamble of all sample runs in Section 5. Only the auxiliary routines — SMLSIZ, ALARM1, and CROUT1 used in module CRSHRO and routines CELL and FLOUT1 in FLTCLS are described in detail below.

3.3.1 Subroutine: SMLSIZ

3.3.1.1 Purpose

To compute the product size distribution on being called by CRSHRO.

3.3.1.2 Usage

CALL SMLSIZ (NS, SOLDIN, PROD, PASS, PARAM).

3.3.1.3 Arguments list

NS	= number of size fractions
SOLDIN	= feed size distribution (weight per cent retained)
PROD	= product size distribution (weight per cent retained)
PASS	= cumulative per cent passing, the sieve SIZE in the product
PARAM	= same as for CRSHRO (Section 2.4.5)

3.3.2 Subroutine: ALARM1

3.3.2.1 Purpose

To test whether the crushing rolls are capable of doing the job demanded. If not, an alarm flag is set and computation is ended on return.

3.3.2.2 Usage

CALL ALARM1 (THRUPT, PARAM, OPT).

3.3.2.3 Arguments list

THRUPT	= throughput (STPH)
PARAM, OPT	= same as for CRSHRO (Section 2.4.5)

3.3.3 Subroutine: CROUT1

3.3.3.1 Purpose

To print conditions at the time of a call to CRSHRO. These conditions include the physical features of the rolls, the physical features of the ore, and its rate of feed.

3.3.3.2 Usage

CALL CROUT1 (THRUPT, PARAM, OPT).

3.3.3.3 Arguments list

Same as for subroutine ALARM1 (see Section 3.3.2.3.).

3.3.4 Subroutine: CELL

3.3.4.1 Purpose

To calculate the mass rate of flow of each species I of size J which is floated from an individual cell. By extension, the corresponding rate of flow of each species I of size J that is not floated is calculated.

3.3.4.2 Usage

CALL CELL (N, NS, NG, SFD, WFD, FEED, SFH, WFH, FROTH, STL, WTL, TAIL, FCOEF, IPRINT, NCELL).

3.3.4.3 Arguments list

N	= cell number
NS, NG	= number of size intervals and specific gravity intervals
SFD, WFD, FEED	= respectively, the solid and water flow rates in STPH and the mass flow distribution of the feed stream
SFH, WFH, FROTH	= same as above for the froth stream
STL, WTL, TAIL	= same as above for the tailings
FCOEF	= vector of flotation rate coefficient of species I of size J, one record for each size I
IPRINT	= print option (0 = printout; 1 = no printout)
NCELL	= number of cells.

3.3.5 Subroutine: FLOUT1

3.3.5.1 Purpose

To display initial conditions under which FLTCLS operates.

3.3.5.2 Usage

CALL FLOUT1 (VOLCEL, SFD, WFD, FEED, PARAM, TYPE, NAME, NS, NG, NCELL, CONS).

3.3.5.3 Arguments list

VOLCEL	= cell volume (ft^3)
SFD, WFD, FEED	= same as for CELL (Section 3.3.4)
PARAM	= flotation rate coefficient array
TYPE	= type of flotation bank (rougher, scavenger or cleaner)
NAME	= vector of mineral species names
NS, NG	= same as for CELL (Section 3.3.4)
NCELL	= same as for CELL (Section 3.3.4)
CONS	= froth water flotation rate for type of bank.

3.4 DATA STRUCTURES

Programs described here are flexible enough to be altered so that unformatted data may be written. Programs CRSHRO and FLTCLS employ flags to suppress starting data output as desired, while CRSHRO incorporates a flag that requests the user to use adequate equipment. Such features may be built into each of the programs as necessary.

3.5 MAINTENANCE AND UPDATES

Maintenance and updates by members of the SPOC project will be offered from time to time, as model improvements become available. Formal maintenance cannot be assured.

4. OPERATING DOCUMENTATION

4.1 OPERATOR INSTRUCTIONS

Programs have been developed and tested for the Michigan Time Sharing System (MTS) at the University of British Columbia and for the CYBER 730 computer at the Computer Science Centre, Energy, Mines and Resources Canada in Ottawa, Ontario, Canada. The CYBER 730 offers time-sharing access through the INTERCOM system.

4.2 OPERATOR MESSAGES

Normal system messages are produced by the host computer. Special diagnostics are issued by CRSHRO when input data are irregular and by FLTCLS when linear interpolation fails after four iterations. The other programs could readily be modified to accommodate such features.

4.3 ERROR RECOVERY

Programs must be restarted on error or when flags are set to warn the user (program CRSHRO for example).

4.4 RUN TIMES

Run times depend on the options chosen, the particular process model and the computer system.

5. SAMPLE RUNS

This section contains sample runs for each of the simulators — PGCRUS, PJCRUS, SCCRUS, TCCRUS, CRSHRO, ATMILL and FLTCLS. Each run consists of a short descriptive paragraph, a list of the names of the main program and subroutines used, and a detailed description of the input variables — in particular, the contents of the vectors PARAM and OPT, which are specific to each simulator. This is followed by the record of an interactive session where, using RDFILE and UDRIVR, default data are read and modified as required. Finally, the output of the simulator using the selected data is printed.

5.1 PGCRUS

For PGCRUS, the primary gyratory crusher, note that the feed size distribution includes the pan size fraction. Output includes the open side set, screen sizes and feed/product size distributions.

```
        SIMULATION OF A PRIMARY GYRATORY CRUSHER (PGCRUS)
       ------------------------------------------------


PROGRAM
DESCRIPTION:    THIS MODEL WAS PROPOSED AND DEVELOPED BY MULAR
-----------     AND USES THE CONCEPT OF SELECTION / BREAKAGE /
                CLASSIFICATION.  THE ONLY DESIGN VARIABLE INCLUDED
                IN THE MODEL IS THE OPEN SIDE SET.


PROGRAMS AND SUBROUTINES REQUIRED:
----------------------------------

 XPGCRUS,CONNEC,RDFILE,UDRIVR,PGCRUS,PGOUT


THE VARIABLES REQUIRED ARE AS FOLLOWS:
--------------------------------


NS      = NUMBER OF SIZE FRACTIONS
NG      = NUMBER OF SPECIFIC GRAVITY FRACTIONS
NC      = NUMBER OF CHARACTERISTICS
SOL     = SOL1 = SOLID FEED RATE (UNUSED)
WAT     = WAT1 = WATER FEED RATE (UNUSED)

FEED    = FEED SIZE DISTRIBUTION (% RETAINED ON SIZE
          INCLUDING PAN)

PARAM   = PARAMETER VALUES - 1 = X00
                             2 = GI
X00     = SMALLEST SIZE THROUGH WHICH ALL PARTICLES PASS
GI      = OPEN SIDE SET IN MICROMETRES

OPT     = OPTION VECTOR (UNUSED)

XMU     = X = SCREEN SIZE VECTOR (MICROMETRES)
```

```
                        DATA ENTRY FOR: PGCRUS
 THE DEFAULT VALUES OF NS,NG,NC,SOL & WAT ARE:

19 1 1 0. 0.

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES OF THE FEED DISTRIBUTION ARE:
.18 33.89 25.99 13.99 8.99 6.99 4.69 2.69 1.29 .68 .33 .15 .065
.038 .019 .0094 .0044 .0022 .002

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES OF THE PARAMETERS  RELATED TO THIS SIMULATOR ARE:
1740000. 165100.

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES OF THE OPTIONS  RELATED TO THIS SIMULATOR ARE:
0.

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES FOR THE ARRAY OF SIZES ARE:

870000. 435000. 217500. 108750. 54375. 27187.5 13593.8 6796.9
3398.4 1699.2 849.6 424.8 212.4 106.2 53.1 26.6 13.3 6.6 -6.6

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES FOR THE ARRAY OF SPECIFIC GRAVITIES ARE:
0.

 CHANGE?(Y/N)
N
```

PRIMARY GYRATORY CRUSHER OUTPUT (PGCRUS)
OPEN SIDE SET = 165100. MICRONS

SCREEN SIZE (MICRONS)	FEED % RET.	PRODUCT % RET.
870000.0	.1800	0.000
435000.0	33.8900	0.000
217500.0	25.9900	.687
108750.0	13.9900	15.829
54375.0	8.9900	23.740
27187.5	6.9900	20.351
13593.8	4.6900	14.482
6796.9	2.6900	9.425
3398.4	1.2900	5.794
1699.2	.6800	3.640
849.6	.3300	2.259
424.8	.1500	1.400
212.4	.0650	.872
106.2	.0380	.557
53.1	.0190	.352
26.6	.0094	.223
13.3	.0044	.142
6.6	.0022	.090
-6.6	.0020	.159

STOP
024100 MAXIMUM EXECUTION FL.
0.445 CP SECONDS EXECUTION TIME.

5.2 PJCRUS

For PJCRUS, the primary jaw crusher, note that input feed size distribution has been "scalped" (i.e., feed has been screened), because jaw crushers do not function properly otherwise. Output is similar to that of PGCRUS.

Starting conditions for PJCRUS are not printed out, although such a feature is easily built into the program.

```
        SIMULATION OF A PRIMARY JAW CRUSHER (PJCRUS)
        --------------------------------------------


PROGRAM
DESCRIPTION:  THIS MODEL TREATS THE PRIMARY JAW CRUSHER AS A
------------  A SPECIAL CASE OF THE PRIMARY GYRATORY CRUSHER
              MODEL USING SCALPED (SCREENED) FEED.  THE ONLY
              DESIGN VARIABLE INCLUDED IN THE MODEL IS THE
              OPEN SIDE SET.


PROGRAMS AND SUBROUTINES REQUIRED:
----------------------------------

 XPJCRUS,CONNEC,RDFILE,UDRIVR,PJCRUS,JCOUT

THE VARIABLES REQUIRED ARE AS FOLLOWS:
--------------------------------

NS     = NUMBER OF SIZE FRACTIONS
NG     = NUMBER OF SPECIFIC GRAVITY FRACTIONS
NC     = NUMBER OF CHARACTERISTICS (WEIGHT,ASSAYS,ETC.)
WAT    = WAT1 = WATER FEED RATE (UNUSED)
SOL    = SOL1 = SOLID FEED RATE (UNUSED)

FEED   = FEED SIZE DISTRIBUTIONS (% RETAINED ON SIZE
         INCLUDING PAN)

PARAM = PARAMETER VECTOR - 1 = XOO
                           2 = GI
XOO    = SMALLEST SIZE THROUGH WHICH ALL PARTICLES PASS
GI     = OPEN SIDE SET IN MICROMETRES

OPT    = OPTION VECTOR (UNUSED)

XMU    = X = SCREEN SIZE VECTOR (MICROMETRES)
```

```
                    DATA ENTRY FOR: PJCRUS
 THE DEFAULT VALUES OF NS,NG,NC,SOL & WAT ARE:

19 1 1 0. 0.

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES OF THE FEED DISTRIBUTION ARE:
.14 45.72 35.19 16.19 2.7 .06 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
0. 0. 0.

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES OF THE PARAMETERS  RELATED TO THIS SIMULATOR ARE:
1740000. 165100.

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES OF THE OPTIONS  RELATED TO THIS SIMULATOR ARE:
0.

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES FOR THE ARRAY OF SIZES ARE:

870000. 435000. 217500. 108750. 54375. 27187.5 13593.8 6796.9
3398.4 1699.2 849.6 424.8 212.4 106.2 53.1 26.6 13.3 6.6 -6.6

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES FOR THE ARRAY OF SPECIFIC GRAVITIES ARE:
0.

 CHANGE?(Y/N)
N
```

PRIMARY JAW CRUSHER OUTPUT (PJCRUS)
OPEN SIDE SET = 165100. MICRONS

SCREEN SIZE (MICRONS)	FEED % RET.	PRODUCT % RET.
870000.0	.14	0.000
435000.0	45.72	0.000
217500.0	35.19	1.159
108750.0	16.19	16.954
54375.0	2.70	24.036
27187.5	.06	20.165
13593.8	0.00	14.133
6796.9	0.00	9.153
3398.4	0.00	5.702
1699.2	0.00	3.480
849.6	0.00	2.100
424.8	0.00	1.259
212.4	0.00	.752
106.2	0.00	.448
53.1	0.00	.267
26.6	0.00	.159
13.3	0.00	.094
6.6	0.00	.056
-6.6	0.00	.082

STOP
024000 MAXIMUM EXECUTION FL.
0.446 CP SECONDS EXECUTION TIME.

5.3 SCCRUS

For SCCRUS, the secondary cone crusher, the feed size distribution excludes the pan fraction which is calculated in the program. Output includes calculated current draw, screen size and feed/product size distributions.

```
        SIMULATION OF A SECONDARY CONE CRUSHER (SCCRUS)
        -----------------------------------------------

 PROGRAM
 DESCRIPTION:  THIS IS THE WHITEN CONE CRUSHER MODEL MODIFIED
 -----------   BY HATCH AND MULAR.  APPROXIMATE RANGES FOR THE
               OPERATING VARIABLES INCORPORATED IN THE MODEL
               ARE AS FOLLOWS (FOR A 7-FOOT CONE):

               CRUSHER CLOSE SIDE SET - 2.5 TO 3.8 CM
               FEED RATE              - 635 TO 789 STPH
               +2.72 CM IN FEED       - 75  TO 94 %
               CURRENT DRAW           - 18  TO 32 AMPS.


PROGRAMS AND SUBROUTINES REQUIRED:
----------------------------------

 XSCCRUS,CONNEC,RDFILE,UDRIVR,SCCRUS,SCOUT

VARIABLES REQUIRED ARE AS FOLLOWS:
----------------------------

  NS      = NUMBER OF SIEVES INCLUDING THE PAN
  NG      = NUMBER OF SPECIFIC GRAVITY FRACTIONS
  NC      = NUMBER OF CHARACTERISTICS
  SOL     = THRUPT = SOLID FEED RATE (STPH)
  WAT     = WAT1   = WATER FEED RATE (UNUSED)

  FEED    = FEED SIZE DISTRIBUTION (% RETAINED ON SIZE)

  PARAM   = PARAMETER VALUES - 1 = SIZZER
                               2 = SETCS
  SIZZER  = APERTURE OF LARGEST SIEVE WHICH RETAINS NO SOLIDS
  SETCS   = CLOSE SIDE SET (CM)

  OPT     = OPTION VECTOR (UNUSED)

  XMU     = SIZE = SCREEN SIZE VECTOR (CM)
```

```
                          DATA ENTRY FOR: SCCRUS
 THE DEFAULT VALUES OF NS,NG,NC,SOL & WAT ARE:

19 1 1 701.1 0.

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES OF THE FEED DISTRIBUTION ARE:
0. 0. 1.5 20.5 28.5 29.4 13.3 3.41 .91 .48 .38 .41 .36 .3 .24
.16 .09 .04 .02

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES OF THE PARAMETERS  RELATED TO THIS SIMULATOR ARE:
174.08 3.239

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES OF THE OPTIONS  RELATED TO THIS SIMULATOR ARE:
0.

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES FOR THE ARRAY OF SIZES ARE:

87.04 43.2 21.76 10.88 5.44 2.72 1.36 .68 .34 .17 .085 .0424
.02125 .010625 .005312 .002656 .001328 .000664 0.

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES FOR THE ARRAY OF SPECIFIC GRAVITIES ARE:
0.

 CHANGE?(Y/N)
N
```

SECONDARY CONE CRUSHER OUTPUT (SCCRUS)
CRUSHER DRAWS 21.1 AMPS

SIZE(I)	PERCENT RETAINED ON SIZE(I)	
	FEED	PRODUCT
87.040000	0.00	0.0000
43.200000	0.00	0.0000
21.760000	1.50	0.0000
10.880000	20.50	.0849
5.440000	28.50	16.9544
2.720000	29.40	43.1478
1.360000	13.30	22.6531
.680000	3.41	7.7510
.340000	.91	3.1499
.170000	.48	1.8261
.085000	.38	1.2437
.042400	.41	.9731
.021250	.36	.7223
.010625	.30	.5341
.005312	.24	.3897
.002656	.16	.2553
.001328	.09	.1505
.000664	.04	.0783
PAN	.02	.0858

STOP
023500 MAXIMUM EXECUTION FL.
0.411 CP SECONDS EXECUTION TIME.

5.4 TCCRUS

For TCCRUS, the tertiary cone crusher, the output is similar to that for SCCRUS. Internally, in both these routines, data statements contain the coefficients by which the effect of abrasion and fracture breakage are combined to calculate the product vector. The current draw is also calculated from internal data. These data statements are specific to secondary and tertiary cone crushers.

```
        SIMULATION OF A TERTIARY CONE CRUSHER (TCCRUS)
        ----------------------------------------------

 PROGRAM
 DESCRIPTION:  THIS IS SIMILAR TO THE MODIFIED WHITEN MODEL FOR
 -----------   THE SECONDARY CONE CRUSHER.  IT WAS DEVELOPED FOR A
               7-FOOT SHORT HEAD CONE CRUSHER EQUIPPED WITH A 300 HP
               MOTOR AT 4.16 KV.  THE RANGES FOR THE OPERATING
               VARIABLES ARE AS FOLLOWS:

                CLOSE SIDE SET        - 0.5 TO 1.0 CM
                FEED RATE             - 221 TO 421 STPH
                +2.72 CM IN THE FEED  -  44 TO 77 %


 PROGRAMS AND SUBROUTINES REQUIRED:
 ----------------------------------

  XTCCRUS,CONNEC,RDFILE,UDRIVR,TCCRUS,TCOUT

THE VARIABLES REQUIRED ARE AS FOLLOWS:
--------------------------------------


  NS      = NUMBER OF SIZE FRACTIONS (PAN INCLUDED)
  NG      = NUMBER OF SPECIFIC GRAVITY FRACTIONS
  NC      = NUMBER OF CHARACTERISTICS
  SOL     = THRUPT = SOLID FEED RATE (STPH)
  WAT     = WAT1   = WATER FEED RATE (UNUSED)

  FEED    = FEED SIZE DISTRIBUTION (% RETAINED ON SIZE(I))

  PARAM   = PARAMETER VECTORS - 1= SIZZER
                                2= SETCS
  SIZZER  = APERTURE OF LARGEST SIEVE WHICH NEVER RETAINS SOLIDS
  SETCS   = CLOSE SIDE SET (CM)

  OPT     = OPTION VECTOR (UNUSED)

  XMU     = SIZE = SCREEN SIZE VECTOR (CM)
```

```
                        DATA ENTRY FOR: TCCRUS
 THE DEFAULT VALUES OF NS,NG,NC,SOL & WAT ARE:

19 1 1 299.1 0.

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES OF THE FEED DISTRIBUTION ARE:
0. 0. 0. 0. 12. 43. 39. 3.62 .76 .42 .24 .2 .19 .15 .12 .08
.05 .03 .14

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES OF THE PARAMETERS  RELATED TO THIS SIMULATOR ARE:
174.08 .737

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES OF THE OPTIONS  RELATED TO THIS SIMULATOR ARE:
0.

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES FOR THE ARRAY OF SIZES ARE:

87.04 43.52 21.76 10.88 5.44 2.72 1.36 .68 .34 .17 .085 .0425
.02125 .010625 .005312 .002656 .001328 .000664 0.

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES FOR THE ARRAY OF SPECIFIC GRAVITIES ARE:
0.

 CHANGE?(Y/N)
N
```

TERTIARY CONE CRUSHER OUTPUT (TCCRUS)
CRUSHER DRAWS 37.1 AMPS

SIZE(I)	PERCENT RETAINED ON SIZE(I)	
87.040000	0.00	0.0000
43.520000	0.00	0.0000
21.760000	0.00	0.0000
10.880000	0.00	0.0000
5.440000	12.00	0.0000
2.720000	43.00	1.1461
1.360000	39.00	39.4465
.680000	3.62	34.9473
.340000	.76	13.4037
.170000	.42	3.9937
.085000	.24	2.2994
.042500	.20	1.5526
.021250	.19	1.0742
.010625	.15	.7211
.005312	.12	.4858
.002656	.08	.3130
.001328	.05	.1979
.000664	.03	.1237
PAN	.14	.2949

STOP
023500 MAXIMUM EXECUTION FL.
0.425 CP SECONDS EXECUTION TIME.

5.5 CRSHRO

For CRSHRO, the crushing rolls, the flag to print starting conditions has been set to 1. Design variables are not necessary to calculate the product size distribution. They are used to test whether user specifications are 'suitable'.

Output includes fraction number, screen sizes, feed and product size distribution and the cumulative per cent passing size of the product. The 'warning' flag that serves to warn of 'incorrect' equipment specifications has been turned to 0, i.e., turned off.

```
                SIMULATION OF CRUSHING ROLLS (CRSHRO)
                -------------------------------------

PROGRAM
DESCRIPTION:    THE MODEL SELECTED WAS FORMULATED BY AUSTIN AND
-----------     SLIGHTLY MODIFIED BY MULAR.  THE CONCEPT USED IS
                THAT BREAKAGE LEADS TO MATERIAL SMALLER THAN THE
                PARTICULAR SIZE RANGE OF INTEREST.  MATERIAL
                REMAINING WITHIN THE SIZE RANGE AFTER PASSING
                THROUGH THE ROLLS IS CONSIDERED MATERIAL THAT
                IS UNBROKEN (BY-PASSED).  FRAGMENTS PRODUCED
                FROM BREAKAGE BUT LARGER THAN THE CRUSHER GAP
                CAN, IN TURN BE EITHER BYPASSED OR RETAINED FOR
                REBREAKAGE.

THE PROGRAMS AND SUBROUTINES REQUIRED:
--------------------------------------

 XCRSHRO,RDFILE,UDRIVR,CRSHRO,SMLSIZ,CROUT2,ALARM1,CROUT1

THE VARIABLES REQUIRED ARE AS FOLLOWS:
--------------------------------------

 NS      = NUMBER OF SIZE FRACTIONS (PAN INCLUDED)
 NG      = NUMBER OF SPECIFIC GRAVITY FRACTIONS
 NC      = NUMBER OF CHARACTERISTICS
 SOL     = THRUPT = MASS FLOW RATE OF SOLIDS IN FEED (STPH)
 WAT     = WAT1   = MASS FLOW RATE OF WATER IN FEED (STPH)

 FEED    = SOLDIN = FEED SIZE DISTRIBUTION =% RETAINED
           SIEVE INCLUDING PAN MATERIAL

PARAM    = PARAMETER VECTOR - 1 = RHOORE
                              2 = SIZMAX
                              3 = DIA
                              4 = REVS
                              5 = LENGTH
                              6 = SET
                              7 = BETA
                              8 = GAMMA
                              9 = PHI
 RHOORE = SPECIFIC GRAVITY OF ORE
 SIZMAX = SIZE OF LARGEST SIEVE WHICH RETAINS NO SOLIDS (MM)
 DIA    = DIAMETER OF ROLLS (MM)
 REVS   = SPEED OF ROLLS (RPM)
 LENGTH = LENGTH OF ROLLS (MM)
 SET    = GAP BETWEEN ROLLS (MM)
 BETA )
 GAMMA) = CONSTANTS IN CUMULATIVE BREAKAGE FUNCTION EQUATION
 PHI  )

 OPT    = OPTION VECTOR    - 1 = NWARD
                             2 = DUTY
                             3 = ISTOUT
 NWARD  = FLAG TO DETERMINE WHETHER CALCULATION SHOULD PROCEED
          ( 0= NO ;  1 = YES )
 DUTY   = CALIBRE OF ROLLS
        = 1:  MEDIUM/LIGHT
          2:  HEAVY
```

```
      ISTOUT = FLAG TO PRINT OUT INPUT DATA
               (0 = NO ; 1 = YES)

      XMU    = SIZE = SCREEN SIZE VECTOR (MM)



                DATA ENTRY FOR : CRSHRO


 THE DEFAULT VALUES OF NS,NG,NC,SOL & WAT ARE:

14 1 1 10. 0.
 CHANGE?(Y/N)
n

 THE DEFAULT VALUES OF THE FEED DISTRIBUTION ARE:
0. 100. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
 CHANGE?(Y/N)
n

 THE DEFAULT VALUES OF THE PARAMETERS  RELATED TO THIS SIMULATOR ARE:
3. 6.35 200. 360. 600. 1.68 7. 1.2 .5
 CHANGE?(Y/N)
n

 THE DEFAULT VALUES OF THE OPTIONS  RELATED TO THIS SIMULATOR ARE:
0. 1. 1.
 CHANGE?(Y/N)
n

 THE DEFAULT VALUES FOR THE ARRAY OF SIZES ARE:

9.5 6.72 4.75 3.36 2.38 1.68 1.19 .84 .59 .42 .297 .21 .149
-.149
 CHANGE?(Y/N)
n

 THE DEFAULT VALUES FOR THE ARRAY OF SPECIFIC GRAVITIES ARE:
0.
 CHANGE?(Y/N)
n
```

OUTPUT FROM CRUSHING ROLLS (CRSHRO)

DUTY OF CRUSHER IS LIGHT/MEDIUM

ORE DENSITY = 3.000 MAXIMUM FEED PARTICLE SIZE = 6.35 MM

LENGTH = .6000E+03 MM

DIAMETER = .2000E+03 MM

REVS PER MIN = .3600E+03

SET = .1680E+01 MM

THROUGHPUT = .1000E+02 SHORT TONS PER HOUR

RESULTS

FRACTION NUMBER	SCREEN APERT.	FEED %	PRODUCT %	PASSING %
1	.9500E+01	0.	0.	.1000E+03
2	.6720E+01	.1000E+03	.1378E-01	.9999E+02
3	.4750E+01	0.	.8621E-02	.9998E+02
4	.3360E+01	0.	.7245E+00	.9925E+02
5	.2380E+01	0.	.1299E+02	.8626E+02
6	.1680E+01	0.	.3210E+02	.5417E+02
7	.1190E+01	0.	.2103E+02	.3314E+02
8	.8400E+00	0.	.1173E+02	.2141E+02
9	.5900E+00	0.	.7345E+01	.1406E+02
10	.4200E+00	0.	.4806E+01	.9254E+01
11	.2970E+00	0.	.3148E+01	.6106E+01
12	.2100E+00	0.	.2079E+01	.4027E+01
13	.1490E+00	0.	.1370E+01	.2657E+01
14	-.1490E+00	0.	.2657E+01	0.

STOP

027600 MAXIMUM EXECUTION FL.

0.344 CP SECONDS EXECUTION TIME.

5.6 ATMILL

In the sample runs for ATMILL, the autogenous mill model, it should be stressed that the *new* feed rate of solids and the per cent of +53880 μm material present in new feed are input data points, along with the measured power draw. The input feed size distribution must include both the new feed and any recycle streams. Necessary input data are the reference DK^{-1} function and the first column of the abrasion breakage array.

In the output from ATMILL, screen sizes and the feed and product size distributions are provided. Starting conditions may be printed out by simple modification to subroutine MILOUT.

```
   SIMULATION OF AN AUTOGENOUS MILL (ATMILL)
   -----------------------------------------

PROGRAM
DESCRIPTION:  THE BASIC MODEL IS AFTER GAULT AND LYNCH.
-----------   THE RANGES OF THE VARIABLES USED ARE AS
              FOLLOWS:

              FEED RATE OF NEW SOLIDS     - 275 TO 608 TONNES/HR
              % OF +53882 MICROMETRES OF
              MATERIAL IN NEW FEED        -  14 TO 56%
              MILL POWER DRAW             -2820 TO 4770 KW


THE PROGRAMS AND SUBROUTINES REQUIRED:
--------------------------------------

   XATMILL,RDFILE UDRIVR,ATMILL,MILOUT

THE VARIABLES REQUIRED ARE AS FOLLOWS:
--------------------------------------

NS     = NUMBER OF SIZE FRACTIONS (PAN INCLUDED)
NG     = NUMBER OF SPECIFIC GRAVITY FRACTIONS
NC     = NUMBER OF CHARACTERISTICS
SOL    = T     = MASS FLOW RATE OF SOLIDS IN FEED (TONNES/HR)
WAT    = WAT1 = MASS FLOW RATE OF WATER IN FEED (TONNES/HR)

FEED   = WEIGHT FRACTION OF SIZE(I) IN TOTAL
         FEED TO MILL (INCLUDES RECYCLE
         STEAM) (% RETAINED)

PARAM  = PARAMETER VECTOR  - 1 = T1
                             2 = W
                   3 TO (2+NS) = DKFNO
            (3+NS) TO (2+2*NS) = ABRKFN
T1     = % OF +53882 MICROMETRES MATERIAL IN NEW FEED TO
         CIRCUIT
W      = POWER DRAW (KILOWATTS)
DKFNO  = DIAGONAL ELEMENTS OF REFERENCE FUNCTION
ABRDFN = FIRST COLUMN OF BREAKAGE FUNCTION WHICH
         REPRESENTS ABRASION BREAKAGE

OPT    = OPTION VECTOR (UNUSED)

XMU    = SIZE = SCREEN SIZE VECTOR (MICROMETRES)
```

```
                    DATA ENTRY FOR: AIMILL
 THE DEFAULT VALUES OF NS,NG,NC,SOL & WAT ARE:

20 1 1 297. 0.

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES OF THE FEED DISTRIBUTION ARE:
1.5 6.32 3.07 6.71 5.78 10.28 13.16 11.66 8.93 5.94 4.95 3.16
2.47 2.04 1.5 1.17 1.1 1.12 1.19 7.95

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES OF THE PARAMETERS  RELATED TO THIS SIMULATOR ARE:
22.6 4770. 0. 0. 0. 0. 0. .0401668 .0686186 .0941232 .6977924
.3445871 .2218842 .112656 .1044727 .110841 .1066319 .0925776
.105502 .150353 .2508468 .9 .0352 .0002 .0007 .0011 .0018 .0022
.0026 .0026 .0026 .0026 .0026 .0026 .0026 .0026 .0026 .0026
.0026 .0026

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES OF THE OPTIONS  RELATED TO THIS SIMULATOR ARE:
0.

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES FOR THE ARRAY OF SIZES ARE:

152400. 107763. 76200. 53882. 38100. 26941. 19050. 13470. 9525.
6735. 4763. 3368. 2381. 1684. 1191. 842. 595. 421. 298. 0.

 CHANGE?(Y/N)
N

 THE DEFAULT VALUES FOR THE ARRAY OF SPECIFIC GRAVITIES ARE:
0.

 CHANGE?(Y/N)
N
```

AUTOGENOUS MILL OUTPUT (ATMILL)

SCREEN SIZE (MICRONS)	FEED % RET.	PRODUCT % RET.
152400.0	1.50	0.00
107763.0	6.32	0.00
76200.0	3.07	0.00
53882.0	6.71	0.00
38100.0	5.78	0.00
26941.0	10.28	1.99
19050.0	13.16	4.69
13470.0	11.66	5.66
9525.0	8.93	3.96
6735.0	5.94	1.46
4763.0	4.95	1.03
3368.0	3.16	.52
2381.0	2.47	.50
1684.0	2.04	.55
1191.0	1.50	.53
842.0	1.17	.47
595.0	1.10	.55
421.0	1.12	.80
298.0	1.19	1.31
-298.0	7.95	75.99

```
STOP
025600 MAXIMUM EXECUTION FL.
 0.358 CP SECONDS EXECUTION TIME.
```

5.7 FLTCLS

In the sample run for the program FLTCLS, the data apply for a flotation rougher bank of cells.

The flag to print starting data was set to 1 and corresponding output is included. Headings and descriptions are self-explanatory. Interaction with other bank types is similar.

```
        SIMULATION OF A FLOTATION CELL (FLTCLS)
        ---------------------------------------

 PROGRAM
 DESCRIPTION:  THIS IS BASED ON THE MODEL OF A FLOTATION CELL AND
 -----------   BANK OF CELLS BY MULAR AND BULL. AN INTERACTIVE
               METHOD USING LINEAR INTERPOLATION IS USED TO
               DETERMINE ESTIMATES OF TAILING VOLUME,
               CONVERGENCE BEING JUDGED BY THE DIFFERENCE BETWEEN
               SUCCESSIVE ESTIMATES.


THE PROGRAMS AND SUBROUTINES USED ARE:
--------------------------------------

  XFLTCLS,RDFILE,UDRIVR,FLTCLS,CELL,FLOUT1,FLOUT2

THE VARIABLES REQUIRED ARE AS FOLLOWS:
--------------------------------------

  NS      = NUMBER OF SIZE FRACTIONS (PAN INCLUDED)
  NG      = NUMBER OF SPECIFIC GRAVITY FRACTIONS
  NC      = NUMBER OF CHARACTERISTICS
  SOL     = FEEDS = MASS FLOW RATE OF SOLIDS IN FEED (STPH)
  WAT     = FEEDW = MASS FLOW RATE OF WATER IN FEED (STPH)

  FEED    = MASS DISTRIBUTION OF THE FEED STREAM

  PARAM   = PARAMETER VECTOR      - 1 = CONS
                                    2 = VOLCEL
                                    3 = NCELL
                        4 TO (3+NG*NS) = FCOEF
  CONS    = FROTH WATER FLOTATION RATE CONSTANT
  VOLCEL  = CELL VOLUME (CU. FT.)
  NCELL   = NUMBER OF FLOTATION CELLS IN BANK
  FCOEF   = FLOTATION RATE COEFFICIENT ARRAY
            (SPECIES I, SIZE J)

  OPT     = OPTION VECTOR         - 1 = IPRINT
  IPRINT  = PRINT OPTION
            0 = RESULTS PRINTED
            1 = RESULTS NOT PRINTED

  XMU     = VECTOR OF UPPER SIZES FOR THE INTERVALS (MICROMETRES)
  SG      = VECTOR OF UPPER SPECIFIC GRAVITIES FOR THE
            INTERVALS

  DER1    = TYPE = TYPE OF FLOTATION BANK
  DER2    = NAME = ARRAY OF NG NAMES OF SPECIES
            FOR TYPE OF BANK
```

```
ENTER FLOTATION BANK TYPE: ROUGHER,SCAVENGER OR CLEANER
rougher

                DATA ENTRY FOR : ROUGHER


 THE DEFAULT VALUES OF NS,NG,NC,SOL & WAT ARE:

9 4 1 324. 335.
 CHANGE?(Y/N)
n

 THE DEFAULT VALUES OF THE FEED DISTRIBUTION ARE:
.0005 .0001 .0082 .3016
.0101 .0002 .1932 6.5484
.0422 .0056 .5743 19.8843
.0876 .0115 .745 20.2085
.0969 .0108 .8158 15.5575
.0944 .009 .6759 11.7539
.0581 .0057 .5132 7.0319
.0282 .0031 .354 4.2388
.0458 .0086 .8556 9.2215
 CHANGE?(Y/N)
n

 THE DEFAULT VALUES OF THE PARAMETERS  RELATED TO THIS SIMULATOR ARE:
14.44 316.67 7. 0. 0. 0. 0. .0017 .0026 .0001 .0001 .0668 .1706
.0013 .0004 .2123 .4349 .0034 .0007 .266 .5057 .0029 .0008 .3187
.3894 .0033 .0009 .3132 .4458 .0034 .0014 .2665 .3229 .0023
.0016 .192 .1231 .0018 .0022
 CHANGE?(Y/N)
n

 THE DEFAULT VALUES OF THE OPTIONS  RELATED TO THIS SIMULATOR ARE:
0.
 CHANGE?(Y/N)
n

 THE DEFAULT VALUES FOR THE ARRAY OF SIZES ARE:

850. 425. 212.5 106.2 53.1 26.6 13.3 6.6 4.
 CHANGE?(Y/N)
n

 THE DEFAULT VALUES FOR THE ARRAY OF SPECIFIC GRAVITIES ARE:
4.2 4.675 5.018 2.581
 CHANGE?(Y/N)
n
```

ENTER NAME OF THE SPECIES FOR EACH SPEC. GRAVITY (16 CHAR. MAX.)
THE FINAL SPECIES MUST BE 'GANGUE'
chalcopyrite
molybdenite
pyrite
gangue

OUTPUT FOR A BANK OF FLOTATION CELLS

ROUGHER

OPERATING PARAMETERS

NUMBER OF CELLS	7	
NUMBER OF MINERALS	4	
CELL VOLUME	316.7	CU.FT.
PERCENT SOLIDS IN PULP	49.2	
FEED RATE (SOLIDS)	324.0	STPH OF SOLIDS
FEED RATE (LIQUID)	335.0	STPH OF WATER
FROTH CONSTANT	14.4	

IDENTIFICATION OF MINERALS	SPECIES NUMBER	SPECIES NAME
	1	CHALCOPYRITE
	2	MOLYBDENITE
	3	PYRITE
	4	GANGUE

FEED FRACTIONS
MINERAL SPECIES

SIZE	1	2	3	4
850.0	.0005	.0001	.0082	.3016
425.0	.0101	.0002	.1932	6.5484
212.5	.0422	.0056	.5743	19.8843
106.2	.0876	.0115	.7450	20.2085
53.1	.0969	.0108	.8158	15.5575
26.6	.0944	.0090	.6759	11.7539
13.3	.0581	.0057	.5132	7.0319
6.6	.0282	.0031	.3540	4.2388
4.0	.0458	.0086	.8556	9.2215
SP.GR.	4.20	4.68	5.02	2.58

FLOTATION RATE COEFFICIENTS

850.0	0.0000	0.0000	0.0000	0.0000
425.0	.0017	.0026	.0001	.0001
212.5	.0668	.1706	.0013	.0004
106.2	.2123	.4349	.0034	.0007
53.1	.2660	.5057	.0029	.0008
26.6	.3187	.3894	.0033	.0009
13.3	.3132	.4458	.0034	.0014
6.6	.2665	.3229	.0023	.0016
4.0	.1920	.1231	.0018	.0022

ROUGHER

INDIVIDUAL CELL OUTPUT

CELL NUMBER	PERCENT SOLIDS IN FEED	RETENTION TIME (MIN)	FROTH SOLIDS (TPH)	FROTH SOLIDS (%)	TAILS SOLIDS (TPH)	TAILS SOLIDS (%)
1	49.165	1.300	.803	39.472	323.197	49.195
2	49.195	1.304	.697	36.141	322.501	49.234
3	49.234	1.308	.620	33.489	321.881	49.278
4	49.278	1.313	.564	31.416	321.317	49.328
5	49.328	1.317	.523	29.818	320.793	49.380
6	49.380	1.321	.494	28.599	320.300	49.436
7	49.436	1.325	.472	27.676	319.828	49.493

FROTH MINERAL ASSAY (%)

CELL NUMBER	COMPONENT 1	COMPONENT 2	COMPONENT 3	COMPONENT 4	COMPONENT 5
1	43.654	6.733	6.273	43.341	
2	37.616	5.160	7.222	50.002	
3	31.711	3.903	8.111	56.275	
4	26.230	2.927	8.907	61.936	
5	21.359	2.186	9.595	66.860	
6	17.185	1.635	10.169	71.011	
7	13.710	1.229	10.635	74.426	

TAILS MINERAL ASSAY (%)

CELL NUMBER	COMPONENT 1	COMPONENT 2	COMPONENT 3	COMPONENT 4	COMPONENT 5
1	.357	.038	4.731	94.874	
2	.276	.027	4.726	94.971	
3	.216	.019	4.719	95.046	
4	.170	.014	4.712	95.104	
5	.135	.011	4.704	95.150	
6	.109	.008	4.696	95.187	
7	.089	.007	4.687	95.218	

MINERAL RECOVERY BASED ON FEED TO CELL

CELL NUMBER	COMPONENT 1	COMPONENT 2	COMPONENT 3	COMPONENT 4	COMPONENT 5
1	23.313	30.541	.328	.113	
2	22.741	29.257	.329	.114	
3	22.082	27.838	.330	.114	
4	21.331	26.323	.331	.114	
5	20.484	24.761	.332	.115	
6	19.545	23.207	.333	.115	
7	18.518	21.713	.333	.115	

MINERAL RECOVERY BASED ON FEED TO BANK

CELL NUMBER	COMPONENT 1	COMPONENT 2	COMPONENT 3	COMPONENT 4	COMPONENT 5
1	23.313	30.541	.328	.113	
2	17.439	20.321	.328	.113	
3	13.083	13.679	.328	.114	
4	9.847	9.334	.328	.114	
5	7.439	6.469	.327	.114	
6	5.644	4.562	.327	.114	
7	4.303	3.277	.327	.114	

ROUGHER

CUMULATIVE CELL OUTPUT

CELL NUMBER	RESIDENCE TIME (MIN)	FROTH SOLIDS(TPH)	FROTH SOLIDS (%)
1	1.300	.803	39.472
2	2.605	1.499	37.851
3	3.913	2.119	36.461
4	5.226	2.683	35.270
5	6.542	3.207	34.248
6	7.863	3.700	33.369
7	9.188	4.172	32.611

FROTH MINERAL ASSAY (%)

CELL NUMBER	COMPONENT 1	COMPONENT 2	COMPONENT 3	COMPONENT 4	COMPONENT 5
1	43.654	6.733	6.273	43.341	
2	40.848	6.002	6.714	46.436	
3	38.175	5.388	7.123	49.315	
4	35.663	4.870	7.498	51.968	
5	33.329	4.432	7.840	54.399	
6	31.175	4.059	8.151	56.615	
7	29.201	3.739	8.432	58.628	

MINERAL RECOVERY BASED ON FEED TO BANK

CELL NUMBER	COMPONENT 1	COMPONENT 2	COMPONENT 3	COMPONENT 4	COMPONENT 5
1	23.313	30.541	.328	.113	
2	40.752	50.863	.656	.227	
3	53.835	64.542	.984	.340	
4	63.682	73.875	1.311	.454	
5	71.122	80.344	1.639	.568	
6	76.766	84.906	1.966	.682	
7	81.068	88.183	2.293	.797	

```
   STOP
   032500 MAXIMUM EXECUTION FL.
    0.598 CP SECONDS EXECUTION TIME.
```

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