SIMULATION OF ORE DRESSING PLANTS - THE BASIC PRINCIPLES

What is Simulation?

In recent years many references appear in the literature to computer simulation as a technique for design and analysis of mineral processing operations. It has become a popular field of research and a great deal of good work has been done to make simulation into a viable and practical tool. Simulation is any procedure that can be used to model a process without actually running it. There are several ways in which a simulation can be achieved but, by far the most effective, is by digital computer. The digital computer is programmed to mimic the behavior of the actual plant and can provide a description of what the plant will do and how it will perform under a variety of circumstances. This is a useful thing to do because the computer can expose many aspects of plant performance without the inconvenience of operating the plant itself under experimental conditions. It is surprising how effective a good computer simulation can be in providing information about the behavior and performance of a mineral processing plant.

Simulation of a complex engineering system is only possible once a detailed understanding of each component of the system has been achieved and simulation provides the engineer with a tool for the prediction of system behavior even if the system does not exist in reality. However the simulator predictions can only be as good as the basic understanding of the component parts. The computer is an essential component of simulation for two reasons: in most systems of interest to the mineral processing engineer, the individual unit operations are so complex that they can only be usefully described in mathematical terms if these can be translated into computer code; in addition the systems of interest reveal complex interactions and interconnections among the individual units. In many cases these complex interactions cannot be described adequately by purely mathematical methods and the ability of the computer to transfer information from one program model to another is exploited effectively to simulate the transfer of actual material, information or energy in a real system. Purely mathematical formulations of complex systems are really effective only when the systems are linear in the mathematical sense. Then the full power of linear and matrix algebra can be brought to bear on the problem. Regrettably most systems of real interest are strongly non-linear and it is necessary to use the heuristic capabilities of the computer to take the place of purely mathematical descriptions.

The relationship between the model description and the real engineering system will be stressed several times during this course. This is vital and is the fundamental principle involved. A computer simulation is an abstract representation of reality constructed in computer code. To be useful it must

represent the appropriate aspects of the real situation in such a way that useful information can be gained. Models for the unit operations are synthesized from mathematical models of the component parts. We will be considering this in detail later in this course.

Simulation techniques have developed over the years and now it is possible to simulate the performance of a wide variety of systems of engineering interest. We will be interested specifically in the simulation of ore dressing plants. The simulator that we will be using has been developed so that it can provide a realistic description of the operation of any ore dressing plant. It is based on the best simulation techniques currently available and uses efficient numerical analysis procedures to ensure that the computations are done accurately and reliably.

What is an Ore Dressing Plant Simulator?

An ore dressing plant simulator is a set of computer programs that will give a detailed numerical description of the operation of an ore dressing plant. The simulator must be provided with an accurate description of the ore that is to be processed, a description of the flowsheet that defines the process and an accurate description of the operating behavior of each unit operation that is included in the flowsheet. The simulator uses these ingredients to provide a description of the operating plant. The detailed description of the ore will include information on its physical and mineralogical characteristics and a method to provide this information is described later. The flowsheet is the familiar graphical representation of the location of the unit operations in the plant together with the network of pipes and conveyors that transmit material between the units. The description of the operating behavior of the unit operations is what is known as modeling and it is necessary to accurately model the behavior of each unit operation before the entire plant can be simulated. In a sense the simulator links together the modeled behavior of each of the unit operations and synthesizes the overall performance.

Four fundamental concepts underlie the construction of an ore dressing plant simulator.

* Ore dressing plants are collections of unit operations connected by process flow streams that transmit material from one unit to the next. The flow of materials is directed by the flowsheet structure.

* Each unit operation processes its own feed materials and will separate it or transform it in accordance with the specific objective of the unit.

* The behavior of the plant as a whole depends on the operating characteristics of each of the unit operations as well as on the nature of the material that is processed in the plant.

* A simulator reduces the actual plant operations, as defined by the flowsheet structure and the behavior of the units, to a sequence of logical mathematical functions. The simulator can then mimic the real plant performance.

We will examine each of these concepts and discuss how they lead to the construction of a viable and reliable simulator. The basic concepts are independent of the precise nature of any particular plant that must be simulated and they lead to the development of simulation software that can be used for all possible plant configurations. The availability of such general purpose software makes computer simulation a useful practical tool in every day engineering. It is a difficult task to write the necessary computer code to simulate a complex ore dressing plant. Most engineers have neither the time, inclination nor skill to do so and it would not be cost effective to write the code for each application. The cost in man hours to generate the code and debug it so that it can run reliably would be enormous. Computerization of any complex engineering systems is a highly specialized business and this is true also in mineral processing and such activities should be attempted only by specialists. Several general-purpose simulators for ore dressing plants are now available and of these MODSIM offers the greatest versatility to the user to modify and adapt the models of the unit operations that are used by the simulator. The standard models that are provided in the package are based on the latest concepts from the modern mineral processing literature. Several of the models that are incorporated as standard have been developed by the author and are not available in any of the commercial simulators. MODSIM is particularly strong in the modeling of mineral liberation phenomena.

In order for a general-purpose simulator to yield useful information on the actual process to be simulated, it must have access to 3 important classes of information. These are defined in general terms as follows:

- The structure of the flowsheet - what unit operations are included and how they are connected.

- The nature of the material to be processed - its mineralogical composition and structure, the size distribution and the amount that must be processed.

- The operating characteristics of each unit in the flowsheet. This requires the full description of the unit operations (the unit models) and a specification of the unit parameters that define the operating characteristics of the individual units.

What can a simulator be used for?

A good simulator is a useful tool to the process plant engineer. Essentially the simulator can demonstrate what a plant will do under any particular operating conditions. It can do so cheaply and without any real risk to the production rate of an operating plant or it can do so before a plant has been built and it does so in the engineer's office.

A. Design studies:

At the design stage a good simulator can be used to

- help the design engineer to find the best flowsheet
- ensure that design specifications will be met under all required operating conditions
- choose the most suitable units
- size the units correctly and so eliminate wasteful over-design and avoid the catastrophe of under design
- optimize the plant operation by achieving best economic combinations of grade and recovery
- identify potential production bottle necks
- provide comparative assessment of competing manufacturers' equipment
- define the performance guarantees that should be met by suppliers
- find out what will happen if performance guarantees are not met.

B. Operating plant performance:

A good simulator can help the plant manager to

- get the optimum performance from his/her plant
- tune his plant to suit variations in feed quality
- find plant bottlenecks
- investigate performance changes by asking "what if" questions
- identify unit operations that are not properly understood
- make better use of those that are.

C. Pilot plant and laboratory investigations

- Test theoretical models for unit operations.
- Test scale-up rules for operating equipment.
- Plan experimental programs to get maximum information from well-designed experiments.

But remember that a simulator can be effective only if it gives a reliable and valid description of plant operations.

The Ore Model

Ore dressing is the process engineering technology that must necessarily come between the mining of mineralogical raw materials and the subsequent extraction processes that recover the useful metals. Ore dressing is directed primarily at the separation of individual minerals or groups of minerals from among the whole range of minerals that make up an ore body. Minerals are, for the most part, crystalline inorganic chemical species and the variety of crystal types is enormously large. Minerals are the raw materials from which are recovered individual elements that are chemically locked within the inorganic crystalline material.

The extraction of these elements by pyro- or hydrometallurgical processing routes is comparatively costly and the concentrating action of ore dressing processes can have a very significant effect on the cost of the extractive metallurgical processes. Because no chemical transformations are involved in ore dressing, the dominant processes involved are those which transform the physical nature of

material and separate solid material using a number of physical attributes of the solid materials to achieve the separation.

The crystalline nature of most mineral ores that occur in nature dictate that the minerals are present in more or less random admixture on a size scale that ranges from a few tenths of a micron up to a few centimeters. The physical separation of one mineral species from another can be achieved by the reduction of the solid material to the particulate state followed by the separation of particles by one or other physical means. The reduction to the particulate state is essential and the technology of any concentration processes is intimately linked to the nature of the particulate material that is produced by comminution of the parent ore. Indeed the transformation of the size of the material by comminution processes is the dominating transformation process that will be of concern to us.

The separation processes that are used to separate valuable mineralogical material from its associated waste or gangue are amazingly varied relying on a wide variety of physical properties of the minerals to effect a separation. The physical properties that are most widely used are the specific gravity and the magnetic susceptibility of the solid material. Very subtle chemical effects, notably the chemical properties of the mineral surfaces are also used with notable success to achieve the separation.

The emphasis in all of ore dressing technology is on the solid material in the particulate state and it is our ability to separate particles from each other that determine the success or otherwise of the ore dressing operation. The principles involved in all the unit operations of interest are associated with the behavior of individual or groups of particles in the equipment. In the early days of ore dressing technology, (the historical records extend back over some two thousand years), the processes were developed on the basis of an empirical understanding of the behavior of particulate solid material in a variety of different situations. During the past three decades or so, the emphasis has shifted to an analysis of the particle mechanics in the unit operations that have evolved on the basis of the earlier empirical understanding. The basic principles of all the major unit operations of ore dressing are now comparatively well understood and these basic principles can be used to analyze the particle mechanics involved in each unit operation. The operation of the unit as a whole is determined by the sum total of the behavior of all the solid particles as they are processed.

MODSIM is designed to exploit the modeling techniques that are based on the particle mechanics of the ore dressing unit operations. The models used in MODSIM are based on the particulate nature of the solid material that is processes and, as a result, models of considerable complexity can be devised and used for the description of the unit operations. This ability to accommodation models of considerable complexity gives MODSIM their versatility and power and a thorough

understanding of the particulate description of the solid material is required to take advantage of the very many advances that have been made in ore dressing modeling techniques during the past three decades.

The Particulate State

The particulate state is usually defined as describing solid material that is reduced in size to particles that range from a few hundredths of a micron to a few centimeters. For solid material of mineralogical origin this size range implies that 1 kg of material will consist of a very large number of particles (ca 1 billion cubes of size 10 μm). Commercial ore dressing plants process many thousands of tons of raw material per day so that the number of particles involved is exceedingly large.

Although the models of ore dressing unit operations are based on the behavior of individual particles in the environment of the process equipment it is quite out of the question to attempt to keep a track of each particle as it passes through the unit operations let alone the complete plant flowsheet with its multiplicity of units and complex flow topology. It is this fact more than any other that has determined the data structures that are required to give a valid description of the particulate solids and still be comprehensive enough to exploit the basic concepts of particle mechanics to provide a description based on sound physical principles.

Because of the large numbers of particles involved it may be tempting to look to chemical processing to provide an analogy for the model structures. This is precluded because of one very significant fact: the basic entities for chemical processing are molecules which for a given compound have invariant properties while for ore dressing the basic entities are particles, no two of which can every be identical. We are therefore faced with the problem of devising a mathematical description that is capable of accommodating the large population of individual particles while still acknowledging the variation of properties from particle to particle. Fortunately a powerful mathematical structure, which borrows heavily from the mathematical theory of probability is readily available and is forming the basis for all of the modern developments in the modelling of ore dressing operations.

The description of the particulate material is based on the concept of the distribution function which is most familiar as a descriptor for the particle size distribution. The notation is straightforward and is very simple to relate to measurements that are made in the laboratory as is shown in the following section.

The particle size distribution.

The most obvious characteristic of a particle that is significant from the point of view of its behavior in an ore dressing operation is its size. Size itself if very difficult to define precisely but fortunately the method of description to be used does not require precise definition nor precise experimental determination of particle size. Considerable leeway is permissible without compromising the accuracy of the method. The most common measure of particle size is the smallest square wire mesh that will permit the passage of the particle under gravity with prolonged shaking. Such a size is readily measured in the laboratory to sufficient precision for practical purposes by the familiar sieve analysis procedure.

The essential feature of the mathematical description is the particle size distribution function $F(d_p)$ defined as follows:

> $F(d_p)$ = mass fraction of particles in the population that will pass through a square mesh sieve having an opening with side = d_p

$P(d_p)$ is an ordinary function of d_p but it does have some important properties that should always be borne in mind. These properties are:

$$P(0) = 0$$
$$P(\infty) = 1$$
$$P(x) \geq P(y) \text{ whenever } x \geq y$$

The value of P is measured experimentally at a number of fixed sizes that correspond to the mesh sizes of the set of sieving screens that are available in the laboratory. This data is usually presented in tabular form showing mesh size against fraction smaller than that mesh. Graphical presentations are very useful and are often preferred because it is generally easier to assess and compare particle size distributions when the entire function is immediately visible. A variety of different graphical coordinate systems have become popular with the view to making the distribution function plot as or close to a straight line. The particle size axis, usually the abscissa is plotted on a logarithmic coordinate scale. The ordinate scale works according to whether the distribution function $P(d_p)$ is close to log-log, log-normal or Rosin-Rammler. Specially ruled graph papers are available for this purpose and three typical rulings are given in the appendix. The mesh sizes in the standard sieve sizes vary in geometric progression with each mesh size a constant factor larger than the previous one. The constant factor is usually a fractional power of 2 (very often $\sqrt{2}$). Such a geometric series will plot as a series of equidistant points on a logarithmic scale.

Although the distribution function $P(d_p)$ is perfectly well defined and is amenable to direct measurement in the laboratory, it is not directly useful in most cases for modelling of ore dressing unit operations. For this purpose a derived density function is used. The discrete particle size density function $p_i(d_p)$ is defined as follows:

$f(d_p)\,\Delta d_p = F(d_p + \Delta dp) - F(d_p)$

= mass fraction of the particle population that has size between d_p and $d_p + \Delta d_p$

Δd_p is the so-called size class width and is usually not constant but successive values form a geometric series. This leads to the idea of a particle class which includes all particles in the population which have properties falling in a narrow size interval or class. If the interval is sufficiently small it is possible to assign a single value to the property that defines the class so that each particle in the class may be assumed to behave as a particle having the class average property. In the case of particle size this representative size is generally taken as the geometric mean except for the two extreme classes which have no geometric mean. It is usual to extend the average sizes as geometric series to the two extreme classes and this is generally satisfactory in practice. MODSIM operates with the individual particle classes and consequently the particle size distributions must be specified in the differential form.

The key to the success of this approach to ore dressing modelling is the use of narrow class interval so that the behavior of all particles in the class can be realistically modelled using the class-average property. This in turn implies that a large number of particle classes must be specified. MODSIM is created specifically to handle large numbers of particle classes efficiently and is thus an ideal vehicle for the simulation of ore dressing flowsheets using accurate particulate models. The extra effort required to make these accurate calculations is removed entirely from the user.

A typical specification of the size distribution for the feed to a ball mill circuits is shown in Table 1. This is based on a standard $\sqrt{2}$ series and covers the range from 2,78mm to approximately 30 microns in 15 classes. MODSIM will normally use more size classes for its internal calculations than are used to specify the size distribution of the plant feed streams. The Users Manual should be consulted for details of the methods that are used to specify the size distributions and to select the numberof size classes to be used in the calculations.

Mineral Liberation and the Grade Distribution

The mineralogical composition of the particles that are processed in ore dressing operations varies from particle to particle and this is of paramount importance in the operation of ore dressing equipment. The very objective of ore dressing operations is the separation of mineral types to produce concentrates having a greater relative abundance of the desired mineral. The objective of the comminution operations is the physical separation of the minerals by fragmentation. Unfortunately, except in very favorable cases, the minerals do not separate completely and many particles, no matter how finely the material is ground, will contain a mixture of two or more mineral species. Some particles will indeed be composed entirely of a single mineral and they are then said to be completely liberated. The amount of mineral that is liberated is a very complex function of the crystalline structure and mineralogical texture of the ore and the interaction between these and the fracture pattern that is induced by the comminution operation. Considerable research has been devoted to the liberation phenomenon in recent years and several good models are available to describe the liberation characteristics of an ore. In order to properly allow for incomplete liberation of the mineral species an additional distribution function is defined but before this is done it is necessary to devise a method for representing the mineralogical composition of a particle.

TABLE 1.1 Particle size distribution in the rod mill product

Size class	Size interval microns	Representative size microns	Particle size distribution density %
1	+2360	2780	2.4
2	-2360 +1700	2000	3.1
3	-1700 +1180	1416	4.0
4	-1180 +850	1000	5.0
5	-850 +600	714	6.6
6	-600 +425	505	9.1
7	-425 +300	357	13.1
8	-300 +212	252	16.4
9	-212 +150	178	12.7
10	-150 +106	126	7.6
11	-106 +75	89	4.9
12	-75 +53	63	3.7
13	-53 +38	45	2.8
14	-38 +27	32	1.8
15	-27	22	6.8

When only two mineral species are involved, say a valuable mineral and a gangue, this is not difficult. It is necessary only to specify the mass or volume fraction of the particle that is composed of mineral. We normally use the symbol g to represent this fraction (the grade of the particle). When more than two mineral species are relevant the situation is somewhat more complicated and *g* will be a vector having more than one component, each component representing the mass fraction of a single mineral species. The fractions must accordingly sum to unity. To handle this complexity the concept of the distinct particle type is defined. Just as in the case of the particle size, finite classes are defined each of which is characterized by particles of an average mineralogical composition. The number of classes that should be used will depend on the mineralogical complexity and the liberation characteristics of the ore that is to be processed in the simulated process. One class is usually allocated to each of the pure minerals that are present because it is assumed that some of each mineral is perfectly liberated. MODSIM will automatically allocate such perfectly liberated classes but will only allocate particle classes to accommodate incompletely liberated minerals if specifically requested by the user. If such a request is made, the user must define the particle composition that is required to define each particle type. The most common example of this scheme for the classification of particle types is the familiar washability data for coal. The standard washability analysis separates the coal into a number of narrow relative density classes each one of which can be characterized by the ash content of the coal. The greater the ash content the greater the relative density. A typical washability analysis for a sample of coal is given in Table 2.

TABLE 1.2. Typical washability data for coal.

Particle Type	Relative Density Interval	Fractional Yield %	Cumulative Yield %	Ash Content %
1	F1.30	18.64	18.64	4.30
2	1.30-1.32	11.15	29.79	5.11
3	1.32-1.34	6.67	36.47	6.22
4	1.34-1.36	7.12	43.58	7.15
5	1.36-1.38	6.87	50.45	9.04
6	1.38-1.40	6.22	56.67	10.80
7	1.40-1.42	5.47	62.14	12.20
8	1.42-1.44	5.04	67.18	13.90
9	1.44-1.46	5.02	72.20	16.10
10	1.46-1.48	4.60	76.80	17.90
11	1.48-1.50	3.77	80.57	21.30
12	S1.50	19.42	100.0	40.60

The equivalent data specification for use within MODSIM is given in Table 3. Note that no particle classes have been allocated to completely liberated particles because perfectly liberated coal and ash particles are never observed.

For accurate and reliable simulation of coal washing plants it is necessary to specify the washability of the coal in as many size fractions as possible. MODSIM can accommodate such data easily and in fact will give greatly enhanced performance when more complete data are available.

A number of convenient data input formats that are specific to coal are provided in MODSIM. If the proximate analysis is available for each washabilty fraction in each size class, this data can be input directly and MODSIM will then calculate the proximate analysis of the material in every stream of the plant. This will give a very compltete description of the coal washing operation. MODSIM will require as a minimum the ash content for each washability fraction. MODSIM will also keep track of the calorific value and the sulfur content (both pyritic and organic) in each process stream including the products. See Table 4.5 for an example of the summary output from the simulator when the proximate analysis, the calorific value and the sulfur content are known in each washbilty fraction of the feed material.

No comparable standard data formats are in common use for other mineral systems so that the mineralogical composition must be specified for each particle type. This is the liberation spectrum for the ore. It is now becoming quite common to see the liberation spectrum for binary ores specified in 12 particle classses - one for each of the lberated minerals at each end of the spectrum and ten classes that describe the mixed particles at intervals of 0.1 in g. Ores with more than two mineral components that must be described using more particle type classes and it is only recently that liberation models for multicomponent materials have been developed.

The liberation spectrum is of course a strong function of the size of the particle. In general the finer the particle the more likely to find particles that are completely liberated. It is necessary therefore to specify the distribution of material among the particle types for each size class. However, if the plant that is to be simulated includes comminutiom units, it is often sufficiently accurate to assume that all the feed material is concentrated in the particle type class that includes the average mineral composition. The liberation of the minerals will be generated by MODSIM's liberation model. MODSIM cannot accommodate variations in the mineral distribution for the grade classes for the various particle sizes. In general that would not be necessary even for the most detailed of unit models.

TABLE 1.3 Data from Table 1.2 specified in a format suitable for use within MODSIM.

Particle type	Mineral distribution for this type	Distribution density of particle types	Specific gravity of this type
1	0.9570 0.0430	0.1864	1.10*
2	0.9489 0.0511	0.1115	1.31
3	0.9378 0.0622	0.0667	1.33
4	0.9288 0.0712	0.0712	1.35
5	0.9096 0.0904	0.0687	1.37
6	0.8920 0.1080	0.0622	1.39
7	0.0878 0.1220	0.0547	1.41
8	0.8610 0.1390	0.0504	1.43
9	0.0839 0.1610	0.0502	1.45
10	0.8210 0.1790	0.0460	1.47
11	0.7870 0.2130	0.0377	1.49
12	0.5940 0.4060	0.1942	1.67*

* estimated from a plot of % ash vs l/sp. gravity

Physical Properties of the Particles

All ore dressing operations rely on one or another physical property to effect the desired concentrating action in the unit. Since the objective of ore dressing is the separation of the valuable minerals from the others, it is necessary that the physical properties vary from particle to particle. The variation of physical properties can very conveniently be accounted for by specifying the value of the physical property for each particle type. Each particle in the type class may then be considered to have the value of the physical property assigned to that type class.

The most important of the physical properties that is used in ore dressing is the particle specific gravity. This property forms the basis of all the gravity, dense medium and centrifugal separation processes and, after flotation, these processes account for the largest tonnage of material processed. The specific gravity of a particle is determined by its mineralogical composition. Thus the specific gravity of a composite particle is a weighted sum of the specific gravities of the constituent minerals with the weighting coefficients being the volumetric fractions of the mineral components. MODSIM therefore will compute the specific gravities of each particle type once the distribution of minerals has been defined for each particle type and the specific gravities of the individual minerals have been specified. This is the natural method of specification and relieves the user of the burden of calculating a specific gravity for each particle type. However in some situations it is not possible

to specify the specific gravity of the pure mineral species. This is true for example with coal since the carbonaceous material in coal is made up of a mixture of macerals and definite specific gravities cannot be assigned to the individual mineralogical components. Under these circumstances it is necessary to determine the specific gravity of each particle type by direct observations. This is precisely the situation with coal when the washability function is determined because the mean specific gravity of each washed fraction is immediately known from the specific gravities of the liquids at each stage of the washability analysis. This is illustrated in Table 3. MODSIM will request the user to specify whether specific gravities of individual minerals will be specified or whether the specific gravities of the particle types will be specified.

Other physical properties may also be specified and the user can specify as many as are required to suit the models that are ultimately to be used in the simulation.

Within MODSIM the physical properties are identified by number and are available to the model subroutine through the array PPROP. The disposition of physical properties in this array is indexed according to array INDPP as described in section 4.7. This gives the user access to the physical properties for use within his model subroutines.

Distribution of Flotation Rate Constants

The distributed rate constant model for flotation has become so widely accepted that special provision has been made to specify a distribution of rate constants as primary data is MODSIM. Each particle type can have associated with it a distribution of flotation rate constants. The user is required to specify the total number of rate constants that will cover all the particle types. The distribution of particles over these flotation rate constants must be specified for each particle type. The distribution over every rate constant must be specified but zero values are permitted.

As an example consider the situation in which two minerals are to be separated by flotation. Assume that the mineralogy and liberation characteristics can be adequately accounted for by classification into three particle types: liberated mineral, liberated gangue, and a middling. Many mineral systems have a flotation behavior that can be characterized by classifying each particle type into a floatable and nonfloatable component. It is in fact remarkable how accurately many flotation systems can be modelled on this simple basis. Assume that this description is adequate for the present example and then four flotation rate constants will be required and the distribution of particles over these rate constants for each of the particle types may be as shown in Table 4.

A further facility is provided by MODSIM regarding the specification of flotation rate constants. In general the flotation rate constants for a particular particle type will vary from flotation bank to flotation bank. This could be due to interstage addition of reagents or to changes in the chemical environment as pulp moves as flotation concentrates to cleaner stages. Another factor that contributes to variation of flotation rate constant is the change in the nature of the froth particularly in cleaner plant simulation, the user can specify whether he wishes to specify special value of the flotation rate constants at every separate bank of flotation cells. The distribution of particles of a particular type over the rate constant classes may not however be changed. In other words any particle that is in the slow floating class remains in that class. It is only the value of the rate constant for that class that changes.

Plant Feeds and water Addition

MODSIM can accommodate multiple feeds to the plant that is being simulated. The characterization of the feed material for each feed must be done according to the methods described in the previous sections. Material in all of the feeds must have identical class structures but the distribution of particles over the classes can vary from feed stream to feed stream. For example if the plant takes a feed of coarse material and a feed of fine material, the particle size distribution will be very different for the two feeds. However both feeds must have their size distributions specified against the same size class intervals. Obviously the coarse feed will have none or very little material in the fine size classes and the fine feed will have nothing in the coarse size classes.

Table 4. Example of Distribution of Flotation Rate Constants.

Particle Type	Distribution of particles over rate constants			
	k_1	k_2	k_3	k_4
1. Liberated mineral	0.8	0.0	0.0	0.2
2. Middlings	0.0	0.7	0.0	0.3
3. Liberated gangue	0.0	0.0	0.5	0.5

Here $k_1 \geq k_2 \geq k_3 \geq k_4 = 0$

The tonnage and water content of each feed must be specified. Dry feed is permissible. Water feeds may be added although these should be added to mixers or sumps only, never directly to a unit. This is not an important restriction since it is always possible to precede any unit with a mixer if water

is to be added to the unit. Two options are provided for the specification of water addition rates: the absolute addition rate may be specified or alternatively the user can specify the percentage solid that is required in the stream that leaves the mixer or sump to which the water is added. In the latter case, MODSIM will continuously adjust the water addition rate to match the calculated total solid rate in the sump discharge to maintain the requested percentage solids. This device is very useful for the simulation of control actions that are incorporated to maintain a specified solids content in the slurry at any point in the flowsheet.

Models for Ore Dressing Operations

The modular design of MODSIM has been developed specifically to give the user complete freedom in the choice of models for the unit operations. The only restriction on the models is the basic structure that requires that a unit model should be capable of receiving the details of the unit feed from the simulator and producing the appropriate product streams. This, of course, is the natural function of a unit model since it mirrors the actual behavior of the unit which transforms a feed material into the appropriate product streams. The details of the feed material provided by the simulator to the model subroutine is in accordance with the particulate model of the solid phase that has been described above. The subroutine is supplied with the mass flowrate to the unit in every particle class that has been defined. The parameters for the appropriate unit model as well as the vector of physical properties are also available to the model subroutine. The water rate in the feed is also supplied. This information gives the user almost unlimited scope to include models as simple or as complex as is desired to model the unit operations. Details of the subroutine structure are given in section 4.7.

Examples of Some Simple Simulations

EXAMPLE 1 Ball mill circuit

A ball mill operates in closed circuit with a hydrocyclone classifier. It processes rod mill discharge at 800 tons solid per hour. The size distribution of the feed is the rod mill discharge given in Table 1 in section 2.1 and the pulp is 76% solids. The circuit flowsheet is shown in the diagram. The hydrocyclone should be operated at 50% solids. The size of the mill will give a residence time of 7 mins. The ore can be taken as silica having a specific gravity of 2.67.

Draw the flowsheet using MODSIM and specify the necessary data.

Simulate the circuit and obtain the size distributions in the feed and the product.

Investigate the effect of hydrocyclone diameter on the D_{50} cutsize.

Investigate circuits with 1, 2 and 3 hydrocyclones in parallel.

The output file and report file together with a plot of the particle size distributions is included in Appendix 1.

EXAMPLE 2 Flotation cell

The flotation constants associated with the ore described in Table 4 are $k_1 = 1.23 \times 10^{-2}$ s^{-1}, $k_2 = 5.12 \times 10^{-3}$ s^{-1}, $k_3 = 8.2 \times 10^{-4}$ s^{-1}, $k_4 = 0$

Simulate the operation of a single 4-cell rougher bank of cells. The feed pulp density is 34% solids and solid holdup in the cells is 450 kg solid/m^3 of cell volume. Plot the grade-recovery relationship as cell volume varies from a m^3 to 10 m^3. The feed rate is 135 tons/hr. The effect of particle size on the flotation kinetics can be ignored and the unliberated particles may be assumed to contain 16.8% mineral on average. The feed contains 10% liberated mineral, 5% unliberated particles and 85% liberated gangue.

Note: The simple kinetic model with distributed rate constants should be used for the flotation cells. This is identified as model FLTN in MODSIM.