MINDEV 97

PAPER NO 10

METALLURGICAL PROCESS DEVELOPMENT FOR PLANT DESIGN

DAVID LUNT, IAN RITCHIE, JOHN FLEAY
MINPROC ENGINEERS LIMITED
LEVEL 8, 140 ST GEORGE'S TERRACE
PERTH WA 6000

TELEPHONE 08 9347 4777
FAX 08 9347 4747
E-MAIL MINPROC@PERTH.NET

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

ABSTRACT

The key issues in the conceptualisation and testing of treatment options for gold and base metals mineral processing projects are discussed. A prerequisite of this process is the need for close interaction between geologists, mining engineers and metallurgists to facilitate an understanding of the orebody based on the parameters impacting on each discipline. Typical testwork programs for unit operations, including comminution, flotation and gold processing are described.

INTRODUCTION

The development of a suitable process to treat an orebody appears, on the face of it, to be a relatively straightforward matter. However, selecting the optimum process whilst maintaining the overall project development schedule is a complex task. This requires careful balancing of time and budgetary constraints against the benefits of a more closely defined process design.

The key to a successful process plant design is the implementation of a well-structured, comprehensive testwork program. It is important that this program is developed and executed in parallel with the exploration of the deposit and that the results are used to assist in the planning and understanding of the continuing exploration.

Testwork programs for gold and base metals projects are discussed in the context of:

- Mineralogy and sample selection;
- Comminution circuit design;
- Flotation circuit design;
- Refractory gold plant design;
- CIP/CIL plant design; and
- Additional testwork requirements.

Whilst this paper focuses on the technical aspects of development programs, it is recognised that other elements can have a major bearing on a successful outcome. These include the quality of management and the organisation of the team. Integrated teams that include key personnel from the consultant and resource owners organisations are recommended as means of facilitating a smooth transition from the study to project execution.

MINERALOGY AND SAMPLE SELECTION

A key objective in the achievement of an optimal process design is to ensure that a circuit and reagent scheme is developed that can cater for the variability in the orebody, whilst still providing near optimum economics on the majority of the process plant feed.

An understanding of the geology and mineralogy of a deposit, and the consequent sample selection for testwork, has a significant impact on the effectiveness of the plant design. The following factors are important in ensuring that an integrated approach to the design of the processing plant is achieved:

- understanding the deposit from a process perspective by the geology and mining disciplines;
- detailed evaluation of geology, mineralogy and mining method of the deposit by the process design team; and
- assessment of the metallurgical requirements for sample selection.

Frequently, there is insufficient interaction between the major disciplines and this can adversely affect the costs and schedule of the process design phase and, ultimately, the commissioning and operation of the project.

UNDERSTANDING THE DEPOSIT FROM A PROCESS PERSPECTIVE

The basic mineralogy and geology of a deposit dictate the plant design and testwork requirements and it is important that the whole team has an appreciation of the extractive metallurgy of the ore.

For this to occur, process input is required early in the exploration phase to ensure that potential process issues are addressed. For example, exploration drilling and geological analysis can infer a potentially economic gold deposit based solely on gold grades. However, process factors, such as refractoriness leading to low recovery or gangue components leading to high reagent consumption, can complicate the processing of the ore and may render the deposit uneconomic.

It is necessary that such issues are identified and understood so that process variables can be assessed throughout the evaluation phase. Scoping metallurgical testwork can be used to evaluate process options that, in turn, can significantly impact on the exploration and geological requirements.

It is also important that the exploration and mining teams have an understanding of the potential process implications of the ore. It is not uncommon that a deposit is almost completely explored and a mine plan developed without qualified process input. This can create a disjointed approach to the development of the project. The mine plan can be completely at odds with the optimum processing requirements. Either the process design has to be modified to suit the mine plan or a new iteration of the mining plan is required to better suit the processing requirements. Either way, both money and time can be wasted. The optimum mine plan must recognise the balance between low cost, bulk, non-selective mining and the requirements of the process plant in treating the different ore types within the orebody.

DETAILED EVALUATION OF GEOLOGY AND MINERALOGY

Before designing a sample collection and testwork program, a thorough understanding of the ore types to be processed is necessary. The process design team must be able to categorise the deposit into areas possibly requiring different processing methods. Therefore, the first stage in the process design must be a complete review of the geology and mineralogy of the deposit. In parallel with this, the mining methods and mine plans should also be assessed. Whilst the results of testwork programs can be used to differentiate between ore types, in the authors' experience the cost and time requirements for testwork programs can be reduced significantly through prior use of geological and mineralogical data.

Factors that should be considered in the sampling and testwork program include :

- *General ore type* : The general type of ore will ultimately dictate the plant design and the detail of sampling and testwork required. A simple, near-surface, free-milling gold ore may require only a small amount of sampling and testwork. A complex base metals sulphide deposit will dictate a much more detailed sampling and testwork program due to the increased technical complexity and risk associated with the plant design.

- *Multiple deposits* : It is common that ores from multiple deposits or pits will be treated in one processing plant. These deposits may vary significantly and may impact on the whole methodology of the project development. It is also important to understand the metallurgical variability within each of these deposits, regardless of how small they may be.

- *Different ore lodes or lenses* : Within a single deposit, there can be significant changes in ore characteristics between different lodes or lenses.

- *Rock type variations* : There may be significant variations in rock types, both in the ore and in host rock, that should be considered.

- *Depth* : Mineralogy often changes with depth. The process plant typically receives ore from different depths, in accordance with the mine plan, especially from open pits. Hence, depth is a variable to be accounted for in the design of a sampling program. Oxidation of the upper areas of a deposit commonly leads to the formation of oxide and transitional ore zones above the primary ore zones. Each zone can respond differently to a metallurgical process, and a staged approach to processing may be required with different processing strategies for each ore zone. The successful design and rapid start-up of the Ashanti Sansu project in Ghana was in no small part due to lessons learnt during the commissioning of other projects in the area. These included a better understanding of the impact of oxidation of the sulfide minerals through a deep transition zone between oxide and sulfide zones (Lunt, Ritchie and Kirby, 1994).

- *Head grade* : Head grade of valuable metal is often the only quantitative datum available across the deposit. Therefore, sample collection and testwork should recognise head grade as an important variable. It is important that head grade analysis is not confined to the valuable elements, but also includes those elements which can constrain throughput and recovery, eg. sulfur and arsenic values. Failure to recognise this has been noticeable in some recent refractory gold projects. It is a significant omission, since the throughput of the oxidation circuits is dictated by sulfur grade.

- *Mining plan* : The mining plan dictates a schedule of ore delivery to the process plant. The ore characteristics can significantly change over the life of the mine and may influence the plant design. The requirement for campaign processing or blending of ore types should be considered.

In the case of Kanowna Belle, soft oxide ore encountered early in the life of the mine allowed a staged plant design. The Stage 1 plant consisted of a relatively low capital cost plant with the ability to treat high tonnages of oxide ore through a simple CIL circuit. Harder, refractory ore encountered several months after start-up required additional crushing within the comminution circuit, the addition of a refractory processing circuit and operation at a lower throughput. This staged design reduced the initial capital cost of the plant and maximised initial gold production (Lunt and Lane, 1997).

METALLURGICAL REQUIREMENTS FOR SAMPLE SELECTION

The aim of a sampling program is to collect the optimum number and quantity of samples that allows a suitable plant to be designed and metallurgical performance to be predicted.

For a completely homogenous orebody, a single sample could be used. However, no deposit is this simple and, typically, there are variations of rock type, ore grade and mineral occurrence with which to contend. A single representative sample, composited from a weighted average of all ore types, might be suitable for evaluation of plant design and metallurgical recovery and grade. Unfortunately, ore is seldom presented to the processing plant in such a manner.

Unless a significant blending process is allowed for prior to processing, varying ore types can be mined and processed with little or no blending. The design of the plant, therefore, has to cater for the anticipated schedule of ore for treatment and sample collection must recognise this.

Typically, three major sample types are used in the metallurgical evaluation of a deposit :

- *Variability samples* : These are individual drillhole intersections or specific composites that represent ore types exhibiting different metallurgical responses, as indicated by the mineralogy/geology and expected process performance. They are used to assess the variability of the orebody, to determine whether the plant design will be suitable for all ore types, and to evaluate metallurgical recovery and/or grade. In this context, it is also important to ensure that testwork is carried out on samples representing the ore to be fed initially to the plant.

- *Composite samples* : Composite samples are used for testing reagent or flowsheet variables where comparative testwork must be carried out on the one sample. Typically, several composite samples may be required to assess the major ore types. The number of these composites needs to be rationalised to minimise testwork costs and time.

The composites should represent the ore types that will dictate the plant design, eg. the hardest major ore type, the most difficult ore to float, etc. Factors that should be considered in sample composition and representivity include:

  - metallurgical and geological definition of the "ore type"
  - variability of the ore (continuity of mineralisation)
  - the number of intersections included in the composite
  - the drill hole intersection angles through the orebody
  - special distribution of intersections
  - weighting of intersection samples to make up the composite

There is little value in trying to achieve a representative composite of the entire deposit, as the processing plant will probably never treat such ore at any one time.

- *Bulk samples :* Bulk samples are used for pilot plant testing or large scale tests. Pilot plant tests are usually required to demonstrate a high risk process, to increase the confidence level on a marginal project or for the production of concentrate or other downstream products for other testwork (eg. roasting). Pilot plant testwork does not necessarily provide better testwork data than bench scale work and should be evaluated carefully in terms of the high cost of sample collection and the difficulty in achieving adequate sample representation.

Representation of such samples is a major issue. The cost of large scale drilling, a trial pit or shaft usually dictates the mining of ore from the upper parts of the deposit and the resultant sample is typically transitional to some degree, and may not be representative of the design ore type. This factor demands a correlation of results with those of the design ore types by laboratory testwork, adding another variable to the process design. If design proceeds on the basis of a bulk sample which represents only one ore type or part of the deposit, there is significant scope for subsequent problems in plant operation. As cost is likely to preclude bulk samples of all ore types, it is important that standardised test methodologies or regimes are used to correlate the performance of the bulk sample with other ore types.

There are several types of sample material commonly used for metallurgical testwork :

- *Reverse circulation (RC) drill chips* - Fundamental problems caused by the stratification of heavy particles within RC drill chip samples can result in poor representation. The RC chips also tend to have a bimodal size distribution, with both coarse chips and a large amount of very fine material. The problem is exacerbated with friable ore types, eg. sericites, and can affect testwork results. This leads to another problem arising from the potential oxidation of the sample due to the high fines content. Despite the problems with RC drill chips, the low cost of sample collection compared with other methods makes it a popular choice for simple metallurgical tests such as gold and copper leaching tests. Their use in comminution and flotation tests should, generally, be avoided.
- *Diamond drill core* - Fresh diamond drill core provides excellent material for metallurgical testwork. Comminution and flotation testwork generally requires drill core of varying sizes to achieve satisfactory results. NQ (50 mm) and HQ (63 mm) diamond drill core is commonly available from the exploration phase. The core is usually cut into quarters. Typically, only one quarter will be available for metallurgical testwork. There is a number of comminution tests that require at least whole (uncut) HQ core or whole PQ (75 mm) core. Drilling program plans should account for these process sample requirements and may need to include holes drilled specifically for metallurgical sample collection.
- *Trial mine samples* - Large samples can be generated from RC chips or drill core, but, as the quantity requirements increase, trial open cut or underground mining may become more economic. Unfortunately, costs usually impose significant limitations with mined bulk samples. Further details of sampling methodology and statistics are provided by Sinclair (1980)

COMMINUTION CIRCUIT DESIGN

Comminution circuits invariably account for a major portion of the capital and operating costs of the process plant. Therefore, the design and engineering of this unit operation, play a major role in maximising the net present value of the project. Decision-making in this area has, as one of its key objectives, the need to balance operating phase risks against capital costs.

A number of flowsheet options exists for the comminution of primary crushed ore, the most common of which are:

- stage crushing followed by rod and/or ball milling;

- single stage semi-autogenous grinding (SAG) or fully autogenous grinding (FAG); and
- two stage milling, incorporating fully or semi-autogenous milling, followed by ball or pebble milling.

The above listing is not exhaustive and there are numerous variations within the broad circuit types.

Nowadays, staged crushing followed by rod and/or ball milling tends to be of limited application, and is typically limited to smaller plants (<1.5 Mt/a) treating harder, more competent ores. The industry is now relying more and more upon SAG milling and to a lesser extent on autogenous milling, primarily due to the lower capital cost and simpler operation.

TESTWORK REQUIREMENTS

The testwork requirements for SAG milling are greater than for conventional milling and must be carefully planned due to cost and the possible large sample requirements. A hierarchy of testing methods exists, broadly along the lines summarised in Table 1:

Table 1

Testwork Hierarchy

Test	Typical Sample Requirement	Applications
Large scale pilot runs	20 - 100 t of bulk sample	Prior to detailed design
Small scale continuous piloting	200 kg of ore or drill core	Final Study, variability
Advanced Media Competency	100 kg of ore or drill core	Final Study, variability
Physical properties	10 - 25 kg per test	Preliminary study, variability

Several testing methods are available, and the sample requirements are listed in Table 2. Further details of the test procedures can be found in the bibliography at the end of this paper.

Table 2

Comminution Testwork Procedures

Test	Feed Size	Sample size
Unconfined compressive strength	50 mm	~ 10 kg
Bond crushing work index - low energy - high energy	 - 90 + 60 mm - 40 + 20 mm	 10 kg 10 kg
Bond rod mill work index	- 12.7 mm	25 kg
Bond ball mill work index	- 3.35 mm	25 kg
Bond abrasion index	- 20 + 12 mm	5 kg
JK Tech parameters (Dropweight or pendulum test)	 - 100 mm	 100 kg
Advanced Media Competency	- 200 mm PQ drill core	~ 1 000 kg ~ 150 kg
A.R. MacPherson test	40 mm	~ 200 kg
Minnovex test	25 mm	2 kg
Pilot plant	200 mm	~ 10 - 15 t per trial

A key aspect of testing is the required feed size. It is common for "critical size" problems to occur in SAG milling at particle sizes coarser than 30 mm. The Advanced Media Competency test and pilot plant testing can both provide positive identification of such problems. Similarly, these methods can determine whether ore is amenable to fully autogenous milling, which is heavily dependent on the competency of material in the coarser size fractions. More recently JK Tech has modified it's pendulum test procedure to a drop weight procedure, which also has the potential to identify this problem.

Larger scale pilot runs require tonnage samples of ore which generally necessitates the development of sampling adits or other small mine techniques. The time required for this activity, including the test runs and data assessment, can be several months. This represents a significant cost, both in terms of the work itself and the impact on the overall schedule. On the other hand, the pilot data obtained can increase the metallurgist's understanding of the ore behaviour and facilitate reductions in design margins, an important consideration for larger projects. Larger scale pilot plant testing reduces the technical risks of the project.

For small to medium sized projects, it may be possible to finalise designs based on small-scale pilot tests and physical properties at the expense of some additional design margin and the inclusion of circuit safeguards (eg. larger mills; recycle crushers; variable speed drives). This philosophy, implemented with a good background knowledge of the testwork limitations, can provide a significant reduction in the development schedule (Siddall and White, 1989; Barratt, 1989; Lunt, Thompson and Ritchie, 1996).

It is difficult to be definitive in identifying those projects which require large scale pilot testing. This needs to be assessed in terms of sample availability, ore variability, whether the ore exhibits unusual or difficult properties, the size of the project, the owner's policy and other issues. These factors notwithstanding, the authors would normally advocate large scale testing for projects rated in excess of about 5 Mtpa. For example, Newcrest adopted a comprehensive piloting policy for the Cadia Project (17 Mta), whilst many smaller projects, such as Kanowna Belle, have been designed on the basis of bench-scale testwork (Lunt and Lane, 1997).

Barratt (1989, 1996) has developed a procedure for the design of SAG mill circuits based almost entirely on small scale testwork. Whilst there are many examples of successful application of this methodology, similar approaches to mill circuit selection and design, in particular at Three Mile Hill in the WA Goldfields, met with significant problems. These were due to the existence of competent material above 40 mm in size which was highly resistant to breakage in a mill. For such ores, multiple stage crushing (two or three stages) ahead of milling is often more appropriate.

The problems experienced with projects such as Three Mile Hill have resulted in the development of more rigorous testwork programs. Typically, these programs use small scale tests, such as Bond crushing, rod and ball mill work indices and Unconfined Compressive Strength (UCS) testing, to characterise the orebody and identify suitable comminution circuits. Testing methods such as JK Tech dropweight and pendulum tests and Advanced Media Competency evaluation are then used on selected composites. For the largest projects, pilot plant testing on a small number of bulk samples is also required. Examples of the application of this methodology at Kanowna Belle, Ashanti, Iduapriem, Bronzewing and Cadia have been described elsewhere (Lunt, Thompson and Ritchie, 1996; Lunt, Ritchie and Kirby, 1994; Lunt and Lane, 1997).

The Kanowna Belle comminution circuit was designed on the basis of small scale testwork, including JK Tech modelling and Advanced Media Competency testing. This testwork indicated that, although the ore is very hard and competent, a SAG mill circuit using recycle crushing would be appropriate. Table 3 compares design and initial plant operating data.

Table 3

Comparison of Circuit Design and Operating Data - Kanowna Belle

Parameter	Units	Design	Operation
Mill throughput	tph	137.5	170
Ball work index	kWh/t	19	-
SAG transfer size	P_{80}, micron	300 - 1 250	300
Ball size	mm	up to 150	125
Mill product size	P_{80}, micron	74	71
SAG mill power draw pinion	kW	2 010	2 134
SAG circulating load	%		18
Ball mill power draw	kW	2 196	1 649
SAG mill speed	% critical	70-78	78

A comparison of test programs for four projects in Table 4 indicates how the program has been tailored to the particular requirements of the project.

Table 4

Comparison of Test Programs

	Ashanti	**Iduapriem**	**Kanowna Belle**	**Cadia**
Plant capacity, Mt/a	2.2	1.5	1.25	17
Ore characteristic	Soft-Medium	Medium	Hard	Hard
Pilot plant tests	0	0	0	19
Advanced media competency	0	0	2	>10
MacPherson tests	2	2	1	0
JK Tech tests	2	3	5	12
Work indices	10	6	12	>30

For the harder, more competent material, it is important to test at the coarser size fractions to assess the need for recycle or secondary crushing. For the larger projects, it is important to minimise design factors and contingency due to the capital cost of the mills, whilst for smaller and softer applications the cost of additional testwork should be balanced against the cost of a larger mill. As discussed above and by Siddall and White (1989) it has been common practice in Australia to avoid the costs and difficulties of pilot plant testing by putting in additional capital cost, such as a larger mill or a recycle crusher. Whilst this approach is appropriate for a smaller plant, for larger operations the balance of costs indicates the need for more thorough testwork.

FLOTATION CIRCUIT DESIGN

The major factors that influence the development of flotation circuit designs are :

- valuable mineral recovery and concentrate grade;
- deleterious mineral rejection from concentrate;
- operating costs (reagent consumptions, power consumption etc.), and
- capital costs (size of concentrator required, materials of construction).

Many of the variables that affect flotation can change significantly from one ore type to another, requiring empirically designed testwork programs which must be repeated for each major type. This can result in lengthy and expensive testwork programs.

In order to minimise the amount of testwork conducted whilst adequately evaluating the effects of ore variability, the majority of flowsheet and reagent development testwork is conducted on only a few composite samples, depending on the complexity of the deposit. The optimum reagent scheme is confirmed on numerous variability samples to determine the response of the various ore types.

Once a suitable flowsheet is developed, larger scale testing is commonly conducted on representative bulk samples.

PRELIMINARY FLOWSHEET DEVELOPMENT

The basic strategy for flotation design is to develop a laboratory flotation flowsheet and reagent scheme that is suitable for the major ore types in the deposit. To minimise testwork costs, a single composite representative of the most typical ore type may be used. Several composites representing the major ore types will be required if there are major differences between ore types that are expected to require different processing routes, such as oxidised, transitional and primary ores.

Testwork will normally begin with batch laboratory rougher and cleaner flotation tests to evaluate the major variables such as :

- mineralogical variation;
- head grade variation;
- liberation and grind size requirements;
- reagent types, quantities and addition points;
- concentrate regrinding requirements;
- pulp density and viscosity effects;
- water quality; and
- flowsheet alternatives.

After a suitable flowsheet, grind size and reagent scheme have been determined, locked cycle testwork is generally used to ensure that the selected flowsheet and reagent scheme are suitable for continuous closed-circuit operation. If locked cycle tests are undertaken, it is important to ensure that sufficient cycles are tested to ensure that equilibrium is reached.

EVALUATION OF THE EFFECTS OF ORE VARIABILITY ON FLOTATION

The processing scheme selected in the preliminary flowsheet development should be used to assess all the major ore types identified in the review of the orebody geology. A bench-scale batch testwork procedure can sometimes be used to predict continuous plant operation, typically when an open-circuit flowsheet design is selected. Otherwise, locked cycle testwork is required, with a resulting increase in sample requirements.

The requirement for locked cycle testwork is determined by:

- the complexity of the flotation process, with multi-product, differential flotation circuits generally requiring extensive locked cycle testing;
- the separation efficiency or sharpness of the batch flotation roughing and cleaning stages. Ores that give high stage-wise recoveries and clean rejection of gangue require less rigorous locked cycle evaluation; and
- the effects of general chemistry, such as water quality and particle surface oxidation. Changes in water quality due to the build-up of soluble species or changes to flotation response due to surface alteration can result in losses of values to tailings in locked cycle testwork that are not predicted by batch testwork.

The determination of the appropriate locked cycle program and the assessment of resultant data requires experience in order to maximise cost effectiveness of the testwork program and for effective prediction of plant performance. The simple execution of a locked cycle test does not result in clear definition of plant performance in the majority of test programs. Detailed consideration is required of what has occurred during the test with regard to:

- circulating loads;
- visual assessments of flotation rates; and
- the effects of middlings buildup in the cleaning stages of the test.

This must be combined with the quantified recoveries from the final cycles of the test to arrive at plant performance predictions.

As with most flotation testwork, much of the information relevant to design is not quantifiable and is only gained only through conducting or observing the actual testwork.

If variability testwork indicates major deficiencies in the flowsheet developed, then further testing on the major composites could be required to establish a more robust process or parallel processing options.

PILOT PLANT TESTING

Reasons for conducting pilot plant flotation testwork are:

- to generate sufficient concentrate and tailings samples for downstream process testwork (eg. roasting, thickening);
- to confirm the effect of flowsheet changes;
- to confirm metallurgical response for continuous operation;
- to increase confidence for capital raising, etc. and
- to allow operator training prior to plant operation.

Pilot plant testing is generally seen as being more representative of plant processing than laboratory bench-scale tests. The successful pilot plant testing of an ore seems to evoke a sense of comfort with the flowsheet and reagent scheme.

There are several factors that can complicate this. The high cost involved in generating large quantities of sample for pilot plant testing can result in a compromised sample. Trial pits and shafts are usually mined to the minimum depth required. This can result in the inclusion of supergene or transitional material that may respond differently to the primary ore. Also, the sample is usually only from one specific area in the deposit which may differ significantly from the design ore type.

The cost of the sample generation can also result in short pilot runs. Pilot plants can be difficult to operate, and a lack of sample can result in less than optimum operating conditions due purely to time constraints. It is, therefore, crucial that pilot plant programs are carefully planned and managed.

RELATING LABORATORY DATA TO PLANT DESIGN AND SCALE-UP

The relationship of laboratory and pilot plant data to actual plant design varies significantly from ore to ore. For example, results achieved in the laboratory with a primary chalcopyrite ore are typically comparable with plant results. However, more difficult to float ores, such as serpentine-hosted nickel sulfides, can provide unexpected plant results due to subtle differences between laboratory and plant operating conditions.

Important variables that can affect the relationship between laboratory and plant performances include :

- *Power input* : Laboratory and small scale flotation cells typically have high power input per unit volume of slurry. This conditions the pulp with high shear, which is not typical of plant operating conditions where shear is minimised to reduce wear. Pilot plants with multiple interstage pumping can also result in high shear and power input into pulps. Careful evaluation of the power sensitivity of an ore should be conducted to assess this (Fleay and Lane, 1994).
- *Short circuiting* : Batch laboratory machines operate in essentially plug flow conditions, whereas continuous pilot plant or commercial plant machines result in significant short circuiting between cells. Laboratory cells also exhibit higher power intensity and air flow. A general scale-up factor of 2-3 is normally applied to laboratory flotation times to account for these factors.
- *Cell design* : Generally, conventionally agitated flotation cells are used for laboratory and pilot testwork. The flotation response in these cells is usually a good indicator of the type of cell that would be suitable for the plant design. For example, very fast-floating ores requiring very high concentrate grades may be suitable for column flotation with froth washing, whereas slow-floating ores would be more suited to conventional flotation cells. Small pilot scale cells are available, such as columns and Jameson cells, for evaluation on a pilot scale. However, there are as many questions raised in the scale-up of these cells as are answered by the use of the specific machine type.
- *Grinding Environment* : Laboratory grinding conditions can be significantly different to plant grinding conditions (eg. close circuit operation, media and liner materials). Apart from generating different size distributions, electrochemical effects should also be considered (Fleay and Lane, 1994). Such effects can have a dramatic impact on the concentrate grade and

recoveries in plant operation compared with testwork predictions. Remedial actions can range from simple reagent regime changes to major flowsheet modifications. Therefore, it is important that the effects of plant grinding conditions are assessed or at least considered during the testwork program.

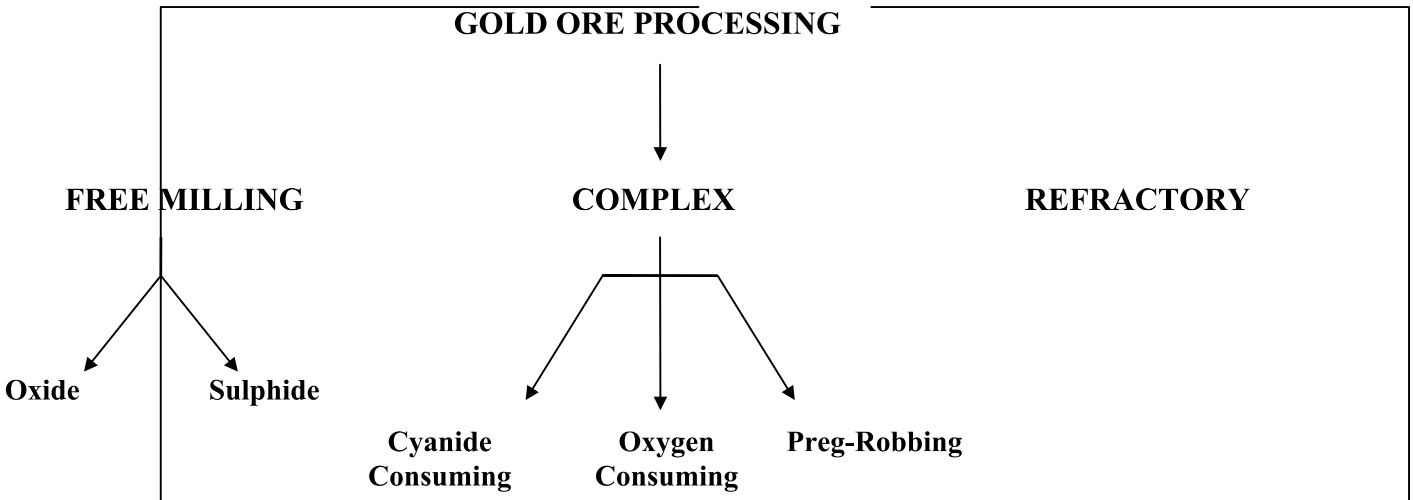
REFRACTORY GOLD PLANT DESIGN

The treatment of refractory gold ores, in particular the competing technologies and their relative advantages and economics, has become a major segment of most gold metallurgy-oriented conferences in recent years. A common theme is the increasing refractory nature of gold ores being treated. This is despite ores such as those at Kalgoorlie having required roasting for liberation since the last century.

Papers on refractory gold treatment have examined the characteristics of refractory ores and the causes of reduced recovery (eg. La Brooy, Linge and Walker, 1994), the available technologies and their relative economics (eg. Litz, Carter and Kenny, 1990) and the selection of a suitable process route (eg. Nicholson et al 1993, Weston et al 1994). The most comprehensive collation of data on such processes is provided in the different editions of technology surveys and conferences published by the Randol group.

Differing classifications and definitions of “refractory ore” have been published. Due to the many factors which can impact on the recovery of gold, it is perhaps not feasible to develop a universal characterisation that can be applied to all gold-bearing rocks. La Brooy, Linge and Walker (1994) have provided the framework for characterisation shown in Figure 1.

Figure 1



In this characterisation, “free-milling” is defined as ore which gives over 90% recovery under conventional cyanidation conditions. Those ores that give “acceptable” economic gold recovery only with the use of significantly higher chemical (eg. cyanide, oxygen, carbon) additions are defined as “complex”. “Refractory” ores are thus defined, by exception, as those which still give inadequate recovery. It is implicit in this that additional recovery requires some degree of pre~treatment prior to cyanidation. Any further characterisation of refractory ores, such as a definition of percentage recovery, is somewhat arbitrary and ignores the impact of economics unique to each ore deposit.

There is a variety of causes for an ore to display refractory characteristics. These include those shown in Table 5.

Table 5
Causes of Refractory Gold

Liberation	Physical locking in silicates, sulfides, carbon etc.
Occlusion	Passivation due to formation of a chemical layer
Chemistry	Formation of auriferous compounds eg. gold tellurides, aurostibnite
Substitution	Elemental replacement by gold in mineral lattice eg. "solid solution" gold in pyritic ores

Whilst these refractory characteristics occur in a variety of ore types, including auriferous base metals and rocks with a high carbon content, the majority of interest in refractory gold processing has related to gold-bearing iron sulfides, such as pyrite, arsenopyrite, pyrrhotite, telluride and the stibnite "family". This paper concentrates on the pretreatment processes available for the latter types of ore.

REFRACTORY PROCESS ALTERNATIVES

The recent resurgence of the gold mining industries in areas such as North America and Australasia initially focused on free-milling oxide ores, largely due to the development of improved open pit mining and gold recovery techniques. With the recognition that many of these deposits continue at depth, but also become more refractory, there has been significant interest in the development of improved techniques and processes for these more difficult ores. Much of this development has been driven by the need for environmentally accepted process routes and, in particular, the need to dispose of by-products such as arsenic and sulfur in a responsible manner.

Table 6 lists some of the processes available which are either in industrial use or in advanced developmental stages.

Table 6
Refractory Process Routes

Type	Industrial Processes	Developmental Processes
Thermal	Whole ore roasting Concentrate roasting Smelting	Pyrolysis Flash roasting
Oxidation	Acid pressure oxidation Alkaline pressure oxidation Biological oxidation Nitric acid oxidation	Bio-heap leaching
Chemical	Hot caustic digestion Chlorine Pressure cyanidation	Ammonia leaching
Physical	Fine grinding	Ultrafine grinding

In some instances, it may be appropriate to combine more than one of these processes in a synergistic manner eg.;

- ultrafine grinding prior to pressure oxidation (Activox®);
- hot caustic leaching of roaster calcines;
- chlorination of carbonaceous oxidation products, and
- biological oxidation of pyrrhotite prior to pressure oxidation.

REFRACTORY PROCESS SELECTION

In 1987, at the time of process selection for the Bogosu project in Ghana, the only processes considered to be in a suitable stage of commercial development were pressure oxidation and concentrate roasting. Five years later, for the Sansu Sulphide project of Ashanti Goldfields, it was necessary to undertake a long and extensive evaluation of four alternative processes, namely pressure oxidation, biological oxidation, concentrate roasting and the Freeport whole ore oxygen roasting process. Other options such as nitric acid oxidation and ultrafine grinding were also considered. The testwork programs and engineering studies involved in this evaluation took over two years to complete at a cost over US $2 M (Nicholson et al, 1993).

Whilst it may not be necessary to undertake such a detailed evaluation for all refractory gold projects, it is certainly important not to make an arbitrary selection based on preconceived ideas of process attributes or on what other companies have selected for their deposits or on generic comparisons of process economics. In recent years, our company has been involved in the selection of refractory processes for the following projects and, in each instance, the process selection was based on factors unique to the particular project:

Project	**Process**
Bogosu	Concentrate roasting
Sansu, Ashanti Goldfields	Concentrate BIOX®
Three Mile Hill	Concentrate fine milling
Macraes Flat	Concentrate fine milling
Kanowna Belle	Concentrate roasting
Minahasa	Whole ore roasting
Bakyrchik	Nitric acid oxidation
Golden Spec	Pressure cyanidation

This diversity of process selections demonstrates the importance of considering each orebody on a project specific basis.

Foo and Bath (1989) have published a diagram (Figure 2) describing metallurgical testing of gold ores which is an appropriate methodology for testwork. However, it is important to integrate the metallurgical testwork with continued economic analyses of each process. Simply achieving high levels of gold recovery at acceptable cost does not necessarily mean that the optimum process route has been selected.

It should also be stressed that a selection of the final process route should not be made too early in the feasibility process and before there is an appropriate level of detail available from the metallurgical testwork. The Kanowna Belle development (Weston et al, 1994) demonstrates how the ranking of roasting and biological oxidation was reversed between prefeasibility and final feasibility study stages, due largely to an improved level of recovery from roasting and lower recovery from biological oxidation following pilot plant testwork. In addition, the greater level of detail in the final study highlighted a greater difference in costs than had previously been determined. Due to the decision of the project owners to take both processes to pilot plant testing, this reversal in ranking did not adversely affect the timetable for project development and allowed the optimum process selection to be made.

FACTORS FOR CONSIDERATION IN REFRACTORY PROCESS SELECTION

Based on experience with the projects described above and other projects of a similar nature, the following factors are considered to all be of importance when selecting a process for the treatment of refractory gold ores. It should be stressed that they should all be taken into account at an early stage in the selection and that it is important that process options be kept open for as long as possible due to the potential for unforeseen circumstances having a deleterious impact on the economics of a particular process.

- gold mineralogy
- arsenic content
- sulphide content
- gangue mineralogy
- ore variability
- project scale
- incremental gold recovery
- flotation performance
- site specific environmental considerations
- water quality and availability
- power costs
- availability of neutralisation reagents
- cyanide consumption and costs
- project life
- ability to pilot

It is extremely difficult to propose a generic program for the evaluation and selection of a refractory process. Programs can vary from situations such as Ashanti's on the Sansu project, where both whole ore and concentrate processes were highly applicable, necessitating a long and exhaustive evaluation of the alternatives, to one such as Minahasa, where the preliminary testwork programs and mineralogy demonstrated that whole ore roasting was a more obvious selection without the need for more extensive studies and testwork.

Perhaps the most important step in selecting a refractory process for a particular orebody is to ensure that the mineralogy and metallurgy are well understood prior to making any decisions. These then need to be considered in the context of the constraints of the process location. It should then be practicable to select a shortlist of suitable technologies for more detailed evaluation

CIP/CIL PLANT DESIGN

The process designs of many of the early Carbon-in-Leach (CIL) and Carbon-in-Pulp (CIP) plants for gold recovery were similar, with an almost off-the-shelf approach to plant design. This approach worked well on simple oxide free-milling ores. However, many of the deposits now being explored possess characteristics that can have a significant impact on the plant design and on plant operation. While the main focus is still on gold recovery and reagent consumption, which are the two main economic drivers, there is a number of other parameters that require close attention to ensure that a suitable plant design is achieved for a specific ore.

BASIC TESTWORK PROGRAM AND PROCESS ISSUES

The major issues to be considered during the testwork program and process development phases are:

- *Grind size* : The design grind size should be optimised from an economic analysis at several grind sizes. This economic evaluation should include the power and steel costs, gold recovery, reagent consumption and the capital and operating costs of the milling circuit. The optimum economic milling size is often significantly coarser than the grind size for maximum recovery, due to the impact of the capital and operating costs of the milling circuit.

- *Reagent addition* : The typical reagent suite for gold leaching is lime (for pH control and protective alkalinity) and cyanide. However, oxygen and lead nitrate are just two of many other chemicals that can improve gold leaching with some ore types.

- *Refractory gold* : Any refractoriness of the ore will typically be highlighted during standard leach testing. Gold locked in pyrite or other sulphides can severely impact on gold recovery. Assessment of refractory gold recovery techniques as discussed in the preceding section should be investigated.

- *Preg robbing* : Preg robbing is when gold from the pregnant solution is robbed by components within the ore. This typically occurs due to carbonaceous material in the ore adsorbing gold prior to adsorption onto carbon. Certain clay types can also create this phenomenon. Specific laboratory testwork with activated carbon is recommended to highlight any potential problem in this area. Low gold recoveries with simple leach tests can be due to preg-robbing , which often can be rectified simply by adding carbon during the leaching stages.

- *Copper concentration* : Soluble copper minerals can have a dramatic effect on the cyanide consumption of a CIL plant. Considering that cyanide is one of the major consumable costs of a gold plant, the presence of copper can have a significant effect on the economics of a project. The presence of copper, particularly as cyanide soluble copper, should be evaluated during exploration assaying. The type of copper mineralisation can have a large impact on the amount of copper that is cyanide soluble, and should be assessed in mineralogical and analytical investigations. Several process alternatives are available to treat high cyanide soluble copper gold ores to minimise the cyanide consumption and/or recover the cyanide consumed and the copper that is leached. With very high grade copper ores, copper recovery via flotation can be an economic process route.

- *Silver concentration*: Silver has several implications on the process design. Silver should be assayed in all testwork samples. Moderate silver concentrations can influence the elution and electrowinning circuit size and design. The recovery of silver in very high concentrations needs to be economically assessed and may dictate the use of an alternative gold recovery method to the traditional elution/electrowinning, such as the Merrill-Crowe process.

- *Oxygen demand :* Oxygen consumption should be assessed to determine if supplementary oxygen to that provided by normal air sparging is required. As oxygen is required in the cyanide leaching reaction, it can have a significant impact on the gold recovery during plant operation. Laboratory testwork tends to mask the problems associated with high oxygen-consuming ores due to the large amount of oxygen that can be absorbed in a laboratory testing procedure. Specific oxygen uptake tests are recommended to assess this problem.

- *Pulp viscosity* : The viscosity of the ground ore slurry adversely affects the transfer of pulp through screens and launders, and impacts on the standard plant design. Highly viscous ores may even require viscosity modifiers to be dosed into the pulp to ensure that adequate flow is achieved through a CIL circuit.

- *Water quality* : The quality of process water is another important parameter and impacts on reagent consumption, carbon activity and elution circuit design. It is important that the water to be used for the plant operation is comprehensively assayed. Comparative laboratory leach tests should be conducted with the site water to assess the impact on leaching.

Figure 3 summarises a typical testwork program in diagrammatic form.

ADDITIONAL REQUIREMENTS

For a complete process design package, the design of peripheral equipment must be considered. Often, these are forgotten during the sampling and testwork phases and poor designs can result.

A checklist of key areas to be considered includes:

- ore viscosity
  - agitator design
  - pump selection

- solid-liquid separation
  - thickening
  - filtration

- tailings disposal
  - deposition characteristics
  - stability
  - acid generation

- backfill requirements and production

Unfortunately, the sample requirements for these tests are generally quite large. It is also important that process conditions have been determined prior to undertaking the tests as issues such as pulp density, pH and grind size can have significant impacts. It is, therefore, important to delay the testwork for as long as practicable without delaying project schedule, but also, at an early enough stage, to highlight any potential problem areas which can impact on project economics.

PROCESS SELECTION AND DESIGN

Process Selection and Design

Although there are no hard and fast rules for the design of any unit operation, unlike more established and documented procedures in industries such as coal preparation and chemical engineering, there are well established methodology for the selection of the optimum process design for any new operation. Whilst these must vary between individual applications, for instance between small and large capacity plants or between simple and complex processes, the approach that should be taken can be generalised.

As has been discussed in the previous sections, in each major process area there will be a number of options to be examined, such as:

Comminution	**Flotation**	**Refractory Gold**
Multiple stage crushing	Flash flotation	Whole ore roasting
Single stage crusher	Column cells	Concentrate roasting
Jaw/gyratory crushers	Jameson cells	Pressure oxidation
Rod mills	Conventional cells	Biological oxidation
Ball mills	Self-aspirating cells	Nitric acid oxidation
SAG mills	Open circuit flotation	Ultrafine grinding
FAG mill	Closed circuit flotation	

With this plethora of options it is impractical in the space herein to describe the design process for each and the reader is directed to the bibliography

However the selection and design approach for any process plant is almost always as interactive procedure which follows the cycle of testwork to design study to process comparison (both economic and qualitative) and back to further testwork. It can be argued that this cycle should be followed until the orebody is depleted as the rapid introduction of new technology requires the established process to be continually evaluated against new processes.

Prior to plant construction this cycle is repeated a number of times between the different stages of study, from scoping to detailed, and then to design. Table 7 describes the different levels of study, the information generated in each and level of testwork typically undertaken for each.

Table 7

Types of Estimate and Relevant Testworks

	Scoping Study	**Preliminary Study**	**Detailed Study**	**Design**
Order of accuracy	±30-35%	±20-25%	±10-15%	0
Flowsheets	Block diagram	Overall	Preliminary	Final
Equipment Selection	Major equipment	Description	Preliminary	Final
Layouts	n/a	Outline	Preliminary	Final
Testwork				
- Milling	n/a	small scale	SAG/AG tests	pilot plant
- Flotation	n/a	small scale	locked cycle	pilot plant
- Refractory gold	n/a	small scale	pilot plant	pilot plant
- CIP/CIL	n/a	small scale	small scale	pilot plant
- Other	n/a	n/a	preliminary	detailed

Case Study - Kanowna Belle

The previous sections of this paper have described and referenced more detailed papers on this approach as taken for individual plant area. An example which encompasses all of the unit operations described in this paper is the Kanowna Belle project in Western Australia. As the deposit contained sufficient oxide and free milling ores to allow project commitment prior to selection of the refractory process, the project was able to be fast tracked, allowing revenues to be generated in parallel to detailed study, engineering and construction of the refractory process plant (Weston et al (1994)). The process development for this project included a judicious mix of small scale testwork, supplemented by pilot plant testwork where appropriate.

Comminution Circuit Design - Kanowna Belle.

The design of the comminution circuit has been described in detail by Lunt, Thompson and Ritchie (1996). Following the preliminary studies no decision had been made on the selection of a circuit, but a testwork programme had gathered physical property data suitable for conventional circuits and for preliminary assessment of SAG milling. The first stage of the definitive study therefore examined a wide variety of possible circuit configurations, including less conventional circuits incorporating Water Flush crushers and high pressure grinding rolls. These circuits were characterised in broad ranges in terms of capital and operating costs, applicability to Kanowna ores, technical risk and development schedule. Following this assessment it was realised that two circuits were of similar classification as the most likely optimum route. These were three stage crush - ball mill and SAG mill-recycle-crusher-ball mill (SABC). These two options were each studied at a preliminary study level of engineering and costing. The SABC circuit proved to be economically more attractive as well as having more flexibility for the treatment of the wide range of ore types. However it was considered that there was a degree of risk due to the high competency of the ore and therefore further testwork to assess the potential SAG mill characteristics was undertaken prior to execution of the detailed feasibility study. Due to the depth of the primary ore the schedule and costs of collecting a pilot plant sample were prohibitive and therefore the savings from elimination of this testwork were utilised in applying appropriate design margins and safety measures to the mill design. As seen above this approach proved highly successful.

Flotation Circuit Design - Kanowna Belle

The refractory gold components of the primary ore, contained in an arsenical pyrite, required flotation prior to further treatment (oxidation ore fine grinding) prior to CIL to increase gold recovery.

A comprehensive testwork programme was carried out on a bulk composite. This testwork programme determined optimum flowsheet conditions which were then used to assess the variability of the ore using 16 composite samples selected to represent the major ore types by mineralogy and by depth. This indicated a low degree of variability with no requirement for different reagent regimes for individual samples and provided design data for the Stage 1 plant development. A short duration pilot plant was carried out primarily to produce concentrate samples for oxidation testwork.

Engineering studies and evaluation of the results indicated a simple flowsheet was appropriate and that, based on the engineers experience, column flotation would be a cost effective design. Whilst there appeared to be some potential benefit with flash flotation, this could not be proven and therefore the design proceeded with the provision for a cell to be retrofitted.

Whilst the Stage 1 plant proceeded to construction based on this design, a major pilot plant programme was planned and undertaken in parallel. The purpose of this programme was to produce samples for pilot plant testing of oxidation processes, but also allowed the design flowsheet to be tested. This pilot plant showed the efficiency of flash flotation and also indicated the need for additional cleaning capacity in the cleaning circuit. On the basis of these results a flash flotation cell and a recleaner stage were incorporated into the plant during the Stage 2 development.

Subsequent plant operations confirmed the results of the pilot plant when treating similar ore. However the plant encountered significant amounts of ore with a high sericite content which had not been identified in any of the tests. This oretype required significant changes to the reagent regrime and further additions to the cleaning circuit.

Refractory Process Design - Kanowna Belle

The selection of the refractory process has been described by Western et al (1994). As stated above the refractory component of the gold is contained in an arsenical pyrite. Variability testwork on individual drill core sections indicated a range of gold recovery from 40% to 97%. Testwork on composite samples indicated a typical range of gold recovery from 55% to 65%. Small scale testwork on a number of processes was undertaken prior to a preliminary study by Kilborn Inc of potential refractory processes, including BIOX, whole ore and concentrate roasting, pressure oxidation and ultrafine grinding. Whilst the study indicated that BIOX was the optimum route, it was decided to continue with more detailed examination of concentrate roasting in parallel to that of BIOX, primarily as an insurance should BIOX prove unsuitable. However as the pilot plant programmes and detailed engineering studies proceeded it became clear that BIOX was not necessarily the optimum route. Due to a variety of circumstances the relative economic positions of the two processes were reversed. These included:

- laboratory testing of roasting was unable to simulate the optimum conditions and therefore underestimated achievable gold recovery.

- pilot plant testing of BIOX was unable to replicate gold recovery achieved in small scale tests at economic conditions.

- the costs of suitable water for BIOX was extremely high in the arid conditions of Kalgoorlie where ground waters have extreme saline content.

- the BIOX process consumed greater quantities of power and limestone which are relatively expensive at the site due to its remote location

- the arsenic content is low, thus allowing roasting with only minor quantities of arsenic trioxide for disposal.

Therefore the roasting process was selected for Kanowna Belle and has been successfully operated for over 3 years.

REFERENCES

K.A. Foo and M. D. Bath, 1989, "Trends in the Treatment of Refractory Gold Ores", *Randol*

S.R. La Brooy. H. G. Linge, G.S. Walker, 1994, "Review of Gold Extraction from Ores", *Minerals Engineering,* 7 (10).

J.E. Litz, W. Carter, C.W. Kenney, 1990, "Refractory Gold Treatment Options - Economics Rule the Way", *Randol, Squaw Valley.*

H.M. Nicholson, S. Oti Atakorah, D.J. Lunt, I.C. Ritchie, 1993, "Selection of a Refractory Gold Treatment Process for the Sansu Project", *Biomine 93, pp. 20.1 - 20.11 AMF, Adelaide*

T. Weston, J. Perkins, I.C. Ritchie, H. Marais, 1994, "Concentrate Biological Oxidation in a Hypersaline Environment for the Kanowna Belle Project", *Biomine 94, AMF, Perth*

G.B. Siddall and M.S. White, 1989, "Growth of SAG milling in Australia", in *Advances in Autogenous and Semi-autogenous Grinding Technology 1989,* pp. 169-186, Vol. 1 (Department of Mining and Mineral Processing Engineering, University of British Columbia, Vancouver, B.C.)

D.J. Barrat, 1989, "An Update on Testing, Scale-up and Sizing Equipment for Autogenous and Semi-autogenous Grinding Technology", in *Advances in Autogenous and Semi-autogenous Grinding Technology 1989,* pp. 25-46, Vol. 1 (Department of Mining and Mineral Processing Engineering, University of British Columbia, Vancouver, B.C.)

D.J. Lunt, A. Thompson, I.C. Ritchie, 1996, "The Design and Operation of the Kanowna Belle Milling Circuit", in *International Autogenous and Semi-autogenous Grinding Technology 1996,* pp. 81-96, Vol. 1 (Department of Mining and Mineral Processing Engineering, University of British Columbia, Vancouver, B.C.)

D.J. Lunt and G. Lane, 1997, "SAG Mill Circuit Selection, Scale-up and Sizing", paper presented to IIR Conference on SAG Milling, Perth.

D.J. Barrat, B.D. Matthews, T. deMill, 1996, "Projection of SAG/AG Mill Sizes, Mill Speeds, Ball Charges and Throughput Variation from Bond Work Indices", in *International Autogenous and Semi-autogenous Grinding Technology 1996,* pp. 541-558, Vol. 2 (Department of Mining and Mineral Processing Engineering, U.B.C., Vancouver, B.C.)

D.J. Lunt, I.C. Ritchie, E. Kirby, 1994, "Concentrator Design for Gold Projects in West Africa, *African Mining 1994,* (Institution of Mining and Metallurgy, London)

J.D. Fleay, G.S. Lane, 1994, "Grinding Environment Effects in the Flotation of Kambalda Nickel Ores", in *Fifth Mill Operators Conference,* pp. 43-50 (AusIMM, Roxby Downs).

A.J. Sinclair, 1980, "Sampling a Mineral Deposit of Feasibility Studies and Metallurgical Testing", in Mineral Processing Plant Design, pp115 - B4 (AIME)

BIBLIOGRAPHY

GENERAL TESTWORK PROGRAMMES

R.L. Coleman, 1980, "Metallurgical Testing Procedures", in Mineral Processing Plant Design, pp 144-182 (AIME)

H.R. Spedder, 1985, "Sampling and Testing, in SME Mineral Processing Handbook", pp 30-1 to 30-129 (AIME)

COMMINUTION

F.C. Bond, 1960, "Crushing and Grinding Calculation", British Chemical Engineering, June 1960, pp 378-385 and 543-548.

C.A. Rowland, 1989, “Testing for Selection of Autogenous and Semi-Autogenous Grinding Mills and Circuits”, in Advances in Autogenous and Semiautogenous Grinding Technology, pp 47-60, Vol 1 (Department of Mining and Mineral Processing Engineering, U.B.C., Vancourver, B.C)

D.A. Knight, A.R. MacPherson, V.G. Medina, D.E. Spiller, “Case Histories of using Small Scale Tests to Design SAG mill Circuits”, in Advances in Autogenous and Semi Autogenous Grinding Technology. pp 105-118, Vol 1 (Department of Mining and Mineral Processing Engineering, U.B.C, Vancouver, B.C.

J. Starkey, G.S. Dobby, “Application of the Minnovex SAG Power Index at Five Canadian SAG Plant”, pp 345-360, in SAG 1996, Vol 1 (UBC, Canada).

B. Siddall, G. Henderson, B. Putland, “Factors Influencing Sizing of SAG Mills from Drillcore Samples”, pp 463-480, in SAG 1996, Vol 2 (UBC, Canada).

S. Morell, R.D. Morrison, “AG and SAG Mill Circuit Selection and Design by Simulation” pp 769-790, in SAG 1996, Vol 3 (U.B.C, Canada).

FLOTATION

D.W. Fuerstenance (ed), 1962, Froth Flotation, AIME, New York

D.W. Fuerstenance (ed), 1962, Flotation, AIME, New York

R.D. Crozier, 1992, Flotation, Theory, Reagents and Ore Testing, Pergamon Press

GENERAL

A.L. Mular (ed), 1985, Design and Installation of Concentration and Dewatering Circuits, AIME, New York.

A.F. Taggart, 1945, Handbook of Mineral Dressing, J. Wiley and Sons, New York.