A metallurgical test programme for mine-plant projects

by J. KITAGAWA†, B.Sc. (Chem. Eng.) (Alberta) (Visitor)

SYNOPSIS

The principal objectives of a metallurgical test programme for a 'grass roots' mining project are twofold. The first requirement is to establish the metallurgical viability of the project by demonstrating that acceptable results can be obtained by processing of the ore. The second goal is to obtain essential supporting data to determine whether the project is economically feasible. This involves several functions, which include the establishment of a workable flowsheet, the obtaining of design criteria for the commercial plant, and the collection of the evidence necessary to convince management, and often a third-party expert, that the metallurgy predicted for the ore can be achieved in a full-scale operation. The latter task is facilitated if a coherent overall picture is presented considering the geology of the ore-body, the mining plan, and the mineralogy and metallurgy of the ore. The purpose of this paper is to provide guidance in the establishment of a test programme to meet the above objectives.

SAMEVATTING

Die hoofoogmerke van 'n metallurgiese toetsprogram vir 'n mynbouprojek wat reg van die begin af aangepak moet word, is tweeledig van aard. Die eerste vereiste is om vas te stel of die projek metallurgies lewensvatbaar is deur te bewys dat aanvaarbare resultate deur die verwerking van die erts verkry kan word. Die tweede oogmerk is om die nodige stawende data te kry om vas te stel of die projek ekonomies moontlik is. Dit behels verskeie funksies soos die opstelling van 'n bruikbare vloeidiagram, die vasstelling van ontwerpmaatstawwe vir die kommersiële aanleg, die versameling van die nodige bewyse om die bestuur, en dikwels 'n deskundige derde party, te oortuig dat die metallurgie wat vir die erts voorspel word, in 'n volskaalse bedryf behaal kan word. Laasgenoemde taak word vergemaklik indien 'n samehangende geheelbeeld voorgelê word wat die geologie van die ertsliggaam, die mynbouplan en die mineralogie en metallurgie van die erts insluit. Die doel van hierdie referaat is om as leidraad te dien by die daarstelling van 'n toetsprogram om die bogenoemde oogmerke te verwesenlik.

Introduction

To make a valid economic assessment of a mineral property, it is necessary to know the nature and quantity of valuable products that can be produced, when and how much capital and operating expenditure must be incurred, and when revenue will become available from the products. A large part of this essential information can be derived from data developed through a metallurgical test programme involving the analysis and testing of samples. The task of economic assessment is facilitated if those concerned have a coherent overall picture of the geology of the entire deposit, including the distribution of basic values, the mineralogy of the ore, and the metallurgical response of the various ore zones, as well as a practical mining plan.

Since the number of samples available for the development of the overall picture mentioned above is often limited, a detailed geological examination and a systematic petrographic analysis of each sample as taken are imperative. In addition, the development of a thorough geological and mineralogical knowledge of the ore-body before the execution of the metallurgical test programme is good common sense because this is often the most expensive part of the analyses. It is particularly recommended that the mineral examination should be done thoroughly, since competent laboratory work can sometimes obviate the necessity for pilot-plant testing, especially if the ore is very simple and amenable to concentration.

The organization of a metallurgical test programme for a grass-roots project can be divided into four general steps. The initial step consists of laboratory tests on preliminary samples to develop a basic, workable scheme of treatment. The second step is the gathering of the most complete information possible concerning the geology of the ore-body, the mining plan, and the mineralogy of the ore. The last two steps involve detailed metallurgical testing in the laboratory of drill samples representing the range of feeds expected in the plant, and pilot-plant testwork on one or more bulk samples. The final two phases of testing involve optimization of the treatment scheme, and the establishment of the metallurgical response of the ore and the design criteria for the commercial plant.

It is extremely important that the work should be conducted and the reports presented in a manner to convince management, and often a third-party expert, that the metallurgy predicted can be achieved in a full-scale plant.

The purpose of this paper is to provide guidelines for the establishment of a test programme to meet the above objectives. For convenience, many specific references are made to complex sulphide deposits, but the principles are general and are easily extended to cover virtually any solid mineral deposit.

Preliminary Testing

The metallurgical response of an ore is initially indicated by laboratory tests on preliminary samples, often from drill cores. The production of a saleable product at a reasonable recovery from such tests is generally sufficient evidence that an ore is metallurgically amenable. The number of successful tests required will depend on the extent and variability of the deposit.

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†Bechtel Corporation, U.S.A.

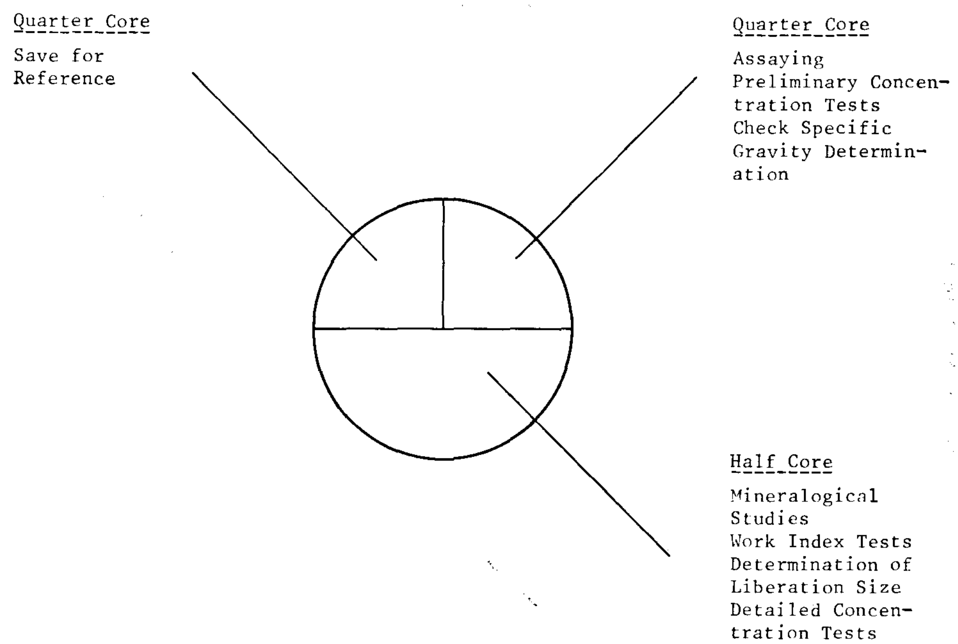

Fig. 1—Splitting of drill cores for testing

Distribution of Drill Core

The diamond-drilling core that is available for the analyses and testwork required is usually very limited. Careful planning by both the exploration geologist and the metallurgist is needed if the maximum useful information is to be obtained from this source. The exploration geologist examines the drill cores initially to log data on the identity of the minerals present along with their associations. At this time, he may also make observations on the relative hardness of the ore and indicate the coarseness or fineness of the mineral dissemination. The whole core is used for these examinations, as well as for the determinations of specific gravity, with no loss of material.

The subsequent analyses and testing of drill cores involve assaying, mineralogical studies, grindability or work index tests, determinations of mineral liberation size, and concentration tests. A suggested way of splitting and distributing the core for these purposes is shown in Fig. 1.

The disadvantages of assaying quarter-core is that the core has to be split before the analytical results can be obtained. This inconvenience is usually justified, however, because the added effort results in material being available for all the tests and studies required at a later stage.

For those ores that are susceptible to rapid alteration when exposed to the atmosphere, adequate precautions should be taken throughout the test programme to minimize oxidation of the samples. This may even include placing the sample in a plastic bag, purging with nitrogen, and sealing and storing in a freezer for subsequent metallurgical testing.

Preliminary Concentration Tests

The sample for preliminary concentration can be prepared from rejects from the crushing and splitting of quarter-cores down to a size suitable for assaying by blending the reject components in the proper proportions to represent the ore-body. A check determination of specific gravity can also be made on this sample. Approximately 50 kg of sample are required for most preliminary testwork.

Before starting the metallurgical testwork, it is recommended that the sample selected for testing should be subjected to a qualitative spectrographic analysis. All the elements that are present in the sample in significant amounts or are of particular interest should then be analysed quantitatively. It would also be desirable to have a mineralogical study conducted on the sample at this stage since this information often proves invaluable to the metallurgist in his testwork. Briefly, the mineralogical information required includes data on the minerals present in the sample, and their properties and grain sizes.

The steps involved in demonstrating that acceptable metallurgical results can be obtained on the ore are empirical, and vary with the skill and experience of the tester or his supervisor. Visual observation of the tests and microscopic examination of the products, as well as the masses and assays of the products, are usually necessary to the planning of each subsequent step. The ore can be considered responsive to metallurgical treatment when it has been demonstrated that the samples representing the range of feeds expected to the concentrator can be processed to produce saleable concentrates at reasonable recoveries. However, in addition to demonstrating that the ore can be treated with reasonable success, the initial tests should indicate the grind, the general flowsheet, and the types and quantities of reagents required in the processing of the ore.

Preparatory Information and Testwork

Detailed testwork on which an economic assessment of the ore-body can be based is initiated once it has been established that the ore can be treated successfully and a reasonable tonnage of reserves has been proven. Before plans for detailed testing are formulated, however, it is recommended that the metallurgist should collect as much background information as possible on the geology of the ore-body, the proposed mining plan, and the mineralogy of the ore. A comprehensive knowledge of these aspects will enable him to plan the test programme to facilitate the presentation of a coherent metallurgical picture of the project. A thorough familiarity of these aspects is also helpful in the establishment of test priorities, which could result in the saving of much time, money, and effort that may otherwise be expended needlessly.

Geology of the Ore-body

The geological information required by the metallurgist includes the more obvious data related to the tonnage and grade of the ore-body, as well as to the minerals present in the ore. The size, shape, plunge, dip, strike, and extent of the ore-body are also helpful in giving a better overall understanding of the ore deposit. Much more detailed information is required, however, in the planning of a rational test programme. To collect the necessary geological facts on the ore-body, the metallurgist, as one of his first duties, should include a detailed examination of drill-core logs, which often contain much valuable information regarding the minerals present in the ore, the assays, the approximate grain sizes of the minerals, the specific gravity and hardness of the ore, and the classification of the ores in the deposit into distinct geological categories or types. A thorough knowledge of these categories, as well as the tonnage, grade, and physical location of each of these ore types within the ore-body, is essential since this information indicates the heterogeneity or homogeneity of the ore-body. This aspect cannot be over-emphasized since the metallurgical response of the different ore types may sometimes influence the mining plan to permit a sound basis for blending or separate treatment of these ores. In addition, this information can be used in establishing the relative economic importance of each metal and each type of ore at any given metal price. This in turn permits the metallurgist to establish priorities in the tests to be carried out.

If the treatment process involves flotation, particular attention should be given to ore that may fall within the zone of influence of fault or shear zones since the material adjacent to these areas is often exposed to ground waters and may be oxidized. These ores, in addition to being refractory, may produce poor results on ore normally amenable to flotation if they are mixed. When the minerals concerned contain copper sulphides, the presence of secondary minerals such as covellite, digenite, bornite, and chalcocite should be carefully noted because these minerals are associated with geological alteration.

If the geological data regarding the degree of oxidation, as well as the areas or zones affected by alteration, are incomplete, they should be studied in detail by the mineralogist during his examination of core samples.

The metallurgist should also be familiar with the drawings showing the diamond-drill grid and the cross-sections of the ore-body. The former drawing is particularly important in relating the borehole number with its location in the ore-body. The other drawings indicate the length of drill core intersecting the ore-body, as well as the types of ore intersected in each borehole. The amount of deflection of each borehole should be noted, especially for the deeper holes, so that the mass of the core can be adjusted accordingly when representative samples are prepared from drill core.

A site visit, while not always essential, generally aids in an understanding of the geology of the ore-body, as well as providing an opportunity for the properties of the ore to be observed from the drill cores.

Mining Plan

To plan and coordinate the metallurgical testwork properly, the metallurgist must be familiar with the mining plan. This includes a knowledge of the mining method as well as the yearly schedules of the tonnages, the calculated ore grades after dilution, the types of ore to be mined, and the areas from which each material is to be extracted. Information as to whether the mining plan will permit the different types of ore to be treated separately, or together in the desired proportions, is also required. These data will allow the metallurgist, in preparing both the drill and bulk samples for testing, to simulate the plant feeds with respect to the grades, mineralogy, and ratios in which the different types of ore are to be mixed.

Detailed Mineralogy

Samples of drill core should be subjected to detailed mineralogical examination. It is essential that the core should be examined in a systematic manner because random examination will often give misleading results, especially if the ore-body is heterogeneous.

A sketch of how samples for mineralogical examination can be obtained from half-core is shown in Fig. 2. Each sample should consist of a slice of core about 50 mm long and 2 to 3 mm thick, taken longitudinally at predetermined intervals over the entire length of the half-core. Each slice of core should be marked with an arrow as shown in Fig. 2 to indicate the direction of the bottom of the borehole, as this may be helpful to the mineralogist in studies related to the geology of the ore-body. The number of the borehole and the depth of intersection (e.g. 32-267 Borehole 32, Depth 267 m) should also be marked on each sample slice as illustrated in Fig. 2 for identification.

The frequency with which slices of core should be cut from each borehole for microscopic work depends upon many factors, including the total length of mineralized intersection, the number of types of ore, and the intersected length of each of these ore types in each borehole. There are no fixed rules for this, but one suggested criterion is given below:

Length of intersection	*Number of sample slices*
1 m	1
2 m	2
3 m	3
4 m	4
5 to 20 m	5
>20 m	10

Whatever criterion is selected for the taking of samples, it is extremely important to document exactly where each slice of core was cut so that the mineralogical data can be related to the overall ore-body.

If the proper criteria are used in the selection of where sample slices are taken from drill core, there is no reason why the mineralogical studies for ore-dressing requirements and those related to the geology of the ore-body cannot be conducted on the same sample.

The mineralogical studies required for ore-dressing purposes include the following.

(a) *Identification of minerals*. This is essentially a list of the minerals present in the ore and the order of their abundance. If small quantities of gold, silver, bismuth, cadmium, and other metals are present but not detected or identified by microscope, these may still be recovered in the concentrates as either desirable or undesirable constituents. In such cases, consideration should be given to electron microprobe studies to determine how and where these metals occur.

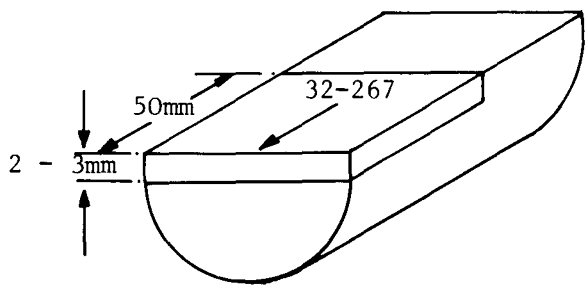

Fig. 2—Samples for mineralogical examination from half-core

(b) *Mineral properties*. Such factors as whether the ore is composed of essentially clean primary minerals or whether alteration has taken place are important. The presence of secondary minerals could indicate geological alteration of a sulphide ore, in which case the degree and extent of oxidation may be critical. If oxidation appears to be a serious problem, the severity of the phenomenon (such as the coating of one or more minerals with a mono-molecular layer of another, which effectively destroys the basis of efficient separation by differential flotation) might be investigated by electron microprobe. Other factors that should be studied are the fineness and predominance of interlocking between the ore minerals, and between the ore minerals and the gangue.

(c) *Grain size or liberation size of the mineral*. This involves the determination of the fineness of grind

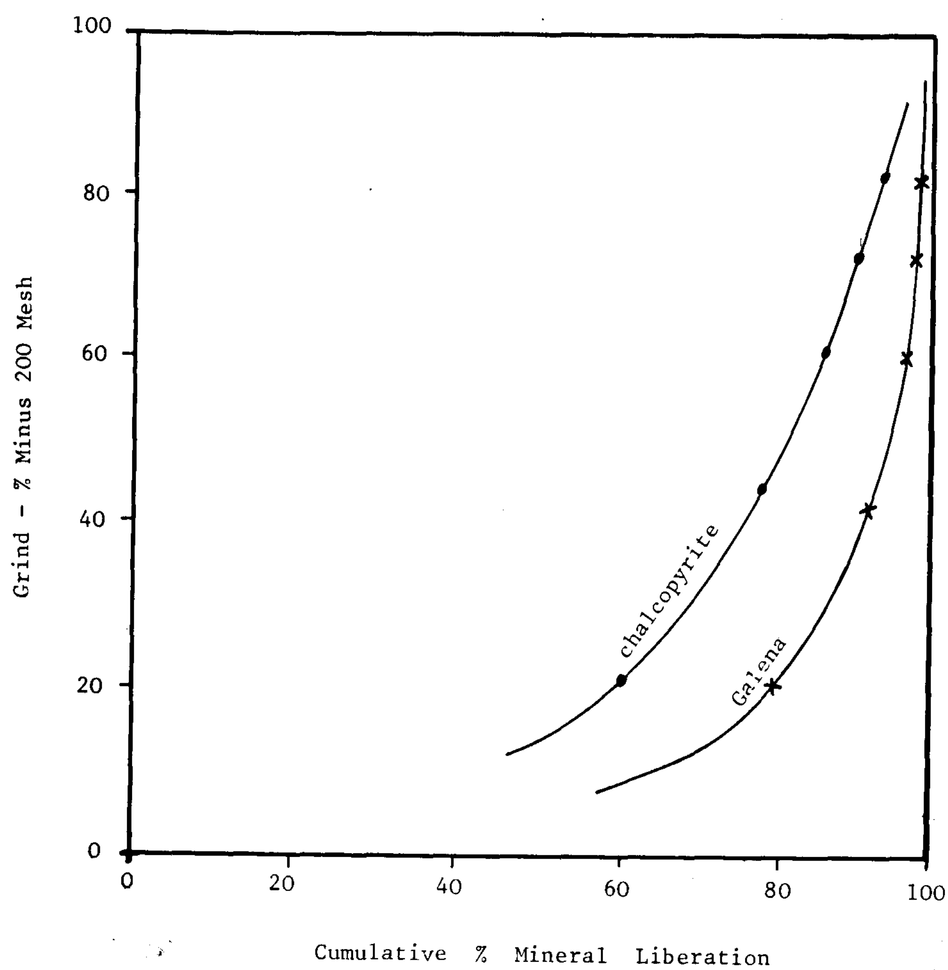

Fig. 3—Graph of particle size versus mineral liberation

required for adequate liberation. The diameter of a mineral grain can be estimated with a special optical device in the microscope. As the grain size of a mineral may not necessarily coincide with its liberation size, it may be preferable for the percentage liberation of each mineral to be determined microscopically in ore that has been ground. Studies of liberation size are generally conducted on sized fractions of ground ore, and are reported as percentages of free and locked minerals; however, it is also possible for an adequate study to be conducted on ground ore that is not sized. Regardless of the method selected, a plot of the grind versus the cumulative percentage liberation for each mineral, as illustrated in Fig. 3, can be drawn if the determinations of mineral liberation size were made on identical samples that had been ground to varying finenesses.

The plot would then indicate the grind required for the desired percentage of mineral liberation. The determination of liberation size should be made on a composite drill-core sample representing the entire ore-body. Additional determinations on drill core combined to represent smaller blocks of ore are required if the exploration geologist reports that the grain size varies throughout the ore-body. This information will then indicate the range of grinds required for a desired percentage of mineral liberation in addition to providing the data required for the determination of the tonnage of ore that falls within each grind.

Detailed Laboratory Tests

The detailed laboratory testwork should include work index tests, which will provide information for sizing of the grinding mills, as well as concentration tests, which provide the basis for the optimization of the treatment scheme and the establishment of design criteria for the commercial plant. These tests should be conducted on a composite drill-core sample representing the entire ore-body. If the drill-core logs indicate that the ore-body is heterogeneous, it is recommended that the tests should be conducted on composite samples that represent smaller blocks of ore covering the range of expected plant feeds. These tests will reveal the variations in metallurgical response, flow sheets, and treatment scheme that may be necessary for acceptable results to be achieved on the entire deposit.

Work Index Tests

The purpose of the work index tests is to indicate the size of grinding mills required for the commercial plant. To be meaningful, the tests must be carried out in conjunction with the determination of liberation size. Rod-mill work indices can be determined for any grind from 4 to 65 mesh; however, the normal range is from 8 to 28 mesh. The ball-mill work index can be determined for any sieve size below 28 mesh. It is important that the mesh of closing sieve selected for both tests is such that the ground product from the test is slightly finer than the product required in the commercial plant. Failure to take this precaution may result in undersizing of the grinding units for the commercial plant, especially with ball mills, where the power required to grind minerals that are already at their natural grain size may increase very sharply with any increase in size reduction.

If autogeneous or semi-autogeneous grinding is to be considered for the commercial plant, the appropriate grinding tests should be conducted. A simple method of predicting the requirements of autogeneous grinding mills for processing ore from a new deposit has been presented by MacPherson[1].

Concentration Tests

Extensive batch studies are usually required before a workable flowsheet can be developed, and before the grinding and concentration conditions established during the preliminary tests can be optimized. In concentration studies involving flotation, laboratory locked-cycle tests can be used to establish the basis for the metallurgical results expected in the commercial plant, if the flowsheet is simple and the ore is amenable to metallurgical treatment, and pilot plant testing can be omitted. However, continuous pilot-plant tests on bulk samples are required for the prediction of full-scale plant metallurgy on complex ores.

The following are the main factors that must be established and optimized during the detailed laboratory testwork if flotation is involved:

(a) requirements for the primary grind,
(b) requirements for conditioning,
(c) flowsheet,
(d) requirements for the regrinding of middlings,
(e) residence times for roughing, scavenging, and cleaning, and
(f) reagent requirements in regard to types, quantities, and points of addition.

It is recommended that settling and filtration tests should not be conducted on sulphide or other heavy-mineral concentrates from laboratory tests in which the material was ground in closed circuit with a screen, because such material is generally significantly coarser than that produced in a plant where classification is carried out with cyclones or classifiers.

Pilot-plant Testing

The primary object of the pilot plant is to demonstrate that the metallurgical results indicated by laboratory testing can be obtained on a continuous basis, and to establish a basis for the projection of the expected metallurgy into a commercial plant. Once the metallurgy is established, the necessary criteria for the design of a full-scale plant are obtained.

The testing of bulk samples representing the entire ore-body is required so that the overall feasibility of the project can be determined. Additional pilot-plant runs on samples representing ore that is to be mined during the first five years of operation would also be highly desirable. This would indicate the conditions and flowsheet required, as well as the metallurgical results that can be expected during the critical payback period of the project. The test may be extremely important because one or more factors may differ from the corresponding average factor for the entire deposit.

The Physical Pilot Plant

The size of the pilot plant may vary from a treatment rate of 1,5 t to more than 150 t of ore per day. Satisfactory results can be obtained on any plant within the above size range, provided that the equipment is installed and operated in a proper manner. As a general rule, however, the difficulty in operating and controlling a plant varies inversely with its capacity; therefore, a pilot plant with a capacity of at least 10 t per day would be preferable. An additional disadvantage with very small plants is that adequate equipment to handle the minute flows of slurry and reagents is generally not readily available and must usually be improvised.

The pilot-plant flowsheet should be as indicated by the detailed laboratory testwork. In setting up the plant, it is important to select equipment that will be related to that which is to be installed in a commercial plant. For example, if it is planned to use cyclones in the full-scale plant, cyclones should be used in the pilot plant. If the pilot-plant throughput is so low as to obviate the use of cyclones, a spiral or rake classifier might be considered for classification. This would ensure that wet classification applying gravity sizing would be utilized in both cases. The above example has particular significance in the testing of ores containing minerals of high specific gravity, such as galena, which would be ground preferentially in a circuit utilizing a cyclone or classifier, but would not be ground preferentially if a screen were used.

Preparation of Bulk Sample

The success or failure of a pilot-plant programme depends upon the use of 'representative' bulk samples. There is little problem in obtaining such samples from a homogeneous ore-body, but the task increases in difficulty with the heterogeneity of the deposit. In the preparation of a bulk sample representing a heterogeneous ore-body, it is necessary to blend samples of the various types of ore in the same proportions and grades as they occur in the deposit. This requires that each major type of ore in the deposit is extracted, crushed, mined, and stored separately prior to blending. If the ore is susceptible to oxidation or weathering, proper care must be exercised in the storage of samples to minimize the possibilities of alteration. Each bulk sample should then be submitted to the same chemical analysis, detailed mineralogical and geological examinations, and metallurgical testing as those undergone by the drill-core corresponding to the block of ore in the deposit that is being studied. The resultant comparison between the two samples can then form an objective basis in the establishment of design factors for the commercial plant.

In the preparation of a bulk sample as described above, only the required amount of each type of ore should be utilized in a particular blend that is to be tested. If the rest of the sample of each type of ore is kept separate, bulk samples representing other blocks of ore in the deposit can be prepared as desired. Another precaution to be considered in the preparation of the bulk sample is to keep the ratios and grades of the different types of ore consistent with the mining plan and the geology of the ore-body.

Pilot-plant Operations

A continuous pilot-plant run is made after the grinding and concentration circuit conditions have been optimized. The duration of the continuous run will vary with the complexity of both the ore and the flow sheet, but a run of five days is usually adequate. It is recommended that the concentrates produced from the continuous run should be weighed and assayed so that a physical check can be made on the metallurgical balance. The results of the continuous run will indicate the metallurgy that can be expected in the commercial plant. If the results are acceptable, it is obvious that the flowsheet for the commercial plant can be based on the pilot plant.

Once the expected metallurgy of the commercial plant has been established, the criteria required for the design the full-scale plant should be obtained. The major design of criteria are as follows.

(1) The flowrates and assays of the feed, tailings, rougher concentrate, scavenger concentrate, final concentrate, and cleaner tailings for each circuit.
(2) Settling and filtration tests on final concentrates.
(3) Settling tests on all products (such as feed, tailings, and middlings) that have to be thickened.
(4) Comparative grinding tests on all middling products that have to be reground (for sizing of the regrind mills).
(5) Screen analysis of feed, concentrates, and final tailings.
(6) Complete chemical analyses of concentrates.
(7) Tests to establish transportable moisture limits for all concentrates that are to be shipped by sea.
(8) Reagent requirements in regard to types, quantities, and addition points.

In the collection of flowrate and assay data on the required products, it is recommended that the corresponding averages should be established from as many measurements and determinations as possible because surging of the process streams causes values to vary considerably.

If on-stream X-ray analyses are to be incorporated for process control in the commercial plant, arrangements should be made for the collection of suitable samples so that tests can be done on whether this form of assaying is feasible, especially for complex ores, where the presence of a certain combination of elements may make this form of analysis unsuitable. Such tests are not required for simple ores.

Samples of the final tailings may also be required for appropriate tests if this material is to be used as mine fill.

Lastly, it is recommended that an adequate amount of final concentrate should be collected to serve as samples when sales contracts or in-house smelting tests are arranged.

Conclusions

The core sample for laboratory tests should be prepared so that it is consistent, with regard to the following factors, with the material existing in the deposit, as well as with the ore scheduled for extraction according to the mining plan:

(a) grade,
(b) types of ores,
(c) ratio in which the types of ores are combined,
(d) work index,
(e) mineral liberation size,
(f) minerals present in the ore, and
(g) properties of the minerals in the ore.

The bulk sample for pilot-plant tests should be prepared so that all the above factors are as close as possible to the ore that the bulk sample is supposed to represent. A detailed comparison should then be made between the resultant bulk sample and the drill core from the block of ore that is being studied. If the above factors are similar in both samples, it will greatly facilitate the attainment of a coherent overall picture considering the geology of the ore-body, the mining plan, and the mineralogy and the metallurgy of the ore. If some factors are slightly different, the detailed comparison can be used as an objective basis for the establishment of design factors in the planning of the commercial plant.

Reference

1. MacPherson, A. R. SME–AIME Meeting in Denver, Sep. 1976. Preprint 76-B327.

Company Affiliates

The following members have been admitted to the Institute as Company Affiliates.

AECI Limited.
Afrox/Dowson and Dobson Limited.
Amalgamated Collieries of S.A. Limited.
Apex Mines Limited.
Associated Manganese Mines of S.A. Limited.
Billiton Exploration S.A. (Pty) Limited.
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Rustenburg Platinum Mines Limited (Union Section).
Rustenburg Platinum Mines Limited (Rustenburg Section).
St. Helena Gold Mines Limited.
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Venterspost G.M. Co. Limited.
Vergenoeg Mining Co. (Pty) Limited.
Vlakfontein G.M. Co. Limited.
Welkom Gold Mining Co. Limited.
West Driefontein G.M. Co. Limited.
Western Areas Gold Mining Co. Ltd.
Western Deep Levels Limited.
Western Holdings Limited.
Winkelhaak Mines Limited.