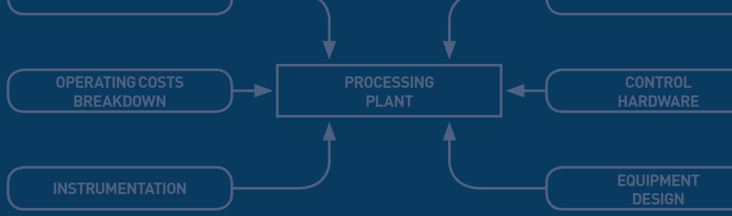

PLANT AUDITING

A Powerful Tool for Improving Metallurgical Plant Performance

BY DEEPAK MALHOTRA

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DEDICATION

To my wonderful wife Jyotisna and daughters Ruchi and Anisha who have been patient while I was away auditing plants worldwide.

CONTENTS

PREFACE

Cut… Cut… Cut…

Cut mill personnel.
Cut operating costs.
Cut research budgets.

Increase… Increase… Increase…

Increase recovery.
Increase throughput.
Increase revenue.

No… No… No…

No time to handle long-range projects.
No money to buy new technology.
No personnel to evaluate, improve, or modify the process flowsheet.

If this sounds familiar, we are talking about the mineral industry.

Mining companies are in the business of making an acceptable profit on their investments. The mining community recognizes that it is necessary to continuously strive for lower unit production costs and increase productivity and revenue in light of declining ore grade to compete in the global market. The burden of achieving this objective falls on the plant manager. He or she must strive to produce a salable product in an environmentally acceptable manner while continuously improving profit margin.

Companies must simultaneously enhance revenue and reduce operating costs to remain a low-cost producer in the long run. This involves continuous evaluation of technologies and reagents, periodic audits to locate revenue losses, and gathering and analyzing statistical plant data to facilitate a clear understanding of the impact of process variables on efficiency.

Mineral companies are caught in a catch-22 situation. They need resources (i.e., trained personnel, time, and money) to accomplish their objectives in a cost-effective and timely manner. Most mill staffs were cut to a minimum level to maintain production during the recent period when metal prices were low. Resources such as time, personnel, and money are scarce, and mill managers and metallurgists struggle to use these limited resources productively.

Both evolutionary and revolutionary changes have enhanced metallurgical performance in the past. Will they continue to do so in the future? How much more improvement can a process engineer achieve from an efficiently operating plant? One visionary metallurgist defined an ideal plant to be one that achieves 100% recovery at 100% grade and zero cost. Is it possible? Definitely not. However, it is a worthwhile goal (or challenge) for a metallurgical engineer to pursue.

A metallurgical engineer needs several tools to make his or her job more efficient. He or she not only needs management support but must also have training in problem identification, data analyses, and problem-solving techniques. It is mandatory that the engineer understands basic economic concepts of capital and operating costs, depreciation and depletion, and cash-flow analyses. Other activities that he or she must be familiar with include team building, team participation, and resource management. The term *resource* implies people, money, and time in the present context.

Since mining companies have gone global, understanding of cultural issues will help the engineer to be better prepared to work worldwide. Understanding technology transfer issues are equally important in helping the process engineer do an efficient job in performing meaningful audits.

This book is based on experience gained during the last 30 years auditing plant operations worldwide. The formal methodology was developed over a period of time and has been implemented successfully in improving plant operations. The book provides managers and engineers associated with all fields of mining (geology, metallurgy, environmental, etc.) and senior executives with an overview of systematic methodology used in plant auditing. It addresses the types of audits as well as when, where, and how to audit the plants. The book covers the systematic approach for global and specific audits. The same methodology can be used in any field to improve operations.

"Hit and miss" methodology for plant optimization has been practiced by metallurgists for decades. PART 1 of this book presents methodologies for plant auditing as a formalized procedure that encompasses all the aforementioned tools to help the metallurgist in achieving his or her goals. PART 2 illustrates through case studies how plant auditing can be successfully used to make significant improvement in plant operations through the evolutionary route. Most of these examples are real-life problems encountered by the author.

ACKNOWLEDGMENTS

The concept of developing a systematic approach to plant audits started more than 30 years ago when I was troubleshooting at the various plants owned by Amax Inc. Over the years, I realized that one could learn from everyone you meet and I am fortunate to have had so many mentors. They have helped me to develop the ideas and formalize them into systematic concepts. Thanks are extended to Bill Horst, Keith Wick, Jim Johnson, Jose Roco, Len Harris, and so many other individuals too numerous to mention here.

And finally I thank my wife Jyotisna, who has stood by me for 39 years, helping and supporting me in all my endeavors. She has assisted in revising the manuscript several times over the last decade.

PART 1

PLANT AUDITING METHODOLOGY

This section of the book provides a formal definition of audit and audit categories. It discusses why, where, and how the audit should be performed. The plant auditing methodology consisting of a formalized nine-step approach is discussed in detail to provide the reader with a good understanding of the requirements for a successful audit. In addition, a brief overview of economic principles and management of resources, which are key to success of audits, is also presented.

CHAPTER 1

THE PLANT AUDIT

THE ECONOMIC PROFITABILITY of any mineral company is dependent on maximizing mineral recoveries while minimizing operating costs. The effectiveness of any strategy to meet this objective is dependent on first obtaining quantitative information at steady-state plant operation and then efficiently using this information to improve or optimize plant performance.

Plant improvement or optimization starts with a plant audit. If one believes there is room for improvement, the benefits for plant auditing can be significant and are often measurable in terms of improved recovery, grade, or throughput and decreased operating cost.

The formal plant audit as a recognized engineering function is still in its infancy. It has been and will continue to be used informally by metallurgists to improve operations. Management wants to know how to quantify the potential benefits of this approach. In that regard, plant auditing today is in a similar position as process control was in the 1970s.

The plant audit can be a management tool that identifies the strengths and weaknesses of the current operation and provides a road map to future improvements. In fact, an audit should be mandatory for management seeking improved profitability.

The reality of market conditions (of low metal prices on a cyclical basis) has caused mining company management to severely cut the technical staff at mining properties. Plant metallurgists and superintendents must devote all their working time toward meeting production goals. There is little or no time for reflection nor a moment to ask the question: "Are we doing as well as we can?" Plant audits undertaken by persons outside the local management offer an independent and unbiased review of current plant practice.

DEFINITION OF *AUDIT*

Audit is a very commonly used word in the English language. Although it is a well-respected activity in the accounting profession, it has a negative connotation for most people. The unpleasant association is due to the abuse of the audit process. It has frequently been used for assigning blame. Audits should not threaten local management staff. All operations can be improved. Senior management should not use results of an audit to punish the plant management.

Metallurgists have raised their concerns regarding use of the word *audit*. Several suggestions for use of alternative wording have been made: *diagnosis*, *evaluation*, *review*, *appraisal*, and so on. Do these words change the primary objective of the task? This author believes they do not. Therefore, it is appropriate that the formal definition of audit be reviewed to understand the nature of what is implied.

Audit has a myriad of meanings, depending on the use and the application involved (Mills 1989). Several definitions include the following:

- A human evaluation process to determine the degree of adherence to prescribed norms (criteria, standards) and resulting in a judgment.
- A formal, often periodic examination and checking of accounts or final records to verify their correctness or any thorough examination and evaluation of a problem (*Merriam-Webster Dictionary* 2003).
- A formal examination of accounts with verification by reference to witnesses and vouchers or to make an official systematic examination of accounts (*The Oxford English Dictionary* 1989).

These definitions contain several key words and/or phrases including *formal*, *verify*, and *norms*. There are implications associated with them.

The word *formal* or *official* implies that the audit function must have a recognized position in the hierarchy of the organization. The audit must also be systematic. Hence, it should be a well-planned and organized activity.

The second key phrase is “checking of accounts or final records to verify their correctness” or “verification by reference to witnesses and vouchers.” This implies that both people and records must be involved. The word *verified* requires that findings must be based on factual information and not hearsay evidence or assumptions.

The third phrase, "prescribed norms," implies that criteria must be available to which findings can be compared. How can one make a judgment if criteria and/or standards have not been predetermined?

Based on these definitions and implications of key phrases, it is reasonable to conclude that an audit is concerned with the methodology as well as the results of that methodology. The output of an audit is a report giving observations and, very often, recommendations for specific corrective action.

A properly planned and conducted audit should be a positive and constructive process. It is a management tool, not a weapon, and should be used to determine where a plant is with respect to standard norms.

CHAPTER 2

AUDIT CATEGORIES

AN AUDIT CAN BE USED WITH A LARGE NUMBER OF MODIFIERS OR PREFIXES like financial, analytical, geological, environmental, mining, quality, plant, and so forth. Hence, depending on the application and user, the word *audit* has a myriad of meanings. For example, to an accountant, an audit means a review of financial accounts to verify their correctness with respect to established norms; to a geologist, it means investigating proven and probable ore reserves, cut-off grades, and so forth.

The types of audits generally associated with the mining industry are shown in FIGURE 2.1. A property audit encompasses one or more of these areas, depending on the objectives of the study. Several elements have to be addressed under each category. TABLE 2.1 lists some of the important factors for each category. This list is for illustrative purposes only and does not include all the factors that should be addressed in each area (Malhotra and Baltich 1989a, 1989b).

One of the commonly used and very effective methodologies for audit is the function-tree approach where the major components of the audit are broken down into various subsections, as illustrated in FIGURE 2.2 for a processing plant. A component of the processing plant, namely process metallurgy, can again be subdivided into various components as illustrated in FIGURE 2.3. The process parameters can be further subdivided if it can be beneficial to the audit.

The discussions in this document are restricted to the processing plant since the main objective is to provide a systematic approach to plant auditing for enhanced metallurgical performance. The approach is generic in nature and can also be used for other categories of auditing.

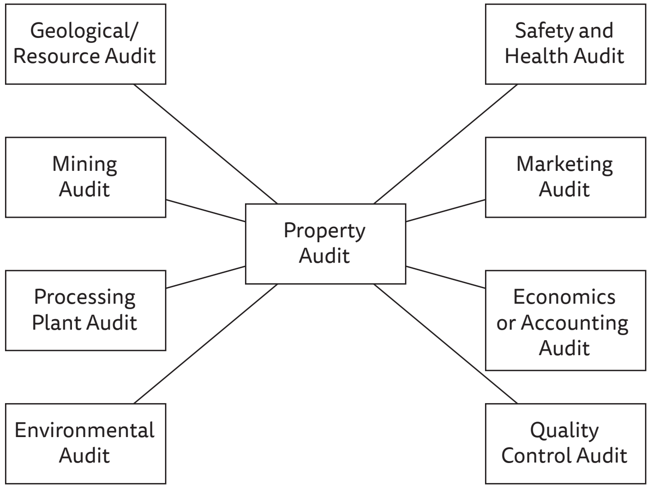

FIGURE 2.1 **Categories of a property audit**

TABLE 2.1 **Elements of a property audit**

Category	Elements
Geological/Resource	Ore reserves Ore grade Cut-off grade Major impurity Mineralogy and mineral associations
Mining	Mining methods Overburden ratio Mining capacity Dilution
Processing Plant	Plant capacity Work index of ore Product yield or recovery Product quality Chemical reagents Equipment efficiency Tailings characterization
Environmental	Dust control Working environment Hazardous chemicals Guards on equipment Water seepage Emissions Air pollutants Water pollutants
Safety and Health	Training Hazardous chemicals Tailings disposal
Marketing	Transportation to market Product markets Specifications Substitutes
Economics or Accounting	Operating cost factors Revenue Profits Sensitivity analyses
Quality Control	Product specifications Feed specifications Process specifications

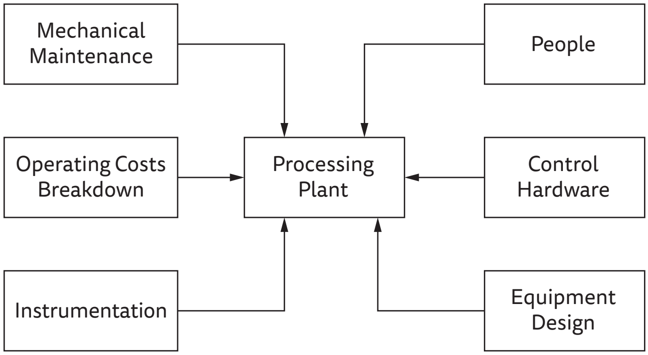

FIGURE 2.2 **Elements of a metallurgical processing plant audit**

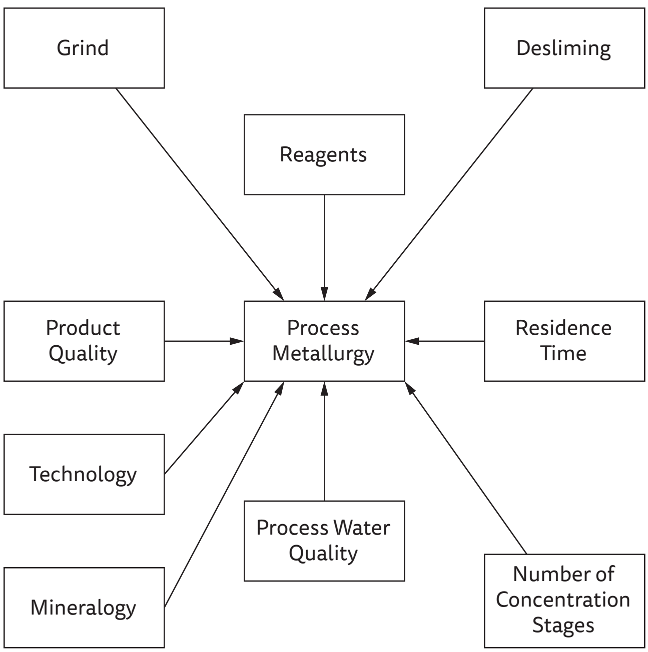

FIGURE 2.3 **Elements of process metallurgy**

CHAPTER 3

PLANT AUDIT—WHY, WHEN, AND WHERE?

A PROPERLY PLANNED AND CONDUCTED AUDIT should be a positive and constructive process. It is generally used for economic reasons (why), performed yearly or more frequently (when) at the plant location (where). It should be used as a management tool to determine where the operation is with respect to predefined norms and what needs to be done to improve plant performance.

CHARACTERISTICS OF A PLANT AUDIT

Based on the author's extensive auditing experience, a successful plant audit has the following characteristics:

- It is expensive and time-consuming.
- It requires genuine commitment from senior management.
- The benefit/risk ratio is reasonably good.
- It should be performed by an independent group not associated with the plant. This can be a separate corporate group or consultants. However, this does not preclude that periodic internal audits should also be undertaken by the plant metallurgist or staff.
- Auditor/auditee/client cooperation is critical to a successful audit.
- It is mandatory that the auditor have broad-based experience.
- A trust relationship must be established between the auditor(s) and auditee(s) before the audit begins.
- Recommendations and/or suggested corrective actions should be implemented to reap the benefits of the audit.

A more detailed discussion on these factors is presented in subsequent sections of this chapter.

POTENTIAL BENEFITS OF AN AUDIT

Audits can be expensive and time-consuming. Hence, management is justified in wanting to know the potential benefits that can be achieved from a formal audit.

These audits generally provide management with a technical road map that can be used to improve plant performance. The potential benefits of the audit include

- Identification of the strengths and weaknesses of the operation;
- Recognition of potential opportunities for improvement;
- Prioritization of plant modification projects;
- Estimation of capital requirements for each area of improvement;
- Application of a systematic, cost-effective approach to problem solving;
- Quantification of the capital costs associated with the proposed modifications;
- Development of historical statistical data to build technical/economic models that can lead to effective decision making in the future; and
- Identification of unintentional senior management actions that create problems for the plant operators (i.e., conflicting goals).

PRESCRIBED NORMS FOR A PLANT AUDIT

Unlike quality or accounting audits, a plant audit does not have prescribed norms to which the audit results can be compared. Any of the following norms may be selected:

- Historical performance of an existing operation
- Performance of other operating properties in the vicinity of the operation

- Performance of other properties in the country and/or those plants that treat similar ores
- Design criteria used for plant construction and commissioning
- The lowest cost producer in the world
- What is called the "Eureka!" standard—100% recovery at 100% grade at zero cost (the metallurgist's dream of an ideal plant)

The question of norms is complicated because various components of a property audit are interrelated and can impact the final results. For example, changing ore hardness (i.e., geological category) will affect process plant recovery. As another example, even if a chemical reagent gives excellent metallurgical results, it cannot be used if it is hazardous to the environment or unhealthy for the workers (environmental factors).

It is important that the norms for the audit be selected by mutual agreement between the auditor, auditee, and client prior to commencement of the audit. The conclusions and recommended corrective actions can be different depending on selection of the norm.

It may be possible to establish realistic local standards by subjecting "real ore" to laboratory tests. This can establish "ideal" targets for grade and/or recovery to which the plant can strive.

CHIEF METALLURGIST'S JOB DESCRIPTION

When a chief metallurgist is hired for a milling operation, he or she is informed of the following primary job functions:

- Being responsible for improvement of plant metallurgy on a continuous basis
- Evaluating and implementing new and cost-cutting technologies in the plant

The metallurgist is supposed to be the gatekeeper of new technologies and ensure that the plant is providing maximum revenue at least cost. He or she is hired as an internal plant auditor. After few months of working at the plant, the metallurgist realizes that his or her job description should actually include other duties being done on a daily basis, which are

- "Fighting fires" on a daily basis, and
- Ensuring that throughput and production quotas are met (i.e., trying to force 10 lb of stuff in a 5-lb box).

Hence the role of chief metallurgist typically changes from being an internal auditor to becoming a crisis manager. An operations audit, though important, is not considered urgent. The companies usually designate corporate team members or hire outside consultants for this function. More often, however, periodic audits are not done at all.

AUDITOR'S QUALIFICATIONS

The interrelationship of the various audit components (geology, metallurgy, economics, environmental, etc.) demand that the auditor have broad-based experience in the mining industry and not be a specialist in only one area (e.g., mining). He or she can involve team members who are specialists in specific disciplines.

The auditor can be internal (from within the organization) or external. Internal auditors are generally less effective because they can be biased by what management wants to hear about the operation. They have an inclination to be subjective rather than objective. An internal auditor's position in the organization hierarchy typically influences the outcome of an audit, whereas the external auditor is generally objective and independent of the activity being audited.

THE TRIANGULAR RELATIONSHIP

Generally there are three viewpoints involved in managing an audit due to the three parties involved: client, auditee, and auditor (FIGURE 3.1). Very often the client and auditee are the same organization. The interpersonal relationship among the participants has significant impact on the effectiveness of the audit. The success of an audit depends on the cooperation of all three parties.

After the client, generally senior management, decides to have an audit of an operation (auditee), it is necessary that the concerned parties meet to reach a consensus on the objective(s) of the proposed audit and the standard against which the results will be compared. This meeting is imperative to ensure that the objective(s) of the audit is constructive and not intended to lead to punitive action. Also, it demonstrates to all concerned parties that senior management is committed to have the audit undertaken.

Despite assurances from the auditor that the study will be objective, the auditor may feel challenged in dealing with the auditee who believes that

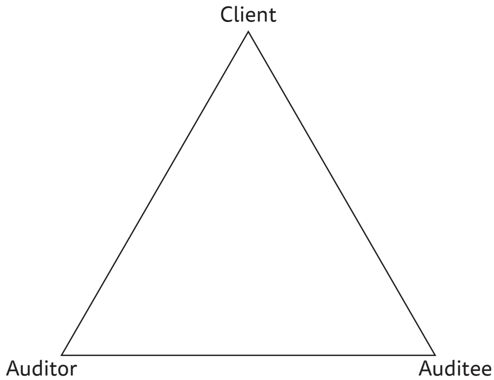

FIGURE 3.1 The triangular relationship

the client may be looking for a scapegoat for poor performance. This attitude from the auditee is the result of a myth—"Who knows more about the operation than me? I have worked in this job for 10 years. Why doesn't management ask me?" The auditee has very little time, if any, to reflect on ways to improve the metallurgical performance.

Be assured that the auditor, especially an external one, has no "axe to grind." The auditor is supported by a team of experts in different disciplines. The team brings vast experience from similar audits at other operations. The auditor pays attention, listens, takes notes, and then listens some more. Then he or she asks questions. The entire focus is on the objective of the audit, that is, finding ways to improve the performance of the plant. The same applies for the other team members.

WHY AUDIT?

An audit can be undertaken for several reasons:

- To improve recovery
- To improve product quality
- To increase production
- To reduce costs
- Because of market changes
- Because of ore changes

Sometimes an audit is performed because plant management needs a checkup to ensure that the plant is operating efficiently.

All these reasons can be summed up in a single phrase: economic improvement. In a free market economy, the basic reason for setting up any business is to make a reasonable profit on investment. Would you invest money in a losing proposition? Economic survival, and hence our job security, depends on operating a profitable mining venture. The consumer—that's you and me—will buy the product at the cheapest cost, regardless of where it is produced or manufactured.

Neale and Flintoff (1992) have provided a different perspective to the reasons for periodic auditing. They note two key factors governing changes in an operation: the opportunity must be recognized, and the justification for change must exist. Both factors emphasize the critical role of successful plant auditing. Without plant audits, many opportunities for improvement might go unrecognized. On the other hand, when a situation ripe for improvement is recognized, the hard data from a plant audit can reveal the expected impact of an operating change.

WHEN SHOULD AN AUDIT BE UNDERTAKEN?

The most frequently asked question related to audit is when should it be performed?

There is no strict rule regarding the frequency of an audit. It can be a single event or a repetitive activity depending on the objective and outcome of the initial audit.

The two main types of plant audits are the global audit and the specific audit. A *global audit* identifies the opportunities for improvement, whereas a *specific audit* provides data to justify a change.

Generally a global audit should be performed once a year, whereas specific audits should be performed on a more frequent basis or whenever the operating criteria or ore characteristics change in the circuit.

WHERE SHOULD AN AUDIT BE PERFORMED?

The initial meetings between the auditor, client, and auditee should take place at the location where the audit is to be conducted. At this meeting, the auditor should ensure that the objective(s) of the audit and the prescribed norms are developed and well understood by the client and the auditee. Thereafter, the auditor and his or her team, whether internal or external, should spend the necessary time to gather information at the audit site. The auditing operation should then move off-site to minimize disruption to the ongoing operation.

If a specific audit is being conducted, activities that can be accomplished off-site should be. Even with an internal audit, it may be advisable to move as much of the activity off-site as possible. This provides a formal atmosphere for the audit and eliminates any bias or subtle influencing of the audit results.

Great care should be taken by the client and the auditor to convince the local plant operators (i.e., auditees) that the audit is going to be part of the solution and not part of the problem. The auditor is not there to cut jobs or find scapegoats for poor plant performance but to identify ways to make the operator's job easier and better, and/or to improve plant performance.

CHAPTER 4

GLOBAL AND SPECIFIC AUDITS

METALLURGICAL PLANT AUDITS can generally be divided into two categories: global and specific. An overview of the methodology that can be used for each type of audit is briefly presented in this chapter. Case-study examples for each type of audit are presented in PART 2.

GLOBAL AUDITS

Global audits are usually performed to identify opportunities for improvement. They also provide management with an idea of strengths and weaknesses of the system as well as a road map for improving operations. Because of the availability of limited resources (i.e., people, time, money), process engineers cannot work on all projects related to plant improvements at the same time and achieve acceptable results. Therefore, management can rank the projects by assessing the benefit/risk ratio associated with each opportunity. The best opportunities can then be formalized into projects. Projects can then be prioritized according to the benefits to be realized. This technique leads to more efficient use of limited resources. After the projects have been prioritized, specific audits can be performed.

Most plant metallurgists have dozens of ideas for plant improvements but lack the time to quantify the cost/benefit of each one. The auditor and/or auditing team can assist by ranking the projects in a priority list following a formal global audit.

A systematic approach to global audit can be developed. Very often one finds that the perceived problem is not real and the actual problem may be in an interrelated area (e.g., geology instead of processing). For instance, even though an auditor may be auditing the processing plant, meetings need to be arranged with the geologists, mining engineers, process engineers,

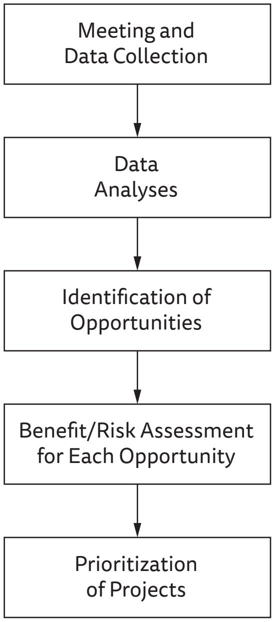

FIGURE 4.1 **Major steps for global audit**

maintenance personnel, safety personnel, senior management, and so on, during the audit to distinguish between the real and perceived causes of the problem and/or proper identification of the opportunities. A partial list of the questions needed to initiate a global audit is given in the appendix.

Global audits require the following five steps (see FIGURE 4.1):

1. Arrange a meeting with the various groups or departments and ask questions. Listen to what the people say and how they say it.
2. Collect historical data available for the plant.
3. Critically review the meeting information and historical data, and identify potential opportunities for process improvements.
4. Determine capital costs for identified opportunities and determine the benefit/risk for each opportunity.
5. Prioritize projects based on the benefit/risk ratio.

SPECIFIC AUDITS

Having identified the opportunities, management needs the justification for change. Specific audits, the objectives of which are well-defined, provide the necessary information for change. A nine-step systematic approach has been developed by the author and is outlined in FIGURE 4.2. It provides a formalized audit procedure that is cost-effective and keeps the project team focused on the primary goals of the audit.

The nine-step approach consists of the following:

1. Define the program objectives.
2. Identify the problem.
3. Review the historical data.
4. Design a sampling campaign.
5. Sample the unit operation/circuit.
6. Perform data analyses.
7. Draw conclusions.
8. Evaluate alternative solutions.
9. Provide recommendations.

The specific audit requires sampling of the circuit and appropriate data analyses to justify the change. A detailed discussion of each step is provided in Chapter 5.

REVOLUTIONARY VERSUS EVOLUTIONARY CHANGE

All parties involved in an audit should understand the difference between evolutionary and revolutionary changes prior to outlining the objectives of the audit. *Revolutionary changes* generally imply that the existing principles do not work efficiently and technology based on new principles is more appropriate. On the other hand, *evolutionary changes* imply improvements to the existing system to enhance performance.

Examples of revolutionary change today may include in-situ extraction of copper, or grinding and flotation in a single machine. Evolutionary changes may include formal operator training, or a tower mill for regrind and flash flotation cells.

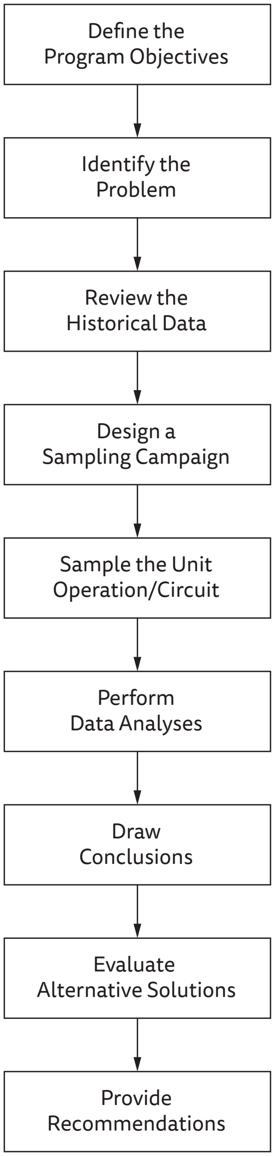

FIGURE 4.2 **Specific audit—a nine-step systematic approach**

It is important to stress that a metallurgical audit is not usually undertaken with the goal of making revolutionary changes (i.e., major flowsheet changes), but rather with the objective of making evolutionary changes (modifications) to enhance plant performance. One should not expect a quantum improvement in an efficiently run operation.

CHAPTER 5

SPECIFIC AUDIT PROCESS

BRIEF DISCUSSIONS OF WHAT IS INVOLVED in each of the nine steps presented in the previous chapter are discussed in the following sections.

STEP 1: DEFINE THE PROGRAM OBJECTIVES

The most critical step in any plant audit is to have a clear understanding of the objectives for the study. These objectives need to be understood not only by the auditor but also by the client and the auditee. They need to be clearly defined or quantified to perform a meaningful audit.

The following list are the possible objectives a client might like to achieve:

- Improve recovery
- Improve product grade
- Reduce operating costs
- Increase plant throughput
- Improve profitability of operation

These objectives may be worth pursuing, but they are ill-defined program objectives. For example, let us look at "improve recovery" as a goal. A plant is currently recovering 85% of the copper values in a concentrate assaying 29% Cu. The auditor improves recovery from 85% to 85.2%, thereby achieving the stated objective. But the concentrate grade also drops from 29% to 28% Cu. Is this acceptable to the client? Most probably not. What about 87% copper recovery at 25% Cu grade of concentrate? The recovery may be acceptable, but the client may not be able to sell the concentrate because of the significant drop in grade.

The ill-defined program objective of "improving recovery" should be translated into the following well-defined objective in meetings with the client and auditee:

> Improve recovery by 1% or more while maintaining the concentrate grade, throughput, and operating cost at the current level.

The well-defined objective becomes a goal to achieve in the audit of the operation. The expectations of the client are quantified; hence there is no misunderstanding of expectations.

STEP 2: IDENTIFY THE PROBLEM

While defining the objective of the study, the problem(s) may automatically be identified. Very often, however, this will not be the case. The auditor should be prepared to ask the appropriate questions from the client and the auditee to identify the real, not perceived, problem(s).

In the case of global audits, the problems may not exist. The client may want an audit to identify the potential opportunities for improvement. He or she may already have the answers and wants a second opinion.

In the case of specific audits, identification of the real problem(s) helps in designing cost-effective sampling campaigns. For example, all the unit operations in the concentrator do not need to be sampled if the bottleneck in the plant is in the grinding circuit.

STEP 3: REVIEW THE HISTORICAL DATA

Mill personnel, in general, are too busy attending to other important tasks in the plant and hence do not have sufficient dedicated time to review historical data to identify reasons for current problems. The auditor should review the available data and arrive at potential reasons for the problem(s).

This process will also help the auditor avoid duplicative efforts. It helps eliminate alternative solutions that may not have worked in the past. It also gives the auditor backup information for designing the sampling campaign.

As an example, one auditor reviewed 15 days of grinding mill sampling data that was worthless because the ball mill discharge was coarser than the ball mill feed. This demonstrates that the correct sampling procedure needs to be implemented.

It is often useful for plant management to establish an ongoing relationship with an outside auditor whereby that auditor gets daily and monthly reports. Thus the auditor can identify changes in plant performance that local management personnel might miss because they are busy attending to other job duties.

STEP 4: DESIGN A SAMPLING CAMPAIGN

If the objective is to sample the entire plant, designing a sampling campaign can be complex. The complex flowsheet needs to be divided into several sections. Examples are provided in PART 2 to illustrate how this should be done.

The most reliable information must be obtained for the resources (i.e., personnel, time, and money) one can afford to spend. Sampling the plant is not only expensive, it is also time-consuming. Hence, careful planning will pay off, so take the time to do it right. Remember: It costs twice as much if you have to repeat your efforts. Besides, if you don't have the time to do it right the first time, when will you have the time to do it over (Meyer 1990)?

Involve not only the project team members but also include plant operators in designing the sampling campaign. They know more about the plant and sampling points than the project team may know. Good communication and teamwork is key to successful data collection.

An effective sampling campaign should include the following:

- Determine beforehand if the streams to be sampled are readily accessible.
- Clarify the operating parameters to be recorded during sampling, namely, throughput, ore type, reagent conditions, and so forth.
- Establish the physical analyses required, namely, particle size distribution, grindability index, and so on.
- Determine the necessary chemical analyses.
- Ascertain the quantity of sample required. Don't forget that samples may be needed for bench-scale test work.
- Establish the time and frequency of sample collection. A constant time for collecting samples from all streams is not advisable. A 15-second sample of some streams may result in a 55-gallon sample

while only half a gallon may be collected from other streams. Be flexible and collect the amount of sample that can be comfortably worked with in subsequent processing steps. Make sure samples are representative.

- Sampling methods are important. A sample cutter may be needed as well as 1- to 5-gallon buckets.
- Subsequent sample splitting and preparation methods need to be reviewed carefully.
- Determine how and where the samples will be stored.

> Work backward while planning.
>
> What information is needed to meet the objective?
>
> Organize the sampling campaign to best give you that data.

STEP 5: SAMPLE THE UNIT OPERATION/CIRCUIT

Despite all the preparation done as discussed in the previous step, Murphy's Law can still occur:

"If things can go wrong, they will."

The following list gives some of the numerous hurdles that may be encountered during plant sampling:

- The plant was not designed for sampling.
- Some of the streams that need to be sampled are inaccessible.
- Some of the pumps and sumps will be overflowing.
- The plant will most likely not have instruments for slurry flow measurements.
- Sample size will vary from small to very large.
- Because a large number of samples will be collected and handled, the probability of mislabeling samples is high.

It is generally recommended to sample the circuit at least four times over a 6-hour period. Longer times are desirable to eliminate or at least minimize plant fluctuations if the plant tonnage is large or the ore characteristics are variable. During the sampling period, the operating plant process data needs to be checked and collected if such information is available in the control room. It is important to ensure that the operating conditions do not change drastically during the sampling campaign. If they do, the sampling campaign needs to be abandoned and the procedure repeated from the beginning.

After the samples are collected, proper precautions need to be taken to ensure that the samples split for analyses are representative of the total sample. Shortcuts should be avoided. A scoop of slurry from a 5-gallon sample may not be representative of the total. If the sample is coarse, the sample may need to be dried and crushed to reasonable size (i.e., minus 10 mesh) prior to taking a split for chemical analyses.

During the sampling period, separate samples must be collected for bench-scale testing. Keep in mind that it is easier and cheaper to evaluate the effect of process variables on metallurgy during bench-scale testing than changing process conditions in the plant. Once the optimum conditions are determined in the laboratory, they can then be tested in the plant. The bench-scale testing should generally be done concurrently with plant sampling to minimize the effect of aging of samples on metallurgy.

STEP 6: PERFORM DATA ANALYSES

The project manager has an abundance of data for analysis at this stage. Good judgment is mandatory for obtaining meaningful results.

It is easy to calculate material balance for the circuit if the process flowsheet is simple and does not have too many recycle streams. However, difficulty in calculating an accurate material balance may still be encountered. The reasons for this can be one or more of the following:

- Insufficient data because some streams could not be sampled
- Assay errors
- Sampling redundancy (i.e., first-cleaner concentrate and second-cleaner feed assays are different even though they should be the same if the streams are not recycled in this part of the circuit)
- Sampling errors due to sampling difficulty
- Normal cyclical variations in plant flow rates
- Complexity of flowsheet calculations due to recycle streams

Computer software programs are available to establish consistent material balance for complex flowsheets. However, software packages are only tools to assist process engineers. Remember that garbage in equals garbage out. Good judgment is mandatory to arrive at meaningful conclusions. During subjective judgment in correcting the data or drawing conclusions, the project manager should not forget to relate the material balance in the plant to the operating parameters observed or collected during the sampling period. Also, correlation between bench-scale and plant data should be kept in mind while performing data analyses.

STEP 7: DRAW CONCLUSIONS

The next step is to draw conclusions based on the information collected. These conclusions should be related to the objective(s) of the study.

The conclusions should be presented in a clear, concise manner to management and/or the client. They can be in a bullet list and should not exceed a few pages. A general rule to remember is that if you cannot say in a few pages what needs to be said, you have nothing important to tell.

Very often, observations are made that could help the operation but are not related to the primary objective of the study. These observations should be noted as additional findings.

STEP 8: EVALUATE ALTERNATIVE SOLUTIONS

Prior to recommending major changes in the plant to the client, it is necessary to evaluate alternative solutions. Evaluate all "what if " situations and work out budgets, time, and technical feasibility associated with these situations. Additional bench-scale support work may be necessary to support or reject various alternatives.

Select the best one or two alternatives that meet program objectives as recommendations to management. As stated in step 7, separately list solutions to problems you discovered in the course of your investigation even if they were not part of the objectives of the audit process.

STEP 9: PROVIDE RECOMMENDATIONS

The auditor was commissioned to undertake a study related to specific problems. Hence it is mandatory that the recommendations should relate directly to the objectives of the study. The report should include potential benefits and costs of each recommended solution. Justification for implementing recommendations should also be included in the document.

AUDIT: CORRECTIVE ACTION

The important considerations for each step of the nine-step approach for a formal audit are summarized in TABLE 5.1. A meeting between the auditor, client, and auditee to review the conclusions of the audit is often helpful. It also reinforces the commitment for management to continue the audit process.

The client and the auditee need to take action after receiving the recommendations and suggested corrective action(s) from the auditor. Otherwise, the money and the time spent for the audit will be worthless.

Management should insist that the auditee follow up with the corrective action. Following the corrective action, a follow-up audit may be needed to conclude the study.

TABLE 5.1 **Nine-step systematic approach for metallurgical audit**

Step No.	Item Description	Important Considerations
1	Define the program objectives.	■ Designate project manager for each project. ■ The project manager should have a diverse background in mining, geology, environmental, and mineral processing fields. ■ Translate ill-defined program objectives into well-defined objectives (e.g., change "improve recovery" to "improve recovery by 2% while maintaining operating costs at the same level"). ■ Maintain good communication with management and operating personnel.
2	Identify the problem.	■ This helps in designing effective sampling programs.
3	Review the historical data.	■ The review identifies reasons for current problems. ■ This helps eliminate alternative solutions that personnel may not have worked in the past.
4	Design a sampling campaign.	■ Careful planning will pay off. Determine what you need to know to achieve your objectives. ■ Divide a complex flowsheet into several sections. ■ Involve the project team, including operators. Good communication is key to successful data collection.
5	Sample the unit operation/circuit.	■ Murphy's Law often applies—If things can go wrong, they will: • The plant was not designed for sampling. • Streams to be sampled are inaccessible. • Overflowing of slurry occurs. • No instrumentation exists in the plant. • Sample size varies from small to very large. • Too many samples to be handled; hence, there is a greater chance of mislabeling. ■ Ensure that all information related to plant operators and sampling is properly documented.
6	Perform data analyses.	■ The project manager has an abundance of data for analyses. Good judgment is mandatory for obtaining meaningful conclusions. ■ Software programs are available to establish consistent material balances for complex flowsheets. ■ Relate the material balance to the operating parameters observed during sampling. ■ The correlation between bench scale and plant scale should be kept in mind while doing data analyses.
7	Draw conclusions.	■ They should be related to the objective of the study. ■ Present the conclusions in a clear, concise manner to management.
8	Evaluate alternative solutions.	■ Evaluate all "what if" situations and their economic implications. ■ Select the best one or two alternatives that meet project objectives as recommendations to management.
9	Provide recommendations.	■ Document the potential benefit and cost of each recommended solution. ■ Justification for implementing recommendations should be included in the report/presentation.

CHAPTER 6

METALLURGICAL MYTHS, ECONOMIC CONCEPTS, AND TOTAL RESOURCE MANAGEMENT

SINCE THE PRIMARY OBJECTIVE OF THE AUDIT is to ensure that the company remains one of the lowest cost producers, it is important for the auditor to understand the basic economic concepts as well as being aware of the myths commonly believed by some metallurgists. A brief discussion on resource management (time, people, and money) and not geological resource is presented in this chapter to complement the economic concepts.

METALLURGICAL MYTHS

Every profession has its own set of myths and/or perceptions. Metallurgists are no different. The following perceptions are common among metallurgists throughout the world; the level varies from country to country.

- MYTH 1: Higher metal recoveries lead to higher profits.
- MYTH 2: Grinding the ore finer leads to higher metal recoveries and hence higher revenue and profits.
- MYTH 3: Reductions in unit operating costs associated with increased throughput increases profits.

These perceptions are partly true. Ignorance as well as lack of knowledge of economic principles are the reasons for believing these myths. A wise man once said, "little knowledge is dangerous." A good understanding of the selected economic concepts briefly reviewed in this chapter should not only help clarify these perceptions but also help in auditing the operations.

METALLURGIST'S DREAM: THE IDEAL PLANT

Merriam-Webster Dictionary (2003) defines *technology* as "systematic treatment of art" or "improvement of existing system." It can also be considered as a process for handling a specific technical problem. According to these definitions, technology encompasses all methods/processes that can improve the existing process/system.

From the definitions, it can be inferred that technology is constantly changing. Process engineers/metallurgists are continuously striving to find better methods for doing the same job technically and/or economically.

A good metallurgist is never satisfied with the current plant performance. He or she strives to do better. Why not set the target for the ideal plant—one that produces 100% recovery at 100% grade and zero cost.

Can we realistically achieve this target? No, but there is no harm in setting higher goals than the current status.

PROFITABILITY

The plant metallurgist wants to maximize recovery of valuable minerals while maintaining an acceptable-grade product. It may be possible to increase recovery by making the primary grind finer and increasing the dosage of reagents. However, maximizing recovery does not necessarily maximize profits. *The overall objective of any operation is to maximize profits and not recovery.* However, in some socialist countries, the primary function of government-owned mines is to provide jobs and not necessarily to make money. Maximizing profits is dependent on revenue and operating cost, as the following profitability equation indicates:

$$\text{profits} = \text{revenue} - \text{operating cost} \tag{EQ 6.1}$$

This equation has been simplified to exclude taxes, research and development costs, depreciation, depletion, and capital expenditure. These aspects are discussed when dealing with cash-flow calculations (Malhotra et al. 1993). Four scenarios take place for improving profitability:

1. Increasing revenue while maintaining the operating cost at base level.
2. Decreasing operating cost while revenue stays constant.

3. Increasing both revenue and operating cost as long as the additional revenue is greater than the additional operating cost.
4. Increasing revenue and decreasing operating cost simultaneously.

The most desirable and idealistic situation would be the last alternative. It is obvious that the audit campaigns need to be correlated to both revenue and operating cost to maximize profit. Maximizing recovery increases the revenue but will only increase the profit as long as the incremental revenue is greater than the cost of incremental recovery. Hence it is preferable to discuss *maximizing economic recovery* rather than only recovery of valuable mineral, because the former leads to maximization of profits.

> Maximizing recovery does not always lead to maximizing profits, but maximizing economic recovery does.

The three components of Equation 6.1 are profits, revenue, and operating cost. The primary objective of any business is to make a profit, which is achieved when revenue is greater than operating cost. Revenue and operating cost are a function of the following plant components:

revenue = function (throughput, feed grade, recovery, metal price, quality product by-products/co-products, etc.)

operating cost = function (mining cost, milling cost, smelting cost, general and administrative cost, etc.)

Each component of operating cost can further be analyzed using subcomponents as follows:

milling cost = function (size reduction, product handling, separation process, etc.)

milling cost = function (supplies, salaries, power, etc.)

The auditor needs to acquire cost data for the plant from the client or the auditee and become familiar with the method they use to determine profitability. Different companies break down revenue and operating costs differently into subcategories.

The data for the plant needs to be compared with other operations using a standard procedure developed exclusively by the auditor or the auditee. The cost data may reveal some interesting conclusions.

OPERATING COSTS

The total operating cost consists of a combination of fixed costs and variable costs for the plant:

$$\text{total cost} = \text{fixed costs} + \text{variable costs} \tag{EQ 6.2}$$

Fixed costs include taxes, insurance, depreciation, and so forth. They are the minimum level of costs needed to sustain operation in a holding mode. They may also include items such as utilities, maintenance, supplies, and minimum staff.

Variable costs include staff, reagents, power, and so on, and will vary depending on the plant throughput. Typically, variable costs account for 10% to 20% of the total costs for milling operations. Operating costs vary from mineral to mineral and operation to operation. However, they are sensitive to feed grade. The data for a typical copper flotation plant are given in TABLE 6.1. Most plants make reasonably good returns as long as metal prices stay high. A typical sulfide mineral processing plant consists of crushing, grinding, rougher and cleaner flotation, solid/liquid separation, and drying of concentrate. A simplified process flowsheet is shown in FIGURE 6.1. The typical breakdown of operating costs for a sulfide mineral processing plant are as follows:

- Size reduction: 50%
- Separation processes (flotation, gravity, etc.): 25%
- Product handling: 25%

The gross operating costs for copper production per pound are as follows:

- Mining: $0.66 (34%)
- Mineral processing: $0.72 (38%)
- Smelting/refining/transportation: $0.54 (28%)
- Gross operating cost: $1.92 (100%)
- By-product credit: $0.08
- Net operating cost: $1.84

The mineral processing costs can be further broken down as shown in TABLE 6.2. Interestingly, the chemical reagents account for 5% to 10% of the total operating cost (20% to 40% of the separation cost). What is the operating cost breakdown for your plant?

TABLE 6.1 **Typical plant operation (copper)**

Feed	0.3–0.8% Cu
Recovery	80%–93%
Concentrate grade	28%–30% Cu
Operating cost	$1.50–$3.00/lb
Metal selling price	$3.10/lb

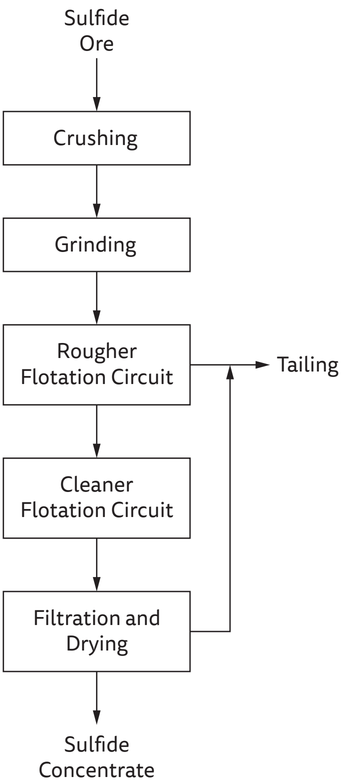

FIGURE 6.1 **Simplified block diagram process flowsheet**

RESOURCE MANAGEMENT

The resources in the mining industry would generally be considered to be the ore. However, the resources in the present context are intended to be *people*, *time*, and *money*. Mining companies do not have an abundance of

TABLE 6.2 **Analyses of milling costs (per pound of copper)**

Total mineral processing cost	\$0.72
Size reduction cost	\$0.36
Separation process cost (reagent cost)	\$0.18 (\$0.036–\$0.072)
Product handling cost	\$0.18
Variable cost (10% of total)	\$0.072

these resources. Hence it is important that these resources be managed efficiently to optimize plant performance.

A majority of the managers who are operating mines have an excellent technical background. They are trained to be engineers who think logically to solve problems. However, they have limited training in managing other resources (i.e., people, time, and money) and sociopolitical considerations efficiently. The latter issue is discussed in Chapter 7.

Each of us has 24 hours a day, 1,440 minutes a day, or 86,400 seconds a day. No more, no less. How effectively we manage our time is dependent on us. We have little, if any, formal training to maximize the results that will affect our careers within the limited time available to us.

Numerous books have been written on time management. Several references are provided in the "Recommended Reading" section at the end of the book. The time management philosophy started by writing notes and checklists and pasting them on a wall or desk to remind individuals of things that needed to be done soon or within a certain time frame. Some people still follow this approach. An engineer's work area in the mill probably has lots of notes pasted here and there.

Appointment books came next. Scattered notes were organized into a book where people made a list of things to do and then prioritized them in order of urgency to complete them. In some cases, the tasks were completed in the order they were written or in increasing order of time required to complete them. Examples of the two approaches are given in TABLES 6.3 and 6.4.

The items taken care of during the day are removed or scratched, and new items are added several times during the day. For example, the boss calls you on the telephone and wants you to give him an inventory of reagents at hand or wants you to talk with a candidate being interviewed for another department. These are examples of time wasters. At the end of the day, you may

TABLE 6.3 **Tasks to be completed by priority**

Typical List of Activities	Time Management Approach
Pump repair	1A
Cyclones plugged	1A
Daily metallurgical balance	1B
Weekly report	2A
Order reagents	1A
Reagent salesperson call/visit	2
Equipment manufacturer visit	2
Mail	2
Time wasters	1
Preventive maintenance	3
Meeting with mine people	2
Technical reading	3
Plant auditing project	3
Operator training	3

TABLE 6.4 **Tasks to be completed by the time required**

	Time Management Approach	
Task	Order Written	Time-Required Approach
Pump repair	1	5 (20 minutes)
Daily metallurgical balance	2	1 (10 minutes)
Weekly report	3	8 (1 hour)
Order reagents	4	2 (10 minutes)
Reagent salesperson call/visit	5	4 (20 minutes)
Equipment manufacturer visit	6	6 (30 minutes)
Mail	7	3 (10 minutes)
Time wasters	8	Anytime
Preventive maintenance	9	9 (1 hour)
Meeting with mine people	10	7 (45 minutes)
Technical reading	11	10 (2 hours)
Plant auditing project	12	11 (4 hours)
Operator training course preparation	13	12 (8 hours)

reflect on your accomplishments for the day. You were very busy and got six items on your list completed. In addition, you took care of three extra items delegated to you by your boss. Even so, you believe that you did not achieve much because you did not efficiently manage your time. If you feel that way, you are not alone. If you cannot manage yourself effectively, how can you manage other resources efficiently?

Steven R. Covey, in his highly acclaimed book, *The 7 Habits of Highly Effective People*, discusses in detail a four-quadrant approach to self-management (Covey 1994). The four quadrants represent activities that are (1) urgent and important, (2) not urgent and important, (3) urgent and not important, and (4) not urgent and not important.

This approach should be studied in detail in Covey's book, and activities listed in the time management charts given in TABLES 6.3 and 6.4 should be organized according to Covey's approach. This methodology will help with the effective management of time.

Once you can efficiently manage yourself, you will find the time to efficiently manage other limited resources, namely people, time, and money.

Engineers can find themselves in situations where they are working on or managing 10 projects simultaneously. They have limited people, time, and money. What can be done? Ask this question—Do I have the budget and people to complete all the projects in 3, 6, or 12 months? Generally, the answer will be no. One can prioritize the projects based on the time or money needed to complete them. Either way, four to five projects can probably be completed in the next 6 months, which may be a good success rate. It may certainly feel good. But the boss may not think so. Why? This is the wrong way to prioritize the projects. Therefore, the following questions should be asked:

- Is there a project that when not completed in 1 month could impact the plant? Environmental-related projects (e.g., dust control) can fall into this category. The Occupational Safety and Health Administration or Mine Safety and Health Administration can shut down an operation if violations occur. These kinds of projects should remain a top priority.

- Are there any projects that have a minimum impact on plant economics? Can they be delayed by 6 to 12 months without impacting the operation? Testing a different frother or flocculant may be important to the salesperson. However, it will have no economic impact on plant operations. During limited resources availability, dedicating time and people to such projects may not be desirable. Such projects should have a very low priority.

- What are the benefit/risk ratios of the other projects? The benefit/risk ratio of the remaining projects needs to be defined and quantified. Once this is done, it is easy to rank the projects and determine the resources required to complete them.

Realistic achievements or goals can be estimated following this approach. This is the first step to efficient management of limited resources and seems to work well for most operations.

CHAPTER 7

SOCIOPOLITICAL AND CULTURAL ISSUES

ENGINEERS ARE TRAINED TO EVALUATE TECHNICAL ASPECTS of geology, mining, and processing. Techno-economic aspects of the project may seem attractive, but these types of project may not advance because of non-technical factors; namely, sociopolitical and cultural considerations that are equally, if not more, important typically do not instigate success. Why? Because of the neglect of the sociopolitical and cultural considerations that are equally, if not more, important.

These issues are on the forefront of most of the mining companies doing business globally. Training engineers only how to speak the local language does not empower them for success in the new country where the mining company is developing the project. They need to understand sociopolitical and cultural ways of the newly adopted country.

This chapter attempts to highlight some of these issues with experiences from the author.

GLOBAL MINERAL INDUSTRY CHARACTERIZATION

Mother Nature has endowed selected regions of the world with mineral wealth. The mining companies in these regions have played a key role in the economic development of the area or country.

The structural setup of the mining industry can generally be classified in two categories: privately owned enterprises that dominate the western developed countries and primarily government owned, either directly or through a series of public-sector undertakings in developing countries.

Regardless of the location and structure of the mining industry, mining ventures have the following characteristics:

- The mineral industry is a capital-intensive operation. For a reasonable size sulfide mineral operation (i.e., >500 tpd [short tons per day]), the capital requirement ranges from a low of US$5,000/tpd to a high of $150,000/tpd.
- The development process cycle (from discovery of resource to commercial production) is reasonably long (3 to 10 or more years).
- Environmental and social regulations are slowing the project development process, thereby adding time and cost to commercialize projects. Environmental costs alone are estimated to account for 15% to 25% of the total project cost.
- Metal prices follow the general economy, which has a 4-to 5-year cycle in the western world. Hence the mining industry experiences "boom and bust" cycles.
- Commercialization of a large deposit requires tremendous resources—land, water, and power. The concept of "sustainable growth," which has gained popularity especially among developing nations, is making it extremely difficult for companies to acquire these necessary resources for commercialization of mineral resources. They have to compete with farm lands and urban/rural growth for these resources.
- Small mining operations cannot afford to mechanize. They are labor intensive. In developing countries, government officials view this as a positive for providing employment, especially in rural areas where most deposits are located.

INCREASING NEGOTIATING EFFECTIVENESS THROUGH CULTURAL CALIBRATION

How do we react when someone mentions cultural differences? *"I am sick and tired of this culture business. Human beings are the same everywhere. Why can't everybody be like me?"*

If you can relate to these statements, consider these real-life incidences:

- American children attending an international school in a Southeast Asian country were fined, during a visit to Thailand, for climbing over a statue of Buddha and posing for photographs.

- A businessman, keen to sell his products to an oil-rich Arab country, returned home extremely frustrated because he had spent more than a week in that country meeting local officials and businessmen without making a firm deal.
- Delicate political negotiations with a Latin American country were almost discontinued because US negotiators made an offer that was considered a severe blow to the pride of the country.
- A United Nations consultant assigned to an Asian country was recalled, at the request of that country, for poking fun at that country's prime minister.
- A hostess who had invited a foreign student from a Muslim country to dinner was embarrassed when that student refused to eat a meal containing pork.

These incidences could have been avoided if

- The American children had been taught that Buddha is to Buddhists what Christ is to Christians,
- The businessman had known that ways of conducting business differ from country to country,
- The political negotiations had been sensitive enough to know that poor countries have as much pride as rich countries,
- The consultant had been advised that people in many countries take themselves and their leaders very seriously, and
- The hostess had not been ignorant of the fact that Muslims do not eat pork.

Here are a few real-life examples the author has experienced in the past few years:

- An engineer overseeing the permitting of a heap leach operation had problems with the state regulators and the project got delayed. As soon as the engineer was replaced, the permit was granted.
- An engineer was responsible for the development work on a project in South America. Every time he traveled there, he told the local engineers how stupid they were. Ultimately, he was unwelcome there.

- An engineer who was extremely bright was discouraged because his retirement fund was worth less now than it had been 15 years earlier. The company had been acquired twice during the last 15 years, resulting in changes of senior management, company culture, and benefits packages.

Cultural differences are real and impact our daily work environment. Ignorance of this reality could cause serious problems for engineers in the mining industry when dealing with the international community.

DEFINITION OF *CULTURE*

Culture is very difficult to define. There is no universally accepted definition. The *American Heritage Dictionary* (2011) defines *culture* as "the totality of socially transmitted behavior patterns, arts, beliefs, institutions and all products of human work or thought characteristic of a community or population."

As children grow up in different physical and social environments, they learn to speak different languages, eat different foods, wear different clothes, like different kinds of art and music, practice different religions, observe different customs, and place different values on various aspects of life. Hence, the term *culture* is used to describe the whole way of life of a people—the way they think and behave, the way they learn, their values, beliefs, attitudes, and tastes.

The main reason the concept of culture is difficult to understand is that we are not always consciously aware of its influence. We speak, think, and act in certain ways because we are conditioned to do so.

Culture is not inherited genetically the way hair color is. It is socially inherited from one generation to another. It also changes continuously. Two powerful types of changes are the technological ones (e.g., automobiles and computers) and those acquired by contact with other cultural influences (Pepsi, Coca Cola, jeans, and McDonalds).

CULTURAL INFLUENCES

The greatest impact of culture is on values, beliefs, and attitudes of individuals growing up in that culture. *Values* are defined as attitudes, preferences, and styles of life, nomadic framework, symbolic universes, belief systems, and network of meaning that human beings give to life. Although there are individual differences within a cultural group, societies do place different values on such things as time, success, age, individual freedom, and so forth. Understanding these differences in a value system is the key to understanding other cultures.

- **Time:** The concept of "time is money" that we typically believe in is not universally accepted in many countries. People often arrive at 11 a.m. for a 10 a.m. appointment. In Africa, "immediately" means 2 days, "soon" means 2 weeks, and "in a while" means 2 months or more. In the western world, the clock *runs*, whereas in China the clock *walks*.
- **Success:** Success in the western world is measured in terms of money. In some countries, such as India, a scholar or religious teacher, even though he or she may be poor, is often more respected than a millionaire.
- **Age:** Western society is youth oriented and elderly people are looked upon by many young people as ignorant. In many countries (i.e., China and India), old age symbolizes wisdom and is therefore respected.

INFLUENCE OF CULTURE AT VARIOUS LEVELS

Culture can have influence and/or impact at various levels: personal, interpersonal, managerial, and organizational. Several excellent papers were presented in an international symposium on this topic (see Malhotra 2001).

CULTURE DISPLAYED IN MANY WAYS

The culture of a people is reflected in many ways: in their language; in the nonverbal ways they communicate; in their customs; in their art, architecture, music, and literature; in their social, political, economic, and legal systems; and so forth.

- **Language (written and oral):** Our language contains words and expressions that reflect our fondness for sports and technology:
  - All systems are go.
  - If I may shift gears now, I would like to turn to…
  - That's an entirely new ball game.
  - I suggest that you touch base with Jim.

However, it can be confusing to people in other countries when we subconsciously use such language.

- **Nonverbal communication:** It is important to understand nonverbal signals used in many cultures in which pleasure or displeasure is conveyed by gestures, facial expressions, tone of voice, coldness of behavior, length of time a visitor is kept waiting beyond the appointed time, silence, and so on. For example, nodding “yes” in the United States means “no” in Bulgaria.
- **Customs:** A custom that may seem strange to someone who lives in the United States may be the norm in another country. For example, a Christian missionary in China who sees a Chinese child place rice outside the tomb of his father might playfully ask, “Chen, when do you expect your father to come out of his grave to eat the rice?” Chen would probably respond, “at the same time your father will come out to smell the flowers you placed on his tomb.”

It is wise not to discuss religion or politics, or poke fun at foreign leaders, when living in other cultures.

PART 2

CASE STUDIES

Several case studies are presented in this section with the primary objective of demonstrating that the methodology presented in PART 1 can be very effectively used to improve operations and/or solve problems. These case studies are a cross section of audits performed by the author. In some cases, the minerals in the plant are shown as metal 1, 2, 3, and so on, to avoid identifying the facility or client.

These examples should be reviewed objectively. There is usually more than one way to solve a problem. You may come up with a better approach. Feedback is always welcome. As one of the author's mentors said, "No one has a monopoly on brains and bright ideas."

CASE STUDY 1

GLOBAL AUDIT

> A gold/silver processing plant was audited with the primary objective of identifying opportunities for potential improvement.

The protocol employed for a global audit consists of the following steps:

1. Visit the plant site.
2. Have discussions with several levels of management (i.e., senior management, geologists, mining engineers, environmental engineers, plant technical personnel, maintenance personnel, and operators).
3. Review available metallurgical and maintenance data.

Discussions should be restricted to technical aspects only. Avoid blaming personnel for any deficiencies in the process. Make personnel feel comfortable and compliment them often during discussions.

A simplified plant process flowsheet is shown in FIGURE 1.1. The process consisted of three-stage crushing, ball mill grinding, a carbon-in-leach circuit, and a gold recovery circuit.

A detailed report was prepared during the audit process that included results of the study. The highlights of the audit were as follows:

- The plant was metallurgically working efficiently despite some older plant equipment being used. Credit for good, efficient operation goes to operating and maintenance management and the operators.

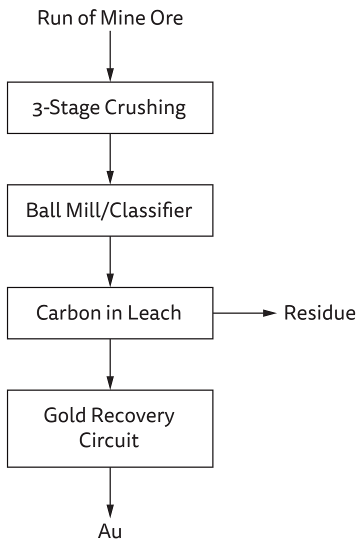

FIGURE 1.1 **Simplified block diagram process flowsheet**

- The operation could be classified as world class with precious metals extractions higher than average of similar operations worldwide.
- The potential areas of improvement identified were generally related to the operating cost reduction, making the operator's job easier, and safety and health issues. The economic impact of these recommendations and associated costs are summarized in TABLE 1.1.
- Based on the global audit results, a specific audit related to the grinding circuit was recommended. This was considered the highest benefit/risk ratio item.

TABLE 1.1 **Global audit summary of potential improvement opportunities**

Plant Flowsheet	Improvement Opportunities	Economic Impact	Cost (local currency)
Crushing	Dust collection Tertiary crusher	Health Less maintenance Finer feed to grind Increased metal value	Capital cost, $250,000 Capital cost, $250,000
Grinding	Increase efficiency ▪ Throughput ▪ Ball change configuration ▪ Process control ▪ Optimum particle size ▪ Reagent addition	Reduced operating cost Smoother operation Less maintenance Higher throughput	Instrumentation—Yes Retrofit—Yes ($100,000) Others—None/little
Classification	Optimization 2-Stage	Increased tonnage	Retrofit—Yes ($25,000)
Leaching	Process optimization ▪ Lime ▪ Cyanide ▪ Time ▪ Particle size Instrumentation ▪ pH ▪ Dissolved oxygen ▪ Free cyanide	Reagent reduction Increased tonnage Reduced operating cost Smoother operation	None. Short-term capital cost limited to $20,000. Long-term online instrumentation needs to be determined.
CCD*/Merrill Crowe	Instrumentation Process optimization	Reduced reagent consumption Increased washing efficiency/higher silver extraction High pulp density in final tail Thickener underflow	Instrumentation. Same as for leaching. Also atomic adsorption unit. None for process optimization.

*CCD = counter current decantation.

CASE STUDY 2

POORLY DEFINED PROGRAM OBJECTIVE

The chief metallurgist initiated a test program to reduce flocculant consumption by 50%.

The proposed program cost was estimated to be $15,000.

DEFINE THE OBJECTIVE

Discussions with mill management indicated that the objective of the study was to reduce reagent cost and hence operating cost.

IDENTIFY THE PROBLEM

No specific problems were related to the use of flocculants in the circuit.

REVIEW THE HISTORICAL DATA

It may be possible to reduce flocculant consumption by 50%. Yearly costs for all reagents used in the plant were reviewed and are presented as follows:

Reagent Type	Cost, $	% of Total
Collector	1,250,000	55.3
Frother	350,000	15.5
Surfactant	450,000	19.9
Depressant	200,000	8.9
Flocculant	10,000	0.4

PERFORM DATA ANALYSES

Data analyses showed that

- 90% of reagent cost was for collector, frother, and surfactant; and
- A 5% reduction of any of these reagents would have a greater impact on cost savings than elimination of flocculant consumption in the plant.

PROVIDE A RECOMMENDATION

Change the emphasis of the program to optimize usage of collectors, frothers, and surfactants, and evaluate cheaper reagents within the same class.

CASE STUDY 3

WRONG SOLUTION FOR THE RIGHT PROBLEM

An iron ore plant in Asia was designed for 10,000 t/d but operated at 7,000 t/d. An engineering company that designed the plant concluded "that the material was too hard to grind in existing mills. Let's buy more SAG mills."

Is buying mills a reasonable conclusion? Maybe not.

At this plant, asking probing questions to operations personnel resulted in an indication that the availability factor for the mills was only 60%. This was due to interruptions of power supply to the plant.

When power was available, the utilization factor was 95%. Hence, increasing the utilization factor would result in plant throughput to more than 10,000 t/d.

The plant needed a power plant and not more mills at the mine site.

CASE STUDY 4

THE MYTH THAT NEW TECHNOLOGY IMPROVES RECOVERY

A conventional cyanidation plant in Asia recovers 95% of the gold in the ore. The plant capacity was being increased from 800 tpd to 1,200 tpd. Global tender was issued for a carbon-in-leach plant. Why?

Carbon-in-leach (CIL) was new technology at the time. The management had perceived that it would increase gold recovery.

A 95% recovery makes this operation one of the best in the world. No CIL testing had been done on the ore.

CIL will not raise recovery, but it will require operator training and create additional problems for management regarding technology transfer.

CASE STUDY 5

PRODUCTIVITY MEASURES

The management of a government-operated copper concentrator in Asia wanted to know how they compared with western world operations.

A copper concentrator processing 6,000 tpd of ore employed 3,000 people for an underground mine operation. The management wanted to know how productive they were as compared to operations in the western world.

One measure of productivity is the number of tons processed per employee, corrected for salary differences. A similar mine producing 35,000 tpd in the United States employs 500 to 1,000 employees:

- Productivity for Asian mine = 2 tpd/person
- Productivity for U.S. mine = 35–70 tpd/person

Assuming that the salary paid in Asia is 10% of that paid for a similar job in the United States, the productivity for an Asian worker would be 20 tpd/person. Hence, the productivity is 50% lower than the same worker in the United States.

CASE STUDY 6

IMPROVING PRODUCTIVITY

> Management knows that it has an excessive number of personnel working in its Asian operation, but they cannot be fired. What can be done?

One or more of the following steps can be taken to compete in the international market:

- When the operation expands from 6,000 tpd to 8,000 tpd, 10,000 tpd, or 12,000 tpd, *do not hire more people*. Retrain the personnel and increase productivity using existing people.
- Offer attractive early retirement packages as is done in the western world.
- Do not replace workers who are retiring or leaving on their own.

Interestingly, these approaches are currently being used in developing countries.

For a more detailed analysis, the productivity index can be broken down further into different categories: mining, milling, smelting, corporate staff, and so forth.

CASE STUDY 7

DIAGNOSTIC TESTING AS A TOOL FOR OPTIMIZATION

An operating property in South America was processing gold- and silver-bearing ore. The gold recovery in the plant was 90% to 92%. They wanted to improve gold recovery.

The plant process flowsheet, shown in FIGURE 7.1, consisted of a primary grind of P_{100} of 200 mesh, a gravity circuit to recover sulfides, and cyanide leaching of the gravity tails. Gravity concentrate was reground and cyanide leached in a separate circuit. Leach residue from the circuit was sent to the gravity tailing leach circuit.

The plant feed sample assayed 10.4 g/t Au and 11 g/t Ag. It contained ore from three mines. The plant gold recovery was 90% to 92%.

Diagnostic leach tests were undertaken to determine deportation of gold in various minerals. The test results indicated the following:

- Direct cyanidation of ore extracted 93.2% of gold after 48 hours of leaching time. The residue assayed 0.7 g/t Au. These results were slightly better than obtained in the plant.
- The leach residue from a direct cyanidation test was roasted under reducing atmosphere at low temperature to break down arsenopyrite. The cyanidation leach following the roast extracted an additional 4.35% of gold, thereby indicating the proportion of gold associated with arsenopyrite.
- A portion of leach residue from the direct cyanidation test was subjected to nitric acid leach to break down sulfides followed by cyanidation. The leach residue from the test assayed <0.02 g/t Au. The gold extraction was 6.8%. Hence, gold associated with pyrite was 2.45%.

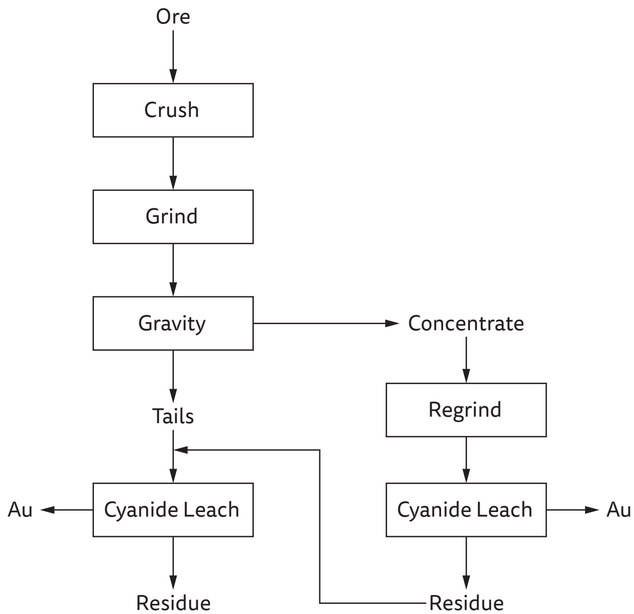

FIGURE 7.1 **Simplified plant process flowsheet**

Approximately 50% of the plant feed was coming from a mine having higher feed grade (i.e., 17 g/t Au) and lower gold extraction. Diagnostic leach testing indicated 88.4% of the gold was free milling, 4.1% was associated with arsenopyrite, 1% was associated with pyrite, and 6.5% was finely associated with quartz. Grinding the ore to P_{80} of 400 mesh, the gold extraction was improved by ±3%.

Recommendations were made to eliminate the gravity circuit and use the extra mill to grind the ore finer in the primary grinding circuit. This would result in 3% additional gold recovery while reducing the operating cost for gravity circuit operation and simplifying the process flowsheet.

CASE STUDY 8

COARSE VERSUS FINE PRIMARY GRIND

> The old concept of single-stage grinding to fine sizes to liberate minerals is prevalent in some Asian and South American countries. This eliminates the need for regrind mills. How good is this concept?

Grinding is the largest consumer of energy and the largest component of operating cost in a beneficiation plant.

It takes 15–20 kW·h/t to grind copper ore to a P_{80} of 400 mesh. For a 6,000-tpd operation, energy for grinding is 90,000 kW (i.e., 6,000 × 15 = 90,000). At $0.10/kW, the energy cost equates to $9,000/d. On the other hand, coarse grinding the ore to achieve more than 90% of recovery requires 6–8 kW·h/t and recovers 10% of the material. The energy cost is $4,800/day (i.e., 6,000 × 8 × 0.1 = $4,800). Now the regrinding mill energy cost will be $480 (i.e., 8 × 600 × 0.1 = $480) assuming 8–10 kW·h/t for fine grinding. The total energy cost will be $5,280/d.

The total energy savings per day will be $3,720. In addition, coarse grind will also eliminate environmental problems related to settling of fines, tailing pond size, and so forth. However, additional capital may be needed for installing a regrind mill.

CASE STUDY 9

THINKING OUTSIDE THE BOX: FINE CRUSHING VERSUS GRINDING*

Is there any incentive for feeding the conventional grinding circuit with finer crushed product?

The crushing circuit generally reduces the top size of the ore from 254 mm to 12.7 mm. The ratio of reduction is small (20 to 25), and the power consumption is between 2 and 4 kW·h/t.

The crushing circuit product is fed to the grinding circuit where the ratio of reduction is generally 100 to 200 and the power consumption ranges from 6 to 20 kW·h/t. Given that the crushing system consumes significantly less energy than the grinding system, is it logical to produce a finer product (i.e., 6.4 mm) in the crushing system?

Let's look at the energy savings if the feed top size to the grinding circuit was reduced from 12.7 mm to 6.4 mm. The data for two cases with different work indexes and product sizes are given in TABLE 9.1. Our plant experience indicated that the crushing energy would increase from 3 to 3.1 kW·h/t to produce a finer product. Based on Bond's work index calculations, the energy savings for a comminution system would be 0.3 to 0.4 kW·h/t. For a plant treating 45.4 kt/d for 350 days per year and paying $0.05/kW·h, the net energy savings amounts to $262,000 to $350,000 per year.

Hence, there is definitely an economic incentive to produce a finer product in the crushing system. Is it possible to do so?

* This case study is from Malhotra 1986.

TABLE 9.1 **Effect of change in feed size to grinding circuit on total comminution energy**

	Case 1	Case 2
Work index	12	15
Coarse crush size: 12.7 mm top size		
F_{80}, µm	8,000	8,000
P_{80}, µm	212	75
Ratio of reduction	37.7	106.5
Crushing energy, kW·h/t	3.00	3.00
Grinding energy, kW·h/t	6.90	15.64
Total energy, kW·h/t	9.90	18.64
Fine crush size: 6.4 mm top size		
New F_{80}, µm	4,748	4,748
New P_{80}, µm	212	75
Ratio of reduction	22.4	63.3
New crushing energy, kW·h/t	3.10	3.10
New grinding energy, kW·h/t	6.50	15.14
Total energy, kW·h/t	9.60	18.24
Savings in energy, kW·h/t	**0.30**	**0.40**

Let's assume that the vibrating screen in the tertiary crushing circuit handles 91 t/h with a screen cloth opening of 9.5 mm. The process data/design parameters are given in TABLE 9.2. The feed to the short-head crusher will be 33.5 t/h. Calculations using the equation for calculating capacity of vibrating screens indicate that changing the screen cloth opening from 9.5 to 6.4 mm will result in increasing the feed to the short-head crusher to 46 t/h. Can the crusher handle the increased throughput under the present operating conditions? Can we change the operating parameters to handle the increased throughput? Wouldn't it be possible to achieve a finer product if the plant was operating at 80% capacity?

A good sampling program can provide a material balance of the crushing circuit, the performance of the unit operations in the circuit, and hopefully indicate process conditions to handle increased tonnage to the crushers.

Based on the assumptions made and the corresponding calculations, it is reasonable to conclude that the desired throughput can be achieved. Hence, the screen should be changed and tested in the plant.

TABLE 9.2 **Impact of change in vibrating screen cloth opening on feed to short-head crusher**

	Screen Cloth Opening Size, mm	
Process Parameters	**9.5**	**0.25**
Total feed to screen, t/h	100	100
Oversize in feed, %	30	40
Half-size product, %	30	20
Designed efficiency, %	90	—
Required screen area, m^2	4.65	—
Total designed screen area, m^2	5.58	—
Actual efficiency, %	>90	82
Crusher feed, t/h	37	50.8

CASE STUDY 10

THINKING OUTSIDE THE BOX: CLASSIFIER EFFICIENCY*

> Why does not the overall classifier efficiency provide a true picture of the classification circuit?

The material and metallurgical balances around the classifier can provide information related to the classifier efficiency and the circulating loads of material and valuable minerals. The following equations provide the definition of overall classifier efficiency (E_C), classifier overflow efficiency (E_{COF}), and classifier underflow efficiency (E_{CUF}).

$$E_C = \frac{\text{t/h minus size} \times \text{material in overflow} + \text{t/h plus size} \times \text{material in underflow}}{\text{total t/h in feed}} \quad \text{(EQ 10.1)}$$

$$E_{COF} = \frac{\text{t/h minus size} \times \text{material in overflow}}{\text{t/h minus size} \times \text{material in feed}} \quad \text{(EQ 10.2)}$$

$$E_{CUF} = \frac{\text{t/h plus size} \times \text{material in underflow}}{\text{t/h plus size} \times \text{material in feed}} \quad \text{(EQ 10.3)}$$

The overall classifier efficiency has been used in evaluating the performance of the classifiers. The information can provide misleading or erroneous conclusions. TABLE 10.1 gives the E_C, E_{COF}, E_{CUF} for two cases. The overall classifier efficiencies are identical in both cases. However, the underflow and overflow efficiencies are different.

* This case study is from Malhotra 1986.

TABLE 10.1 **Classifier efficiencies for two cases**

Case	E_C, %	E_{COF}, %	E_{CUF}, %
1	80	25	99
2	80	50	96

The classifier underflow efficiency gives an indication of the amount of coarse material that reports to the underflow and overflow and could affect the separation process. For example, too much coarse material in the overflow may result in sanding the flotation machines. The coarse material could be middlings and result in recovery loss in the circuit.

The classifier overflow efficiency is an indicator of the amount of finished product that reports to the overflow. In this example, only 25% of the finished product reports to the overflow, while 75% of the finished product reports to the classifier underflow and is recirculated for case 1. In case 2, 50% of the finished product reports to the overflow, thereby reducing the circulating load in the circuit. It is desirable to maximize overflow and underflow efficiencies in the classification operation. However, sacrificing a little on underflow efficiency (i.e., 96% vs. 99%) could help in reducing circulating load by increasing overflow efficiency (i.e., 50% vs. 25%).

CASE STUDY 11

METHOD FOR MEASURING PERFORMANCE OF BALL MILLS

Very often the ball mills in the same operation provide different product size. Can one measure the efficiency of the mills?

The Bond's ball mill work index and the operating work index can be used to evaluate the grinding mill performance as discussed by Rowland (1976). This approach can be used to

- Compare current performance with past performance;
- Compare circuits in a multi-circuit plant; and
- Evaluate the effect of process variables like mill speed, feed size, size of grinding media, and so forth, on grinding efficiency.

The performance of two parallel single-stage ball mills is compared in TABLE 11.1. The results indicate that mill 2 is slightly more efficient than mill 1, even though it has higher power consumption per ton.

TABLE 11.1 **Performance comparison of two parallel single-stage ball mills**

	Mill 1	**Mill 2**
Power consumption, kW·h/t	10.6	11.3
F_{80}, µm	7,500	8,600
P_{80}, µm	220	195
Calculated work index, W_{iO}	19.33	18.58
W_i at 65 mesh	14.5	14.5
W_{iOe} (calculated operating work index)	15.09	14.63
Efficiency factor (W_{iOe}/W_i)	1.04	1.01
Efficiency, %	96	99

Source: Rowland 1976.

CASE STUDY 12

COMPARISON OF ROUGHER FLOTATION CIRCUIT CONFIGURATIONS*

There are various flowsheet configurations for rougher flotation circuit. Which configuration is the optimum for an operation?

The objective of the rougher circuit is to maximize valuable minerals recoveries subject to a minimum concentrate grade that is dictated by the capacity of the cleaner circuit. Generally, the flowsheet configuration in the rougher circuit is one of the following: concurrent, counter current, or open circuit (FIGURE 12.1).

The concurrent configuration has better control over the concentrate grade than the open-circuit configuration. However, to maximize recovery, and hence minimize the valuable minerals in the rougher tailings, any fluctuations in the circuit are counteracted by pulling the scavenger circuit harder by the operators. Because the residence time in the roughers is inversely proportional to the mass flow rate, the net effect is the reduction of the effective residence time in the roughers. This may result in further reduction of the recovery in the circuit. The counter-current configuration reduces the effect of circuit upsets on the rougher concentrate recovery as compared to the concurrent configuration.

Flotation kinetic data for sulfide minerals generally indicates that valuable minerals are either fast floating, which are liberated particles, or slow floaters, which are locked particles or extremely fine particles (<10 Φm). These

* This case study is from Malhotra 1986.

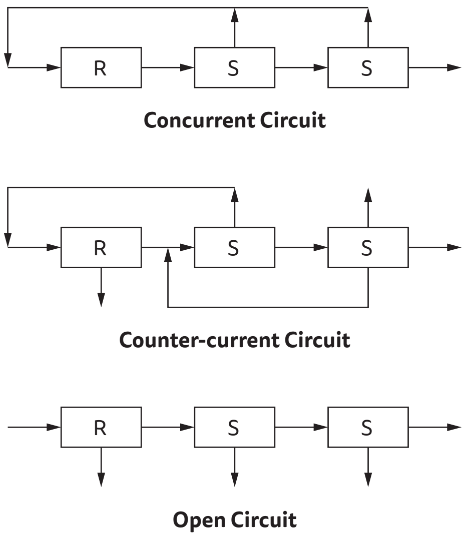

FIGURE 12.1 **Common rougher-flotation circuit configurations (R: roughers, S: scavengers)**

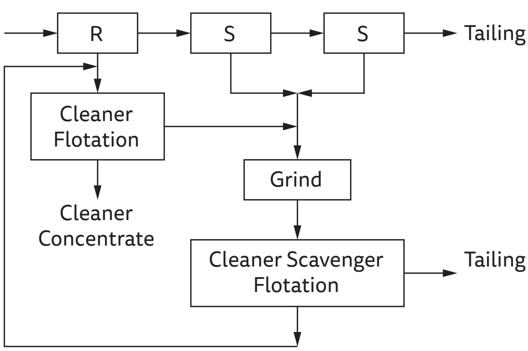

FIGURE 12.2 **Modified rougher/cleaner flotation circuit configuration**

locked particles will generally remain slow floaters unless they are liberated by grinding. Why recirculate the scavenger concentrate back to the roughers? Not much is gained in recovery by doing so. Locked-cycle tests with or without recycling scavengers do indicate the difference in recovery. It will generally be higher for open-circuit flotation. The flowsheet shown in FIGURE 12.2 is becoming more prevalent for sulfide minerals.

CASE STUDY 13

MAINTAINING PLANT THROUGHPUT*

A cyanidation plant in Latin America processed 10,000 t/d of oxide gold-bearing ore.

Plant throughput dropped to 5,000 t/d.

What needs to be done to increase throughput to 10,000 t/d?

DEFINE THE PROGRAM OBJECTIVE

Management wanted to increase plant throughput to its original level of 10,000 t/d. The simplified process flowsheet is shown in FIGURE 13.1.

IDENTIFY THE PROBLEM

The ore characteristics had changed, resulting in a bottleneck in the grinding circuit.

REVIEW THE HISTORICAL DATA

The plant was designed to process 7,500 t/d of ore having a work index of 9. Mineralogy had changed and the new ore had a work index of 17 to 20.

* This case study is from Malhotra et al. 1989.

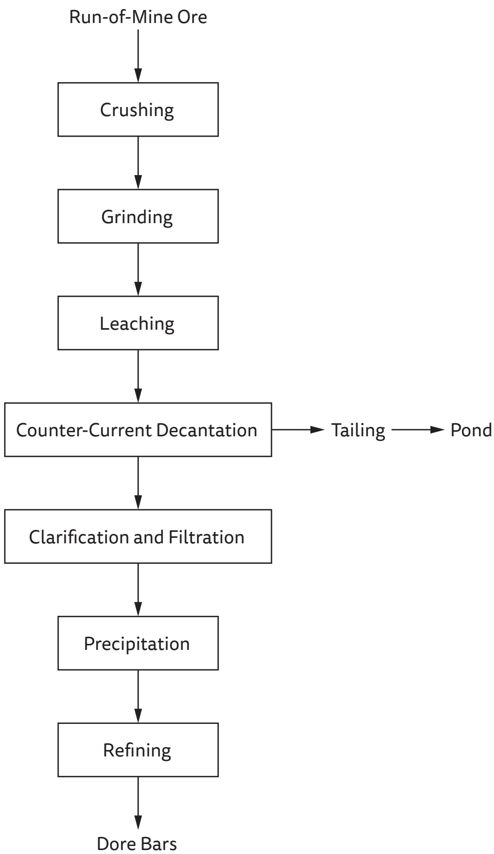

FIGURE 13.1 **Simplified block diagram flowsheet for precious metals recovery**

LAUNDER DESIGN

It became apparent during the initial discussions with management that any changes in the grinding circuit (i.e., coarsening the grind) would have to take into consideration downstream process constraints. Two major indicated constraints were

1. Leach circuit feed had to be maintained at 60% solids to provide sufficient leach time; and
2. Thickener launders sanded up if more than 25% to 30% of feed material was coarser than 65 mesh. This resulted in upsets in the counter-current decantation (CCD) circuit.

The launder design was modified from a rectangular shape to a V shape to avoid settling of coarse material prior to any sampling of the circuit. This eliminated one of the perceived constraints.

DESIGN SAMPLING CAMPAIGNS

Several sampling campaigns were designed and undertaken to generate a material balance for the plant and to determine the performance of the unit operations in the circuit. Later on, additional sampling campaigns were restricted to only the grinding circuit.

SAMPLE THE CIRCUITS

Typical sampling problems were encountered:

- Inaccessible streams
- No instrumentation to measure pulp density, flow rates, and so forth
- Slurry overflowing from several unit operations

Ore characteristics were changing so fast that several sampling campaigns were abandoned. **WARNING: Do not sample the circuit if it is unstable and changing frequently.**

PERFORM DATA ANALYSES

Data analyses showed the following:

- Plant sampling indicated that the CCD circuit was operating at 45% solids in underflow. Theoretical calculations showed that precious metals recovery could be increased by increasing thickener underflow solids to 50% or higher (TABLE 13.1). CCD circuit performance was improved by changing the method and points of flocculant addition. Flocculant consumption was reduced by 40% and underflow solids increased from 45% to 52%.
- Excess lime was being added to the milling circuit to overcome problems in the clarifier and sand filters. The clarifier was operating as a holding tank. A small amount of lime and flocculant was added to the clarifier and a small portion of the sludge was recycled to build a sludge bed instead of returning to the CCD circuit. This modification resulted in producing pregnant solution with lower

TABLE 13.1 **Effect of process variable on recovery of dissolved values in the CCD circuit**

Thickener Underflow Solids, %	Wash-Water Ratio	No. of Stages in CCD Circuit	Recovery of Dissolved Values, %
45	3	4	93.7
50	3	4	98.8
60	3	4	99.8
45	2	4	68.0
45	3	4	93.7
45	4	4	98.0
45	3	3	87.5
45	3	4	93.7
45	3	5	97.0

turbidity, which also resulted in reducing overall lime consumption by 25%.

- Plant sampling indicated that approximately 80% of the precious metals were extracted in the semiautogenous grinding (SAG) mill. The last half of the bank of leach tanks was not extracting any precious metals. Hence, the leach feed pulp density could be reduced without affecting precious metal recoveries.
- Very little grinding was being accomplished in the secondary grinding mill, and the circulating load was high in the tertiary mill (i.e., Marcy mill).
- The ore had two critical sizes: 1 to 2 inches and 10 to 28 mesh. The cone crusher was doing a good job crushing the plus 1-inch material. Ball mills were not grinding the 10 × 28 mesh material.
- Approximately 40% of the SAG mill discharge was finished product.
- Laboratory testing indicated that the critical size could be ground more efficiently in a rod mill than a ball mill.

CONCLUSION

Feed to the ball mills had to be reduced or convert them to rod mills to improve efficiency of grinding.

TABLE 13.2 **Grinding circuit flowsheet alternatives**

No.	Alternative	Comments
1	Do nothing.	▪ Accept lower tonnage ▪ No additional capital
2	Convert Dominion ball mill into rod mill.	▪ Better grinding of 28 mesh material ▪ Slight improvement in the throughput ▪ Small capital cost requirement ▪ Mill out of commission during conversion ▪ Operator training required ▪ Availability of rods
3	Install existing cyclones ahead of Dominion mill and convert mill to rod mill.	▪ Cyclone change requires no capital ▪ Slightly improved grinding in Marcy mills ▪ Small capital cost requirement for converting Dominion mill to rod mill ▪ Downtime required for modification ▪ Operator training required ▪ Availability of rods
4	Install new cyclones ahead of Dominion mill.	▪ Removes finished product as soon as produced ▪ Better grinding in mills ▪ Small amount of capital required
5	Install finer screens and treat cone crusher product in Dominion mill.	▪ Small capital required for circuit modification ▪ Complex flowsheet ▪ Downtime required for modification
6	Install larger ball mills in place of Marcy mills.	▪ Large capital cost required ▪ Downtime required for modification

EVALUATE ALTERNATIVE SOLUTIONS

Several grinding circuit flowsheets were developed and analyzed, keeping in mind the new constraints imposed by management, namely, no capital available for new equipment and the plant could not be shut down for modifications (TABLE 13.2).

PROVIDE RECOMMENDATIONS

The alternative to install new cyclones ahead of the Dominion mill to reduce tonnage to the ball mills was recommended (FIGURE 13.2). This recommendation achieved the objective of increased throughput at minimum capital cost and disruption to the existing circuit.

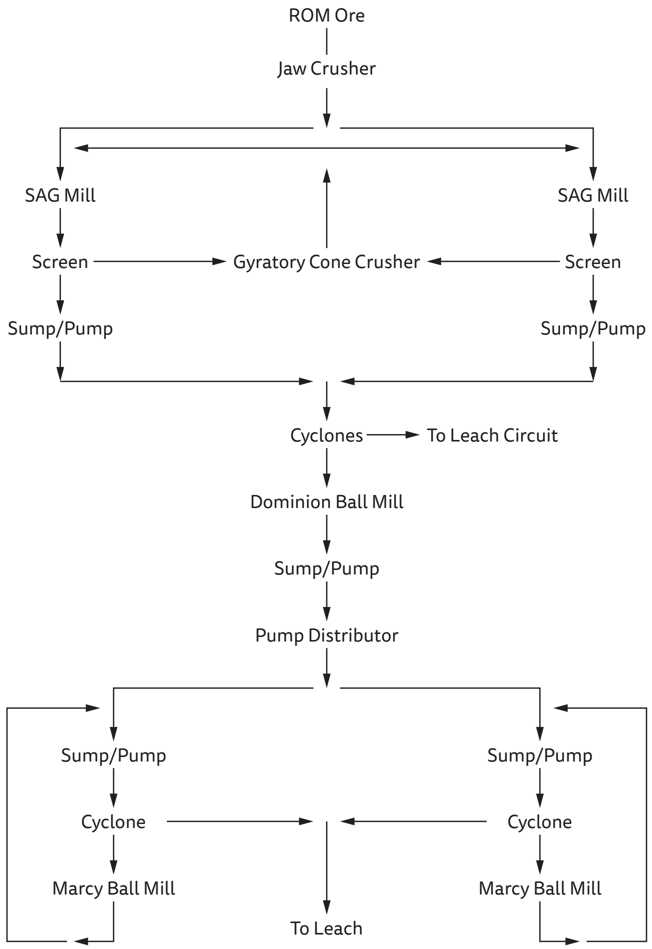

FIGURE 13.2 **Grinding circuit flowsheet for precious metals recovery**

BENEFITS

The following benefits resulted from modification to the plant as recommended to management:

- The modified circuit resulted in smooth operation at 10,000 t/d with a slightly finer grind.
- Significant reagent cost savings (± $1.0MM) were achieved by optimization of the circuit.

CASE STUDY 14

AUDITING A COMPLEX FLOTATION CIRCUIT

A sulfide plant was processing lower throughput than its rated capacity. The optimum process parameters established for the cleaner circuit were not necessarily optimum for the current throughput.

The overall objective of the study was to develop operating guidelines for process parameters to optimize the circuit.

The simplified process flowsheet for the cleaner circuit is given in FIGURE 14.1. The review of the circuit indicated that it was too complex to be sampled with limited resources in one day.

The circuit was divided into three parts—namely, first cleaner, second cleaner, and third-to-fifth cleaners (FIGURES 14.2 to 14.4)—for ease of sampling as well as optimization. Optimization of process parameters was done from the front end of the circuit to the back.

Only the first-cleaner circuit is discussed here, but the methodology used for the three sampling campaigns was the same as for the first-cleaner circuit.

DESIGN A SAMPLING CAMPAIGN

The sampling campaign needs to be carefully planned, making sure the process streams that need to be sampled for assay and flow measurements are identified. The plant must be visited to see if the identified streams are accessible. It should be no surprise to find out that some of the streams cannot be sampled. It must be determined whether the streams can be separately sampled rather than combined with recycle streams.

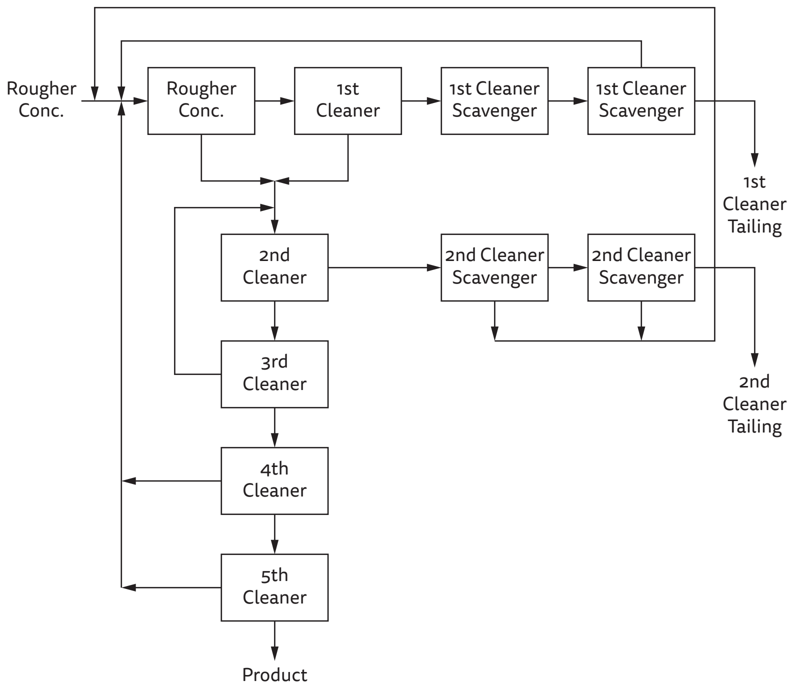

FIGURE 14.1 **Simplified process flowsheet for sulfide metal**

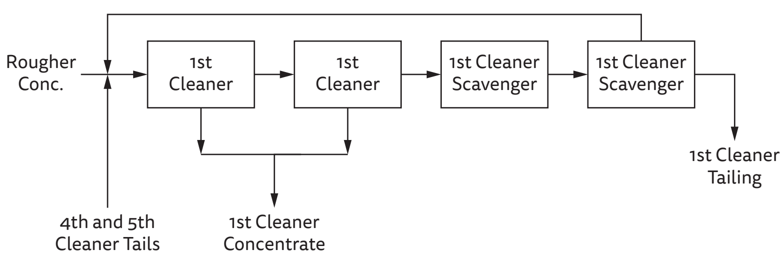

FIGURE 14.2 **First-cleaner circuit**

SAMPLE THE CIRCUIT

One may have to be innovative to obtain the desired samples. Redundancy in sampling is worth it. Collecting extra samples will not cause any harm. For example, at this plant, each cleaner bank was collected separately for a known period of time and then combined. There were two parallel banks of first-cleaner flotation cells in the plant.

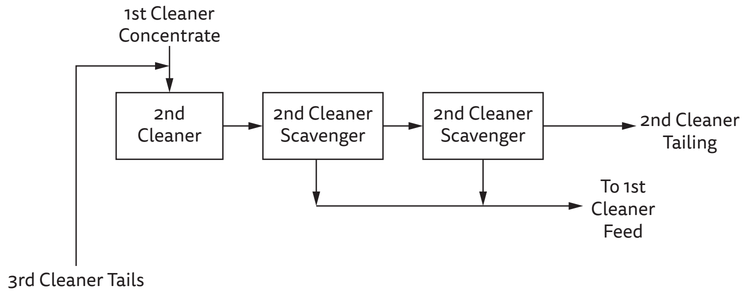

FIGURE 14.3 **Second-cleaner circuit**

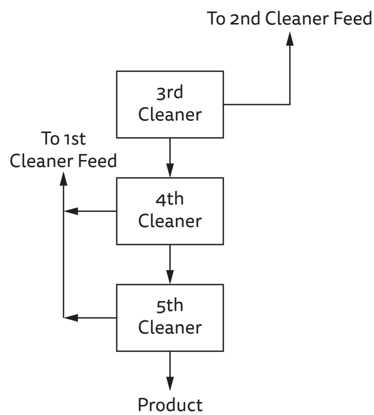

FIGURE 14.4 **Third-to-fifth-cleaner circuit**

During sampling, separate flotation feed samples need to be collected for laboratory tests. It is less expensive to evaluate the effect of process variables in laboratory flotation testing than testing the process variables in the plant.

LABORATORY TESTING

To develop the flotation residence time scale-up ratio between the laboratory flotation batch test and the plant operation, sufficient feed samples must be collected to run tests in the laboratory. These tests should be performed within a short time of collecting the samples to avoid the effect of aging of sample on metal metallurgy.

TABLE 14.1 **Calculations for residence time in the plant**

First-Stage Cleaner (Bank No. 1)	
No. of flotation cells:	24
Flotation cell volume, ft³:	36
Aeration correction factor:	0.85
Effective volume, ft³:	734 (24 × 36 × 0.85)
Flow rate, gpm:	453.9
Residence time, min:	12.1
First-Stage Cleaner (Bank No. 2)	
No. of flotation cells:	24
Flotation cell volume, ft³:	36
Aeration correction factor:	0.85
Effective volume, ft³:	734
Flow rate, gpm:	543.6
Residence time, min:	10.1
Total Residence Time for First-Stage Cleaner: 22.2 min	

Data must also be collected on the sizes of the flotation cells, the number of cells in the bank, and the flow rate to estimate residence time in the plant. The calculations for the first-cleaner flotation are given in TABLE 14.1.

A bench-scale flotation test was performed on an "as collected" sample with the first-cleaner flotation feed. Timed concentrate samples were collected and assayed for metal content. The test data are given in TABLE 14.2. The flotation test data were compared to the plant data. The results indicated that 6 minutes of flotation time in bench-scale testing produced similar metallurgical results as obtained in the plant (TABLE 14.3). Hence, the laboratory-to-plant residence time scale-up ratio for first-cleaner flotation was estimated to be approximately 4.

The flotation test was extended to produce a flotation tailing similar to that obtained in the first-cleaner-scavenger tailing (i.e., 0.226% metal). Laboratory flotation time of 15 minutes was required as compared to 44.3 minutes in the plant. Hence, the plant-to-laboratory residence time scale-up ratio for the first-stage cleaner circuit was estimated to be approximately 3.

The flotation residence time scale-up ratios can be used in subsequent bench-scale test work for predicting the effect of changing process variables in the plant from bench-scale laboratory tests.

TABLE 14.2 Metal recovery—and concentrate grade—flotation time data for bench-scale flotation test with first-cleaner flotation feed

Cumulative Flotation Time, min	Concentrate: Cumulative Recovery, % Wt.	Concentrate: Cumulative Recovery, % Metal	Concentrate: Grade, % Metal	Tailing Grade, % Metal
0.5	4.2	18.5	52.1	10.16
1.0	14.0	48.2	41.0	7.19
1.5	22.6	73.3	38.7	4.11
2.0	25.3	81.1	38.2	3.01
3.0	28.2	88.3	37.4	1.94
4.0	30.2	91.3	36.1	1.48
5.0	31.8	93.2	34.9	1.18
6.0	33.8	95.1	33.6	0.87
8.0	36.4	97.1	31.8	0.55
10.0	38.7	98.1	30.3	0.37
12.0	40.4	98.5	29.1	0.29
14.0	41.9	98.8	28.2	0.24
18.0	44.1	99.1	26.8	0.19
22.0	46.3	99.3	25.6	0.15

TABLE 14.3 Metallurgical results for plant and bench-scale flotation test with first-cleaner flotation feed

Item	Plant*	Laboratory†
Feed, % metal	10.13	11.94
Concentrate weight, %	38.3	33.8
Recovery, %	94.9	95.2
Grade, % metal	28.4	35.6
Tailing, % metal	0.94	0.87

*Residence time = 22.2 min.
†Flotation time = 6 min.

Bench-scale flotation tests were performed with the first-cleaner flotation feed to study the effect of residence time and flotation pulp density on metal metallurgy in the circuit.

- **Residence time:** The test data for residence time evaluation is given in TABLE 14.2. The results indicated that 15 minutes of flotation in the laboratory produced a tailing assay similar to the circuit tailing (i.e., 0.226% metal) in the plant. The metal recovery

TABLE 14.4 **Effect of flotation pulp density on residence time in the first-cleaner circuit**

Flotation Pulp Density, % Solids	Residence Time, min	
	Plant	Laboratory
15	20	7
20	27.7	9
25	36	12
30	45	15
38	61	20

was approximately 99%. Increasing residence time by 7 minutes (approximately 50%) improved the metal recovery by 0.3% with a corresponding decrease in grade by ±3%. Therefore, it is reasonable to conclude that the flotation time in the circuit appears to be sufficient to maximize metal recovery.

- **Flotation pulp density:** It is important to note that for an operating plant, the total effective cell volume is fixed and hence the residence time is strongly dependent on the flotation pulp density. Based on the volume available in the plant, residence time for various pulp densities were calculated for the first-cleaner flotation circuit. Equivalent flotation times for laboratory tests were also calculated and are given in TABLE 14.4.

Five bench-scale flotation tests were performed to evaluate the effect of flotation pulp density on metal recovery (i.e., 15% to 38%). The test data for first-stage cleaner flotation and first-stage cleaner circuit are given in TABLES 14.5 and 14.6. The results indicate that the metal recovery for the first-cleaner flotation and the first-cleaner circuit increases with increasing pulp density due to an increase in residence time. (NOTE: The data was analyzed for varying laboratory flotation time due to different pulp densities and fixed flotation capacity.) However, for designing new plants, the correction factor for time does not have to be applied to the data. The metal grade decreased with increasing pulp density to 30% solids and then remained constant with increasing pulp density. Hence, the first-cleaner flotation circuit can be operated at high pulp density (30% to 38% solids) if the objective is to maximize metal recovery and at low pulp density (15% to 25% solids) if the objective is to maximize metal grade. Given that maximizing recovery while maintaining a reasonably good grade was the objective, the circuit should be operated at 25% to 28% pulp density.

TABLE 14.5 **Effect of flotation pulp density on metal metallurgy for first-stage cleaner circuit**

	% Solids				
	15	**20**	**25**	**30**	**38**
Bench-scale flotation time, min	7	9	12	15	20
Concentrate					
Weight recovery, %	27.2	26.8	32.8	42.5	45.5
Metal recovery, %	93.6	95.3	97.9	99.0	99.7
Metal grade, %	46.9	43.0	38.1	27.9	28.0
Tailing					
Metal grade, %	1.20	0.78	0.39	0.20	0.07

TABLE 14.6 **Effect of flotation pulp density on metal metallurgy for first-cleaner flotation**

	% Solids				
	15	**20**	**25**	**30**	**38**
Bench-scale flotation time, min	2.7	3.7	4.9	6.0	8.2
Concentrate					
Weight recovery, %	18.1	20.8	24.9	33.8	35.7
Metal recovery, %	76.2	86.9	91.7	95.2	96.7
Metal grade, %	58.2	50.7	47.2	33.6	34.8
Tailing					
Metal grade, %	3.86	2.0	1.4	0.87	0.67

PERFORM DATA ANALYSES

The metallurgical balance and the follow-up laboratory testing indicated the following:

- The first-cleaner flotation recovered 98.6% of the metal in a concentrate assaying 28.4% metal.
- The circulating load from the first-cleaner scavenger flotation was 10.2%.
- The flotation time in the first-cleaner circuit was sufficient for maximizing metal recovery. Increasing the circuit residence time by 50% resulted in only 0.3% improvement in metal recovery.
- The laboratory-to-plant scale-up ratio was estimated to be 3 for the circuit.

- The addition of high-grade tailing streams to the first-cleaner flotation resulted in significant reduction of the residence time in the circuit. These tailing streams should be added to the second-stage cleaner flotation circuit.
- The pulp density in the first-cleaner flotation circuit should be maintained at 25% to 28%.

SAMPLING CAMPAIGNS 2 TO 4

Following the recommended changes to the circuit, the second-stage cleaner circuit was sampled and analyzed using the approach previously discussed. Appropriate changes were made to the second-cleaner flotation circuit. The third-to-fifth-cleaner circuit was sampled, data were analyzed, and appropriate changes were recommended. Finally, the optimized overall circuit was sampled to determine the performance improvements.

CONCLUSIONS

The minor changes made to the circuit resulted in ±2% in concentrate grade improvement and ±1% in metal recovery. More importantly, the circuit ran smoothly and the operators did not have to constantly adjust the process parameters.

LESSONS LEARNED

The following lessons were learned from this specific audit:

- If the circuit is too complex, divide it into parts and optimize them. Start evaluation and optimization from the front end of the circuit. Optimize each section and make appropriate changes before proceeding to the next section of the plant.
- Develop a laboratory-to-plant scale-up ratio and evaluate the process variables in the laboratory. It is not only cheaper but easier to do so.
- Make sure to correct laboratory data to reflect the plant situations because the total flotation volume is fixed in the plant.

CASE STUDY 15

AUDITING PROCESS TECHNOLOGY FOR INDUSTRIAL MINERALS

> The process technology worked well on both bench- and pilot-plant scale. However, it produced inconsistent product quality on a commercial scale. Why?

An industrial minerals plant used a novel technology to upgrade phosphate from 16% to 34% P_2O_5. It worked well in bench-scale and pilot-plant operations. However, it had consistently failed to produce the product quality of 34% P_2O_5 in full-scale operation. The reasons for poor performance were postulated by plant management to be one or more of the following issues:

- Unstable grinding/cyclone operation resulting in a wide product size distribution to the flotation circuit
- Coarse particle size from the grinding circuit resulting in sanding of the flotation circuit
- Water hardness
- Poor quality of the collector, namely, sodium oleate

The process flowsheet is given in FIGURE 15.1. The process consisted of grinding the ore assaying 18% P_2O_5, 10.1% MgO (magnesium dioxide), and 5.1% SiO_2 (silicon dioxide) in a ball mill–cyclone circuit to 100% passing 150 mesh. The cyclone overflow was deslimed to remove slimes, which primarily consisted of carbonates and apatite.

The cyclone underflow was conditioned with sodium oleate, and phosphate and carbonate were floated from silica. The bulk-flotation concentrate was

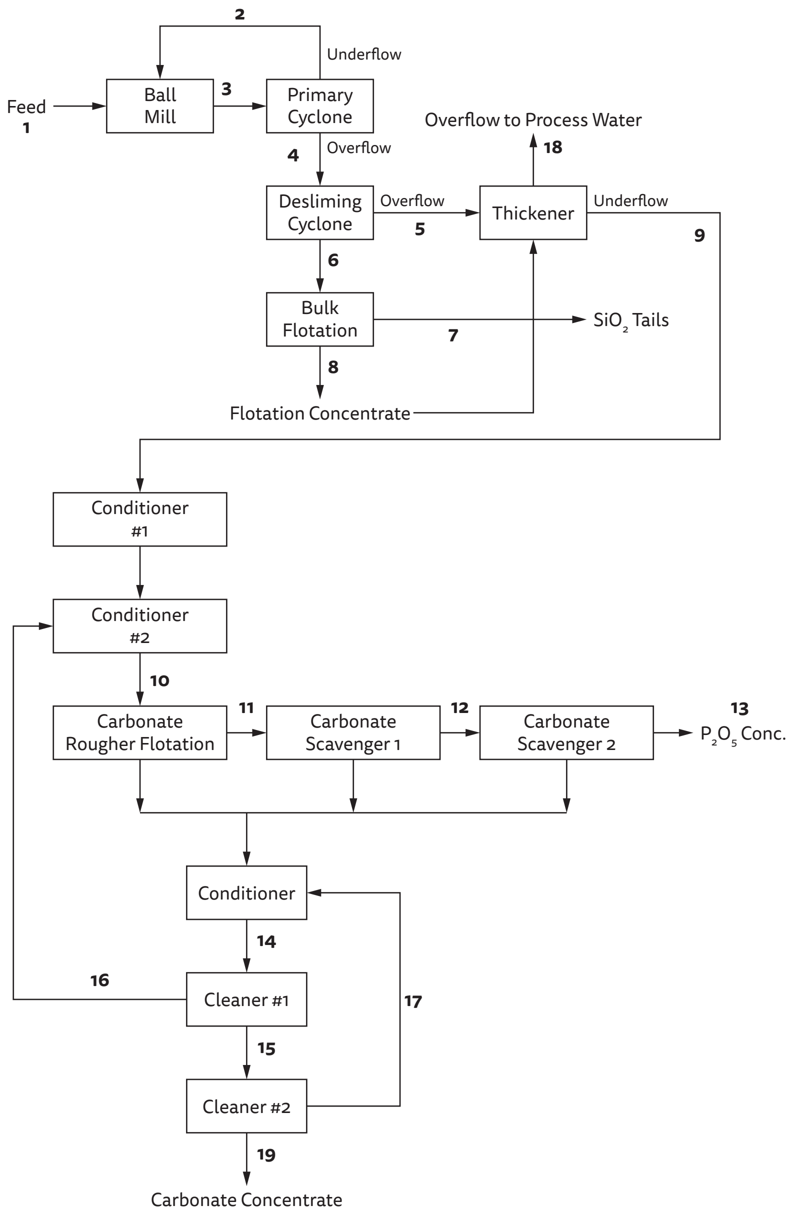

FIGURE 15.1 **Simplified plant flowsheet (numbered streams sampled)**

sent to a flotation circuit to separate phosphate and carbonate. The slurry was conditioned with phosphoric and sulfuric acids to depress phosphate and float carbonate. The carbonate was cleaned twice for further improvement in product quality.

Bench-scale and pilot-plant studies had resulted in several observations:

- The grind had a significant effect on flotation. Excessive production of fines should be avoided since it lowered the concentrate P_2O_5 grade.
- It was necessary that sodium oleate coat all apatite and dolomite particles for good recovery in the first-stage flotation.
- Proper conditioning of depressants (i.e., phosphoric acid and sulfuric acid) and sequence of reagent addition was important for good metallurgy. Any addition of oleate after depressants would float apatite and reduce recovery.
- Several sampling campaigns were conducted and material balances obtained for the circuit. The circuit was divided into two parts, namely, grind to bulk-float and dolomite/apatite separation flotation. This was necessitated because the thickener in between these unit operations had 12 hours of residence time. Hence, the product from the first half of the circuit did not enter the separation circuit until 12 hours later. A typical material balance is given in TABLE 15.1.

Several observations were noted from material balances and concurrent laboratory testing:

- Though the feed to the grinding circuit was consistent, the circulating load varied from 200% to 600%, thereby confirming that the grinding circuit was operating under unstable conditions.
- The desliming cyclone overflow removed 25% to 60% of the feed to the cyclone as slimes. This material did not get treated with oleic acid. Hence, some portion of carbonate did not float in the separation process.
- The feed to bulk-flotation was variable because of extreme variations in desliming cyclone performance. A fixed amount of oleic acid addition to the circuit was not a sufficient collector when the tonnage to the circuit was high. The collector dosage was based on removal of 33% of the fines. Also, when the tonnage to the

TABLE 15.1 **Metallurgical balance of phosphate flotation plant**

			Assay, %			Unit Recovery, %			Overall Recovery, % Based on Feed = 100		
No.	Stream	t/d	P_2O_5	MgO	SiO_2	P_2O_5	MgO	SiO_2	P_2O_5	MgO	SiO_2
1	Plant feed	33.6	18.3	10.1	5.10	100.0	100.0	100.0	100.0	100.0	100.0
2	Primary cyclone underflow	86.4	22.3	8.7	4.76	76.3	68.3	—	—	—	—
3	Primary cyclone feed (ball mill discharge)	120.0	21.2	9.1	4.62	100.0	100.0	—	—	—	—
4	Primary cyclone overflow (deslime cyclone feed)	33.6	18.3	10.1	5.10	23.7	31.7	—	—	—	—
5	Deslime cyclone overflow	8.78	22.5	8.1	2.90	32.4	20.8	1.5	—	—	—
6	Deslime cyclone underflow (bulk float feed)	24.82	16.8	10.8	5.16	67.6	79.2	98.5	—	—	—
7	Bulk float tails	1.49	11.4	5.3	40.18	4.7	2.5	56.6	4.2	2.5	56.6
8	Bulk float concentrate	23.33	17.2	11.1	2.64	95.3	97.5	43.4	95.3	97.5	43.4
9	Thickener underflow	25.4	19.3	10.0	2.97	100.0	100.0	100.0	100.0	100.0	100.0
10	Rougher feed	42.95	17.0	11.3	2.27	—	—	—	—	—	—
11	Scavenger #1 feed	—	19.6	9.8	2.84	—	—	—	—	—	—
12	Scavenger #2 feed	—	22.7	7.8	3.67	—	—	—	—	—	—
13	P_2O_5 concentrate	14.23	31.0	3.1	5.25	—	—	—	90.2	17.9	95.7
14	Cleaner #1 feed	31.95	9.4	15.6	0.56	—	—	—	—	—	—
15	Cleaner #2 feed	14.41	5.4	17.8	0.38	26.0	51.3	14.8	—	—	—
16	Cleaner #1 tails	17.54	12.7	13.8	0.61	74.0	48.7	85.2	—	—	—
17	Cleaner #2 tails	3.24	15.6	11.6	0.70	28.1	13.4	43.9	—	—	—
19	Carbonate concentrate	11.17	4.3	19.4	0.28	71.9	86.6	56.1	9.8	82.1	4.3

circuit was high and the flotation cells had to float a majority of the material (i.e., greater than 90%), the cells sanded. Hence, sanding occurred because of too much material rather than the coarseness of the material.

- Several sources of sodium oleate were tested in the laboratory and it was concluded that they all had an identical metallurgical response. Also, the process water versus softened water produced similar results.
- The sulfuric acid was dripping into the Condition No. 1 and not properly conditioning the carbonate-apatite concentrates since the acid was overflowing the conditioning tank. A pipe was installed in the tank and the reagents added to the conditioning tank through the pipe ensuring proper mixing. Proper conditioning resulted in improving the product quality and a consistent 34% plus P_2O_5 concentrate was produced.
- Recovery of apatite was improved by treating slimes with oleic acid prior to sending them to the thickeners.

LESSON LEARNED

The lesson learned from this audit is: Do not make changes to the critical steps in the process. Follow the steps used in bench-scale and pilot-plant studies in commercial operation, especially for industrial minerals.

CASE STUDY 16

OPERATOR TRAINING

> We build plants costing more than $100 million.
> Then we hire high-school graduates to run them.
> Can operator training in basic mineral processing
> operations help plant performance?

A ±1,000-tpd lead-zinc-silver operation had high operator turnover that was not the fault of management. The operation was audited several times over a period of 2 years. The primary objective was to enhance metallurgy while maintaining a smooth operation.

Minor modifications were made to the plant between sampling campaigns. However, a custom-made operator training course was designed and given to the operators. The course included a basic understanding of the role of the reagents, the importance of residence time and its relation to recovery, and the impact of dilution water added to the launders on recovery.

The metallurgical balance for the various campaigns before and after operator training is given in TABLES 16.1 and 16.2. These results indicate that both lead and zinc recoveries improved following operator training. The improvement was significant and measurable.

TABLE 16.1 **Plant metallurgical balances for sampling campaigns 1 and 2 before operator training**

Product	Campaign 1	Campaign 2	Product	Campaign 1	Campaign 2
	Plant Feed			**Zinc Circuit**	
Pb, %	4.8	4.0	**Recovery, %:**		
Zn, %	8.6	7.3	Weight	14.7	9.88
Fe, %	20.9	21.4	Pb	14.0	6.7
Au, opt*	0.078	0.075	Zn	74.4	58.3
Ag, opt	1.6	1.1	Fe	6.0	4.1
	Lead Circuit		Au	30.6	13.2
Recovery, %:			Ag	33.0	16.7
Weight	3.8	4.2	**Grade:**		
Pb	78.3	79.7	Pb, %	4.35	2.9
Zn	0.8	1.6	Zn, %	47.75	50.35
Fe	0.4	0.7	Fe, %	9.00	9.1
Au	65.0	36.4	Au, opt	0.097	0.105
Ag	47.0	49.6	Ag, opt	3.95	2.85
Grade:				**Plant Tailing**	
Pb, %	77.9	73.7	**Recovery, %:**		
Zn, %	1.8	3.3	Pb	8.2	13.6
Fe, %	2.3	3.6	Zn	24.8	40.1
Au, opt	0.77	0.65	Fe	93.6	95.2
Ag, opt	26.0	13.0	Au	4.4	50.4
			Ag	20	33.7
			Grade:		
			Pb, %	0.44	0.86
			Zn, %	2.6	3.8
			Fe, %	24.2	22.8
			Au, opt	TR	0.05
			Ag, opt	0.69	0.59

*opt = ounces per ton.

TABLE 16.2 **Plant metallurgical balances for sampling campaign 3 after operator training**

Product	Campaign 3	Product	Campaign 3
Plant Feed		**Zinc Circuit**	
Pb, %	4.3	**Recovery, %:**	
Zn, %	10.5	Weight	20.8
Fe, %	20.2	Pb	0.3
Au, opt*	0.082	Zn	88.5
Ag, opt	1.7	Fe	1.0
Lead Circuit		Au	22.1
Recovery, %:		Ag	38.9
Weight	5.0	**Grade:**	
Pb	87.9	Pb, %	2.7
Zn	2.2	Zn, %	47.0
Fe	0.9	Fe, %	8.9
Au	64.8	Au, opt	0.18
Ag	52.9	Ag, opt	3.5
Grade:		**Plant Tailing**	
Pb, %	73.9	**Recovery, %:**	
Zn, %	4.6	Weight	74.2
Fe, %	3.5	Pb	11.8
Au, opt	0.77	Zn	9.3
Ag, opt	17.7	Fe	98.1
		Au	25.4
		Ag	28.7
		Grade:	
		Pb, %	0.54
		Zn, %	1.3
		Fe, %	21.4
		Au, opt	0.018
		Ag, opt	0.42

*opt = ounces per ton.

CASE STUDY 17

APPLICATION OF COMPUTER SOFTWARE FOR OBTAINING MEANINGFUL MATERIAL BALANCE

> The saying "garbage in equals garbage out" is appropriate when it comes to using software for doing material balance for a complex mineral processing flowsheet.
>
> What is required to obtain a realistic material balance for the plant?

Data analyses is a crucial step in any metallurgical balance or plant auditing project. The process engineer is responsible for making sense of the data gathered in sampling campaigns. He or she usually has an abundance of data, including flow rates, chemical analyses, feed tonnage rates, pulp densities, and particle size analyses. The task is to use these data to determine a material balance that closely approximates the actual plant operating conditions.

It is a straightforward matter to calculate material and metallurgical balances by hand if the process flowsheet is simple with few streams and few or no recycle streams. In practice, this is seldom the case. It is extremely difficult and time-consuming to determine a material balance for a complex flowsheet with a large number of streams. The difficulties encountered include

- Complexity of the flowsheet due to the recycled stream;
- Assay error;

- Sampling error;
- Redundant data;
- Missing data; and
- Normal, cyclical variations or surges in plant flow rates.

Computer software packages are available to overcome these obstacles simultaneously using all of the data obtained to establish consistent material balance for complex flowsheets. *However, these software packages are only tools to assist process engineers*. Computers can be high-speed idiots when garbage in is equal to garbage out. *These tools are worthless without the good judgment of the process engineer.*

It is appealing that a process engineer can enter hundreds of data items into a material balance program and watch the software program sort out all the inconsistencies and present a true picture of plant performance. Those who use these programs have seen over and over again computer outputs giving the plant a recovery of greater than 100% or negative flow rates for some process streams.

A systematic five-step approach will alleviate frustration in obtaining meaningful results:

1. Identify the data collection weaknesses.
2. Divide the flowsheet into manageable sections.
3. Account for data errors.
4. Run multiple scenarios.
5. Examine results critically.

These steps are discussed in detail in this case study and followed by an example.

IDENTIFY THE DATA COLLECTION WEAKNESSES

The first step is to review the data you have gathered in the plant and identify the weaknesses in it. Some of the deficiencies may include the following:

- Some streams were very difficult to sample and you are not confident that they were sampled properly.
- Some streams could not be sampled at all and data is missing.

- Samples may have been mislabeled and switched prior to assaying them.
- You collected replicate samples that have wide variations in assays. Therefore, averaging results may not be the best approach.
- There was a plant upset during sampling that affected only a portion of the plant and therefore you are uncertain about the data collected in that part of the circuit.

Use this information while entering data in the material balance program. The confidence limits can be varied on different streams.

DIVIDE THE FLOWSHEET INTO MANAGEABLE SECTIONS

When the flowsheet is extremely complex, it should be broken down into manageable sections. Balance the input and output for the entire flowsheet first. This could be as simple as plant feed, product, and tailing streams only. Then separate the flowsheet into logical sections by unit operations such as grinding and classification, gravity separation, flotation, and so forth. If the process flowsheet has flotation only, split the circuit into rougher and cleaner flotation. Balance each section separately.

There are advantages to approaching the problem this way using software even though computers can handle complex calculations: You can gain valuable insight about the accuracy of the data, and will save time and minimize frustration when putting together the entire flowsheet balance because you will have adjusted the internal and recycle streams appropriately. This step will also help you more readily identify plant problem areas and how they may be affecting overall performance.

ACCOUNT FOR DATA ERRORS

Most software programs allow you to weight errors to account for differences in data accuracy. If you believe that the sampling or assay error is high for a given stream, weight that information accordingly. The ability to account for the confidence in the data is one of the strengths of these software packages.

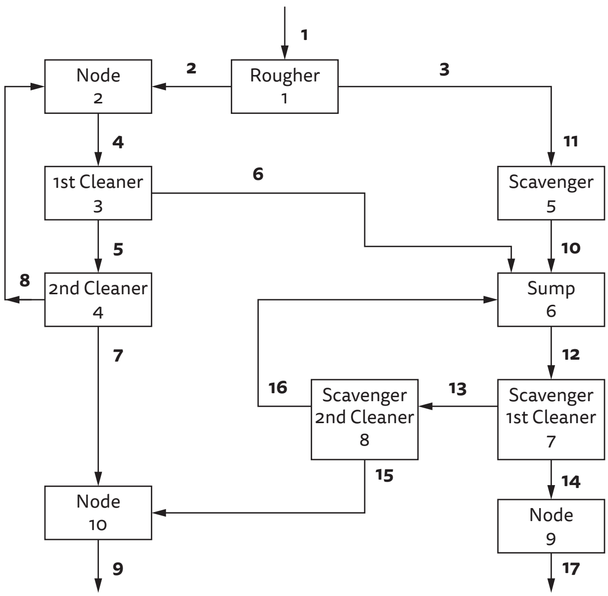

FIGURE 17.1 **Sulfide flotation circuit**

RUN MULTIPLE SCENARIOS

The software program provides the ability to run many scenarios in a short period of time. This provides the process engineer the flexibility to see the impact of redundant or suspect data on the metallurgical balance.

EXAMINE RESULTS CRITICALLY

Review the metallurgical balance to see if it makes sense and represents the operating environment. Significant differences between assayed and calculated values should raise a red flag.

The process flowsheet for a sulfide flotation circuit is given in FIGURE 17.1. In the following figures, unit processes and node numbers are shown in boxes. Streams are indicated by circles. The data collected for analyses included assays for three metals.

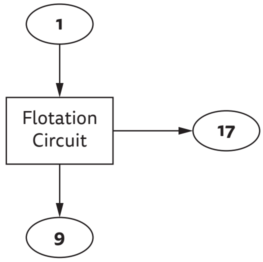

FIGURE 17.2 **Total circuit**

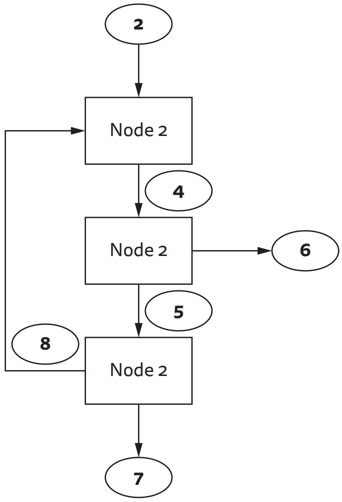

FIGURE 17.3 **Cleaner circuit**

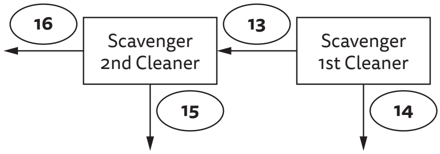

FIGURE 17.4 **Scavenger cleaner circuit**

The data collected did not include reliable flow-rate measurements for the process streams. The reliability for assays was best for M_1, reasonable for M_3, and worst for M_2. Stream 4 was not sampled.

The process flowsheet is divided into several sections, as shown in FIGURES 17.2 to 17.5.

The results of the material balance are given in TABLES 17.1 and 17.2. The measured and calculated assays and flow rate along with the percentage deviation are given in TABLE 17.2. The deviations are higher for metals M_2 and M_3 as expected. The results as calculated by the program do not need to be precise to three decimal places. What is important is the observation that second-cleaner concentrate (stream 7), which assayed 31.591% metal M_1, does not appear to upgrade the first-cleaner concentrate (stream 5), which assayed 31.545% metal M_1.

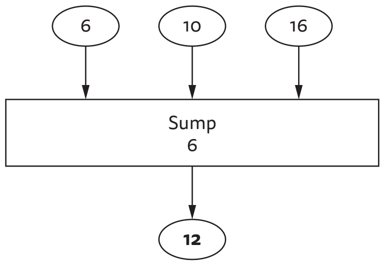

FIGURE 17.5 Sump flows

All software programs will determine the accuracy to different levels. However, *the process engineer should consider the software program only as a facilitating tool and then use common sense when evaluating the data to arrive at meaningful conclusions.*

TABLE 17.1 Material balance assays, flow-rate values, and recovery

	M_1		M_2		M_3		Flow Rate	
Stream	Assay Calculated	Recovery, %	Assay Calculated	Recovery, %	Assay Calculated	Recovery, %	Calculated	Recovery, %
1	0.635	100.00	0.024	100.00	0.112	100.00	100.00	100.00
2	29.351	66.47	0.726	43.90	4.281	54.73	1.437	1.44
3	0.216	33.53	0.014	56.10	0.052	45.27	98.563	98.56
4	29.311	66.47	0.725	43.91	4.275	54.73	1.439	1.44
5	31.545	66.45	0.779	43.85	4.601	54.71	1.337	1.34
6	0.087	0.01	0.013	0.06	0.023	0.02	0.102	0.10
7	31.591	66.45	0.779	43.85	4.601	54.71	1.337	1.34
8	0.312	0.00	0.034	0.00	0.088	0.00	0.002	0.00
9	30.114	92.64	0.764	62.76	5.415	94.03	1.952	1.95
10	8.493	27.14	0.230	19.62	2.225	40.13	2.028	2.03
11	0.042	6.39	0.009	36.47	0.006	5.14	96.535	96.54
12	7.867	27.664	0.214	20.13	2.069	41.03	2.229	2.23
13	23.643	26.71	0.642	19.36	6.305	40.21	0.717	0.72
14	0.409	0.97	0.012	0.76	0.061	0.82	1.513	1.51
15	26.919	26.19	0.728	18.91	7.162	39.33	0.617	0.62
16	3.339	0.52	0.108	0.45	0.992	0.88	0.100	0.10
17	0.048	7.36	0.009	37.24	0.007	5.96	98.048	98.05

TABLE 17.2 **Initial and calculated assay and flow-rate values**

	Assay Values, M_1			Assay Values, M_2			Assay Values, M_3			Flow Rate		
Stream	Measured	Calculated	Deviation, 1% of Metal 1	Measured	Calculated	Deviation, 1% of Metal 1	Measured	Calculated	Deviation, 1% of Metal 1	Estimated	Calculated	Deviation, 1% of Metal 1
1	0.650	0.635	2.31	0.025	0.024	4.00	0.117	0.112	4.27	100.0	100.000	0.00
2	29.1	29.351	0.83	0.730	0.726	0.55	4.72	4.281	9.30	1.4	1.437	2.64
3	0.270	0.216	20.00	0.018	0.014	22.22	0.072	0.052	27.78	98.6	98.563	0.04
4	N/A	29.311	—	N/A	0.725	—	N/A	4.275	—	N/A	1.439	—
5	31.8	31.545	0.80	0.893	0.779	12.77	3.64	4.601	26.40	1.3	1.337	2.85
6	0.087	0.087	0.00	0.013	0.013	0.00	0.023	0.023	0.00	0.1	0.102	2.00
7	32.2	31.591	1.89	0.734	0.780	6.27	5.17	4.607	10.89	1.3	1.335	2.69
8	0.312	0.312	0.00	0.034	0.034	0.00	0.088	0.088	0.00	0.002	0.002	0.00
9	29.1	30.114	3.48	0.694	0.764	10.09	5.93	5.415	8.68	2.1	1.952	7.05
10	9.00	8.493	5.63	0.292	0.230	21.23	2.51	2.225	11.35	1.7	2.028	19.29
11	0.042	0.042	0.00	0.009	0.009	0.00	0.005	0.006	20.00	96.3	96.535	0.24
12	7.00	7.867	12.39	0.187	0.214	14.44	1.95	2.069	6.10	2	2.229	11.45
13	23.0	23.643	2.80	0.644	0.642	0.31	5.10	6.305	23.63	0.6	0.717	19.50
14	0.410	0.409	0.24	0.012	0.012	0.00	0.059	0.061	3.39	1.6	1.513	5.44
15	26.6	26.919	1.20	0.698	0.728	4.30	7.35	7.162	2.56	0.6	0.617	2.83
16	3.35	3.339	0.33	0.108	0.108	0.00	1.00	0.992	0.80	0.1	0.100	0.00
17	0.046	0.048	4.35	0.008	0.009	12.50	0.012	0.007	41.67	98.0	98.048	0.05

N/A = not available.

CASE STUDY 18

CLEANER-FLOTATION-CIRCUIT EVALUATION

Can cleaner-flotation-circuit unit recoveries and upgrading ratios provide an indication of weaknesses and strengths of the plant?

The cleaner-flotation-circuit process flowsheet is shown in FIGURE 18.1. The plant was sampled following protocols discussed in earlier examples. The cleaner circuit data are summarized in TABLE 18.1 for the primary metal M_1. The range of recovery of various impurities is also given in the table.

The performance of the unit operations in the circuit were arbitrarily divided into three categories—namely, good, acceptable, and poor. The metal recovery in each stage should be at least 80% to be considered good. The upgrading ratio should be high (>1.5) in the first two or three stages and reasonable (>1.1) in the final cleaner stages. The impurity rejection should be at least 40% in each stage of flotation to be considered good. Based on these subjective criteria, the performance of flotation unit operations are given in TABLE 18.2. The fourth cleaner-flotation cells were operating poorly. This was due to the flotation pulp density being less than 2%. The dilution was coming from the water addition to the launders. The second cleaner-flotation cells were floating too much weight, thereby resulting in poor performance. So was the case with the sixth cleaner-flotation cells. The flotation residence time in both stages was too high.

This methodology can be used to correlate the performance of flotation stages to flotation pulp pH and density, aeration rate, reagent additions, and the mechanical conditions of the flotation cells.

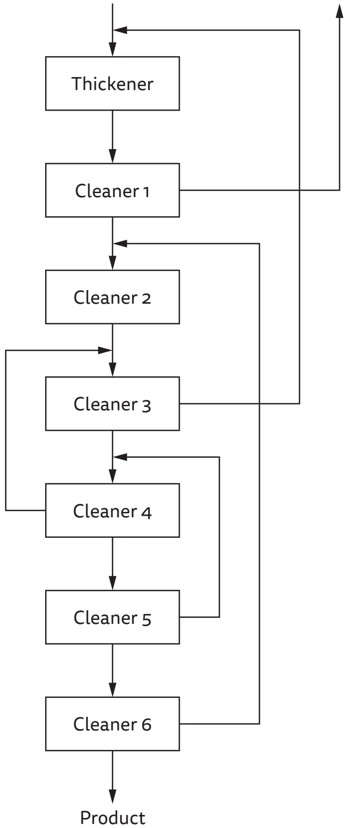

FIGURE 18.1 **Simplified process flowsheet**

TABLE 18.1 **Cleaner flotation circuit results***

Cleaner Stage	Unit Recovery, % Weight	M_1	Impurities	Upgrading Ratio, C/F† for M_1
1	31.7	86.3	10–45	2.64
2	61.5	83.0	68–78	1.39
3	70.0	87.0	38–59	1.33
4	75.0	79.3	48–61	1.06
5	66.7	77.3	36–55	1.09
6	80.0	95.9	64–68	1.06

*Feed to Cleaner No. 1 = 150% M_1.
†C/F = concentrate grade/feed grade.

TABLE 18.2 **Metallurgical performance of unit flotation circuits**

	M_1		
Cleaner Stage	**Recovery**	**Upgrading**	**Impurity Rejection**
1	Good	Good	Good
2	Good	Poor	Poor
3	Good	Good	Good
4	Poor	Poor	Poor
5	Poor	Acceptable	Acceptable
6	Good	Poor	Poor

CASE STUDY 19

OPERATING PARAMETERS AS A FUNCTION OF METAL PRICES*

> Maximizing recovery does not lead to maximizing profits. This is illustrated in the case of copper production at a mill in 1976.

A valid case history was documented in 1976 whereby a concentrator in the southwestern United States was producing copper at a final cost of US$0.83/lb as electro-refined copper cathode. The price of copper at that time fluctuated between $0.60 and $0.68/lb. Attempts were made at all times to lower the unit cost at each division from the mine through the refinery. The sales were in balance with the production as long as the company remained price competitive. The quantity of copper cathodes in inventory normally did not exceed more than 20% of the monthly production in spite of the slump in the market and the high inventories in the Commodity Exchange and London Metal Exchange. This is probably because this was a small-to-medium-size operation and did not significantly impact the worldwide copper inventories. At the same time, the disparity between the selling price and the product cost per pound of copper at this operation had a tremendous impact on its cash flow because of its small to medium size. Therefore, every department constantly investigated how to lower their unit cost.

The various departments approached the problem with the professional aggression of most good mineral processing personnel. A goal was established to increase their recovery and thereby increase their divisor and lower their unit cost. The department's total combined efforts resulted in an increase of 3,066,000 lb of production annually. The total incremental

* This case study is from Malhotra et al. 1993.

production cost of the increased production was US$2,009,050 annually for a unit cost of US$0.65/lb, which was almost at breakeven. The combined effect of 120,000,000/lb/yr at $0.83/lb and 3,066,000 lb at $0.65/lb resulted in a combined reduction of $0.005/lb of total production or a revised unit cost of $0.0825/lb. Although this did not seem like much, everyone pointed out that it was still lowering the cost and provided a new base cost for further reductions. There was yet to be a final economic lesson learned.

The 3,066,000-lb increase in copper production represented an overall annual production increase of 2.55%. Everyone was pleased with this combined effort. However, the losses continued for the next year, and the problem became worse than had been predicted. The continuing budgeted losses had been taken into account along with the continuing slump in the copper market. Yet the losses exceeded the budget.

A review of the previous year following the 2.55% increase in production, along with the slight reduction in unit cost, was conducted from a cash-flow analysis. It became apparent that the revolving inventory had increased by approximately 3,000,000 lb, and they were short by $2,000,000 in budgeted cash availability 1 year after the increase in production.

The new total production at $0.825 lb was presented as a savings of $615,330/yr as opposed to the equivalent production of the old unit cost. However, no one had bothered to coordinate the production cost-cutting goals and methods with the sales department. They did not realize that the company was selling almost in balance with their production, and because of their diminutive size, they could not increase their sales. Therefore, the increase in production at a lower unit cost for the purpose of reducing the average unit cost resulted in increasing what was already a negative cash flow. The negative cash flow was $2,000,000 greater than budgeted, even though production goals were met at the new unit cost. This negative cash flow was tied up in inventory given that the increased production would not sell. The material flow from ore to salable product is shown in FIGURE 19.1.

The numbers in this example may appear to be insignificant by today's standards. However, this was a small-to-medium-size copper operation, and the increase in negative cash flow was substantial in view of the losses that were already occurring. This reduced their staying power until the price of copper recovered.

The size of the mine or the dollar amount is not the issue in this example. The message is that we cannot be just production oriented any longer, striving

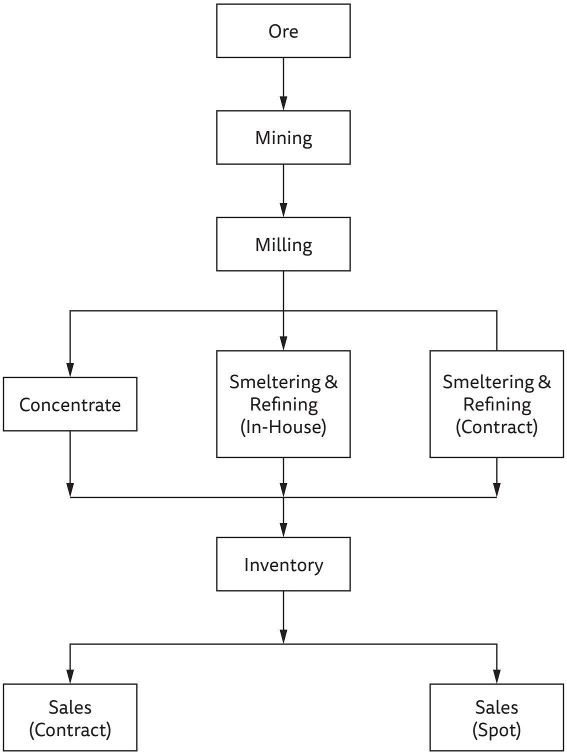

FIGURE 19.1 **Material flow: ore to salable product**

for the lower unit cost via higher production goals. In today's sophisticated markets, the production/cost goals must be coordinated with the marketing and financial departments. Production must be tailored to match the available markets/sales volume potential in combination with the cost versus revenue.

CASE STUDY 20

OPTIMIZING CASH FLOW ON INTERNATIONAL OPERATIONS

Optimization of the parts does not lead to optimization of the whole system at a mining/processing complex.

Many mining operations do not have their own integrated production departments. As a result, many concentrators must meet the minimum-grade standards that are established by the custom smelters to avoid excessive penalties. This often results in the same standards being established by operations that have their own concentrators and smelters, even when there is not any significant freight cost since the smelter is at the same location. Such was the case at one copper mining location in the early 1970s when copper was $0.65/lb.

The mine periodically would have a mixed oxide/sulfide ore for several months at a time with a 0.6% copper head. This mixed oxide/sulfide copper orebody would provide an average recovery of 70% with a targeted copper concentrate grade averaging 28%. This grade was established by management after input from the smelter department as to what was the minimum grade acceptable for good smelter operations and economics. In fact, each operating department furnished management with the volumes and conditions that were the minimum standard as feed to that particular department to produce acceptable economics and operations.

The price of $0.65/lb resulted in a review by the central metallurgical group with the following change in the internal operating philosophy. Observation by the central metallurgical group resulted in the conclusion, supported by a cooperative testing program with the concentrator personnel, that the flotation circuit was not being operated as aggressively as possible because of the established concentrate target grade by the internally owned smelter.

With slightly more aggressive froth removal, the concentrate grade would be decreased to 24%. However, the average recovery increased from 70% to 73% with this particular ore type. A review of the resultant economics pointed out the necessity of evaluating the integrated cash flow on the total property as opposed to the economics of the individual operating departments. The following calculations resulted:

- Concentrator tonnage: 20,000 t/d
- Cu in feed: 0.6%
- Recovery, average: 70%
- Concentrate: 300 t/d
- Concentrate grade, average: 28%
- Smelter cost: $50/concentrate ton

Because the operation also had its own copper refinery, it was applicable to use their cathode producer's sales price of $0.65/lb.

Revenue of standard operations as previously defined:

300 t/d at 28% (185,220 lb/d) × $0.65/lb = $120,393/d

Smelter cost:

300 t/d × $50/MT = $15,000/d

More aggressive flotation operation as a deliberate operating philosophy in the concentrator increased recovery to an average of 73%. The resultant change in concentrate grade and tonnage was 25% and 350 t/d, respectively. It was initially thought that this would be uneconomical because of the increase in smelter cost. However, it became apparent that, with both the concentrator and smelter facilities located on the same property, there was more latitude than initially believed.

Revenue of revised operation (averaged):

350 t/d at 25% (193,158 lb/d × $0.65/lb = $125,553/d

Revenue differential:

$125,553 – $120,393 = $5,160 (increased) revenue/d

Smelter cost (increase):

350 t/d × $50.00 = $17,500

Smelter cost (differential):

$17,500 – $15,000 = $2,500/d (increase)

$5,160 (revenue increase) – $2,500 (smelter increase) =
$2,660 increase in daily revenue

Annual increase = $971,000

It is recognized that the operating cost has changed drastically in 40 years. However, the philosophy of evaluation remains valid today in adapting an integrated cash-flow analyses. This example demonstrates that optimization of parts does not lead to optimization of the whole system.

APPENDIX

TYPICAL QUESTIONS TO ASK DURING PLANT AUDIT MEETINGS

It is highly recommended that the auditing team hold separate meetings with key personnel from different disciplines at the operating site. The auditor/auditing team should first review the primary objectives of the audit before engaging in a formal question-and-answer session.

Plant performance can be affected by a change in the ore type, the method of mining, environmental aspects of the type of reagents used, improper selection of equipment, frequent breakdown of the selected equipment, and so forth. Hence, it is recommended that the audit team meet the following key personnel:

- Geologists
- Mining engineers
- Process engineers
- Metallurgists
- Maintenance personnel
- Planning personnel
- Environmentalists
- Administrative personnel

TOPICS AND QUESTIONS

A partial list of topics that need to be discussed as well as typical questions an auditor needs to ask is provided in the following sections. The auditor can ask follow-up question as the need arises. As one becomes familiar with the process, more questions can be added to this list.

Geology and Resource/Reserve Estimation

Topics:

- Description of the various ore types in the deposit
- Contribution of each ore type to the resource
- Brief review of the geological model

Questions:

- If the audit involves an underground mine, how many years of reserve are there? (Ask the same questions from people in other disciplines. If the answer is variable by a large time frame, then assume poor communication between various departments).
- Have the ore characteristics changed over the last year, 5 years, and so on?
- Does the ore characteristic vary significantly from day to day to impact mining or processing?

Mining

Topics:

- Brief description of mining method
- Description of grade control procedures
- Description of waste-rock facility design with operational and final slope constraints
- Description of water control, diversions, and sediment ponds
- Description of reconciliation between grade model compared to mine production data and mine production compared to process plant production

Questions:

- How do geologists and mining engineers work together?
- What are the limiting factors in the expansion of production in the mine for open pit or underground operation?
- If the audit involves an underground mine, how many years of reserve are there? (Ask the same questions from people in other disciplines. If the answer is variable by a large time frame, then assume poor communication between various departments).
- Have the ore characteristics changed over the last year, 5 years, and so on?
- Does the ore characteristic vary significantly from day to day to impact mining or processing?

Process Facilities

Topics:

- General plant and facilities' arrangement drawing
- Simplified plant flow diagram
- Description of all unit processes and metallurgical and water balances
- Historical process production for at least last 3 years
- Historical plant operating costs with detailed breakdown of major items
- Historical process recoveries
- Design and operating parameters for process facility
- Reasons, if any, for deviation from design process capacity/ parameters

Questions:

- If you were to modify the plant, what would you do?
- What steps would you recommend to improve the process metallurgy and reduce the operation cost?

Maintenance Personnel

Topic:

- Breakdown of personnel by area: mechanical, electrical, and so forth

Questions:

- What is the maintenance policy? Set schedule? Spare parts?
- If you were able to replace one piece of equipment, which one would it be? (The answer could provide a clue to the most troublesome/bottleneck equipment in the plant.)

Environmental Personnel

Topics:

- Organization of site environmental management and staff
- Listing of permits and status, terms and conditions, reporting requirements, and any citations or issues with noncompliance
- Site health and safety plans, procedures for worker training, safety and accident prevention, incident response and investigation, and medical monitoring

Questions:

- What is your corporate environmental policy?
- What are your water quality management plans?

Administrative Personnel

Topic:

- Standard comminution procedures

Questions:

- Has there been any formal training in safety, health, and the process?
- What is the company's vision?
- What incentive plans are in place for employees?
- Are there periodic meetings held among all disciplines together

REFERENCES

The American Heritage Dictionary of the English Language, 5th ed. Culture. 2011. Boston, MA: Houghton Mifflin Harcourt.

Covey, S.R. 1994. *The 7 Habits of Highly Effective People*. New York: Simon and Schuster.

Malhotra D. 1986. Flowsheet auditing for improved metallurgical performance. Presented at 115th SME-AIME Annual Meeting, New Orleans, LA, March 2–6.

Malhotra D. 2001. *Politics of Mining: What They Don't Teach You in School*. Littleton, CO: SME.

Malhotra, D., and Baltich, L. 1989a. A systematic approach to plant auditing. In *Advances in Coal and Mineral Processing Using Flotation: Proceedings of an Engineering Foundation Conference, Palm Coast, Florida, December 3–8, 1989*. Edited by S. Chander and R.R. Klimpel. Littleton, CO: SME. pp. 338–346.

Malhotra, D., and Baltich, L. 1989b. Plant auditing and flowsheet optimization. Presented at Evaluation of Industrial Mineral Projects Workshop, Golden, CO, April 10–11.

Malhotra, D., Lizardo, S.T., Dominquez, N., and Garcio, O. 1989. Auditing and optimization of Pueblo Viejo gold processing plant. In *Precious Metals* '89. pp. 49–59.

Malhotra, D., Dowling Jr., E.C., and Riggs, W.R. 1993. Impact of metal prices on operating philosophy. In *Flotation Plants: Are They Optimized?* Edited by D. Malhotra. Littleton, CO: SME.

Merriam-Webster Dictionary, 11th ed. 2003. Audit; technology. Springfield, MA: Merriam-Webster.

Meyer, J.J. 1990. *If You Haven't Got the Time to Do It Right, When Will You Find the Time to Do It Over?* New York: Simon and Schuster.

Mills, C.A. 1989. *The Quality Audit—A Management Evaluation Tool*. New York: McGraw-Hill.

Neal, A.J., and Flintoff, B.C. 1992. The plant audit. *CIM Bull*. 85:72–77.

The Oxford English Dictionary. 1989. Audit. New York: Oxford University Press.

Rowland Jr., C.A. 1976. The tools of power: The Bond work index, a tool to measure grinding efficiency. Presented at SME-AIME Fall Meeting, Denver, CO.

RECOMMENDED READING

Beware the Naked Man Who Offers You His Shirt. Harvey B. Mackay. William Morrow, New York, 1990.

Coach Yourself to Success. Talane Miedaner. Contemporary Books, Lincolnwood, Illinois, 2000.

Confessions of an S.O.B. Allen Neuharth. Doubleday, New York, 1989.

Customer Mania! It's Never Too Late to Build a Customer-Focused Company. Kenneth H. Blanchard, Jim Ballard, and Frederic E. Finch. Free Press, New York, 2004.

Empowerment Takes More Than a Minute. Ken Blanchard, John P. Carlos, and Alan Randolph. Barnes & Noble Books, New York, 1996.

First Things First. Stephen R. Covey, A. Roger Merrill, and Rebecca R. Merrill. Simon and Schuster, New York, 1994.

Getting Things Done When You Are Not in Charge. Geoffrey M. Bellman. Berrett-Koehler, San Francisco, 1992.

Great Leaders Grow. Ken Blanchard and Mark Miller. Berrett-Koehler, San Francisco, 2012.

Gung Ho! Ken Blanchard and Sheldon Bowles. William Morrow, New York, 1998.

How Full Is Your Bucket? Tom Rath and Donald O. Clifton. Gallup Press, New York, 2004.

How to Present Like a Pro. Lani Arredondo. McGraw-Hill, New York, 1991.

How to Run a Successful Meeting in Half the Time. Milo O. Frank. Simon and Schuster, New York, 1989.

If It Ain't Broke...Break It. Robert J. Kriegel and Louis Palter. Warner Books, New York, 1991.

If You Haven't Got the Time to Do It Right, When Will You Find the Time to Do It Over? Jeffrey J. Mayer. Simon and Schuster, New York, 1990.

Leadership and Self-Deception. Arbinger Institute. Berrett-Koehler, San Francisco, 2002.

Managing Management Time. William Oncken Jr. Prentice-Hall, Englewood Cliffs, New Jersey, 1984.

Organized to Be Your Best! Susan Silver. Adams-Hall, Los Angeles, 1989.

Overpromise and Overdeliver. Rick Barrera. Penguin Group, New York, 2005.

Politics of Mining: What They Don't Teach You in School. Deepak Malhotra. SME, Littleton, Colorado, 2001.

Principle-Centered Leadership. Stephen R. Covey. Summit Books, New York, 1990.

Speak Up with Confidence. Jack Valenti. William Morrow, New York, 1982.

Teaching the Elephant to Dance. James A. Belasco. Crown Publishers, New York, 1990.

The Achievers. Raymond C. Johnson. Truman Talley Books, New York, 1987.

The Art of Getting Things Done. Richard W. Brislin and Paul Pedersen. Praeger, New York, 1991.

The Articulate Executive. Granville N. Toogood. McGraw-Hill, New York, 1996.

The Best of Inc. Guide to Managing People. Editors of *Inc*. Magazine. Prentice Hall Press, New York, 1989.

The Do's and Taboos of International Trade. Roger E. Axtell. John Wiley and Sons, New York, 1989, 1994.

The 4 Disciplines of Execution. Chris McChesney, Sean Covey, and Jim Huling. Free Press, New York, 2012.

The On-Time, On-Target Manager. Ken Blanchard and Steve Gottry. William Morrow, New York, 1962.

The Power of a Positive No. William Ury. Bantam Books, New York, 2007.

The Step Dynamic. Laddie and Judy Blaskowski. GroCorp Publications, Colorado, 2007.

The 10 Natural Laws of Successful Time and Life Management. Hyrum W. Smith. Warner Books, New York, 1994.

Time Management for Executives. Lauren R. Januz and Susan K. Jones. Charles Scribner's Sons, New York, 1981.

To Do...Doing...Done! G. Lynne Snead and Joyce Wycoff. Simon and Schuster, New York, 1997.

Top Performance. Zig Ziglar. F.H. Revell, Old Tappan, New Jersey. 1986.

What Got You Here Won't Get You There. Marshall Goldsmith. Hyperion, New York, 2007.

When Fish Fly. John Yokoyama and Joseph Michelli. Hyperion, New York, 2004.

Who Killed Change? Ken Blanchard, John Britt, Judd Hoekstra, and Pat Zigarmi. William Morrow, New York, 2009.

Working with Difficult People. Muriel Solomon. Prentice-Hall, Englewood Cliffs, New Jersey, 1990.
"Yes" or "No." Spencer Johnson. HarperCollins, New York, 1992.
You Don't Need a Title to Be a Leader. Mark Sanborn. Doubleday, New York, 2006.

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NOTE: *f*. indicates figure; *t*. indicates table

PLANT AUDITING

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About the Author

With more than 30 years of experience in metallurgical and mining auditing, Gaudin Award recipient **Deepak Malhotra** is eminently qualified to write this first book on plant auditing. Since leaving AMAX in 1990, he has been president of Resource Development, Inc., a mining and metallurgy consulting and testing firm. He has served in several SME leadership positions, including chairing several international symposia.

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