Section 30

Analysis of Plant Performance

Colin S. Howat, Ph.D., P.E., *John E. & Winifred E. Sharp Professors Department of Chemical & Petroleum Engineering, University of Kansas; Member, American Institute of Chemical Engineers; Member, American Society of Engineering Education.*

GLOSSARY

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Nomenclature

Symbol	Definition	SI units	U.S. customary units
$\mathbf{B}$	Matrix of linear constraint coefficients		
$\vec{\mathbf{b}}$	Vector of bias		
b	Bias		
C_p	Heat capacity	kJ/kgmol/K	Btu/lbmole/F
c	Number of components		
$\vec{\mathbf{d}}$	Vector of weighted adjustment in measurements		
d_j	Weighted adjustment to measurement j		
$\vec{f}$	Vector of constraints		
$g\langle\rangle$	Operator on the measurements and equipment boundaries		
H_0	Null hypothesis		
H_a	Alternative hypothesis		
$\mathbf{J}$	Variance-covariance matrix of measurements		
K_{ij}	Equilibrium vaporization ratio for component i on stage j		
k	Specific rate constant		
$\mathbf{Q}$	Variance-covariance matrix of measurement adjustments		
Q	Heat transfer	kJ/hr	Btu/hr
Q_{jj}	Variance of adjustment to measurement j		
$\mathbf{R}$	Variance-covariance matrix of constraint residuals		
R_{ii}	Variance of constraint residual i		
$\vec{\mathbf{r}}$	Constraint equation residuals		
r_j	Single constraint residual		
S	Stream flow	kgmol/hr	lbmole/hr
T	Temperature	K	°F
t	Time		
$\mathbf{X}_1$	Matrix of all measurements		
$\vec{\mathbf{X}}_1^m$	Vector of measurements		
$\hat{\vec{\mathbf{X}}}_1^m$	Vector of adjusted measurements		
$\hat{\vec{\mathbf{X}}}_1^M$	Vector of estimated measurements from the model		
$\delta\vec{\mathbf{X}}_1$	Deviation between adjusted and measured values		
$\mathbf{X}_2$	Matrix of equipment boundaries		
$\vec{\mathbf{X}}_2$	Vector of component flows		
$X_{i,j}$	Component i flow in stream j		
x_{ij}	Entry in the measurement matrix; liquid mole fraction of component i on stage j		
$\hat{x}_i$	Individual adjusted measurement		
x_i	Individual measurement		
$\tilde{x}_i$	True value of individual measurement		
$\bar{x}_i$	Mean value of individual measurement		
y_{ij}	Vapor mole fraction of component i on stage j		
$y_{i,j}^*$	Equilibrium vapor mole fraction of component i on stage j		

Greek Symbols

Symbol	Definition	SI units	U.S. customary units
$\vec{\beta}$	Vector representation of parameters		
σ_i	Uncertainty in individual measurement		
θ_{ij}	Tray efficiency of component i on stage j		
ρ_j	Stream density	kg/m^3	lbm/ft^3

Superscripts

Symbol	Definition
M	Measurement
$\mathbf{m}$	Measured
P	Plant
$\mathbf{T}$	Transpose
T	Total

Subscripts

Symbol	Definition
i	Matrix, vector position
j	Matrix, vector position

GLOSSARY

accuracy Proximity of the measurements to actual values. Data frequently contain bias, a deviation between the measurement and the actual value. The smaller the deviation, the greater the accuracy.

bias Offset between the measurement and the actual value of a measurement.

equipment boundary Limit in equipment operation. This could refer to design limits such as operating pressure and temperature. More often, the concern of the plant-performance analyst is the upper and lower operating limits for the equipment. These boundaries typically describe an operating range beyond which the equipment performance deteriorates markedly.

equipment constraints Limits beyond which the equipment cannot be operated, either due to design or operating boundaries.

fault detection Process of identifying deteriorating unit operating performance. Examples are instrument failure, increased energy consumption, and increased catalyst usage.

gross error Extreme systematic error in a measurement. The bias or systematic error is sufficiently large to distort the reconciliation and model development conclusions. Gross errors are frequently identified during rectification. Validation steps also are used to identify gross errors in measurements.

identification Procedure for developing hypotheses and determining critical measurements. Identification requires an understanding of the intent of the process and intent of the plant-performance analysis to be conducted.

interpretation Procedure for using the plant measurements or adjustments thereof to troubleshoot, detect faults, develop a plant model, or estimate parameters.

measurements Plant information. These provide a window into the operation. They may consist of routinely acquired information such as that recorded by automatic control systems or recorded on shift logs, or they may consist of nonroutine information acquired as part of a plant test.

model Qualitative or quantitative relationship between operating specifications and products. The quantitative model can be relational (e.g., a linear model) or physical (e.g., one comprised of appropriate material and energy balances, equilibrium relations, and rate relations). The parameters of these models (e.g., linear coefficients in the relational model; or tray efficiency, reactor volume efficiency, and heat transfer coefficients in a physical model) can be estimated from plant data.

plant A group of processing units. Within this context, it is the entire processing facility, typically too large to be the focus of a single plant-performance analysis. The terminology in plant-performance analysis is inconsistent. Often the study is of a particular unit and rarely of the entire plant. However, the terms *plant test* and *plant data* refer to unit tests and unit data and will be used consistent with *practice.*

parameters Model constants that relate the operating specifications to measures of product quality and quantity. Estimation of these is a frequent goal of plant-performance analysis.

precision Measurement of the random deviations around some mean value. Precision is compromised by sampling methods, instrument calibrations, and laboratory calibrations. Reconciliation methods have been developed to minimize the impact of measurement precision.

process constraints Chemical engineering fundamental relations for the unit. Examples include material balances, energy balances, hydraulic balances and, at times, thermodynamic equilibria. These constraints may be equality constraints such as material balances or inequality constraints such as those found in hydraulic balances (i.e., $P_{out} \leq P_{in}$ for a process vessel). Obvious process constraints may not always apply due to internal or external leaks, vents, and process misunderstanding.

reconciliation Procedure for the adjustment of the measurements to close the process constraints. The purpose of reconciliation is to provide a set of measurements that better represent the actual plant operation.

rectification Procedure for the identification of measurements that contain gross errors. This process is frequently done simultaneously or cyclically with the reconciliation.

systematic error Measure of the bias in the measurements. It is a constant deviation or offset between the measurement and the actual value. This term is frequently used interchangeably with *bias.*

troubleshooting Procedure to identify and solve a problem in operating unit. This is the most frequent interpretation step in plant-performance analysis.

uncertainty A general term used for measurement error. This includes random and systematic errors in measurements.

unit Battery limits of equipment under study. The unit under study may consist of a single piece of equipment, a group (e.g., a distillation tower with auxiliary equipment), an entire process (e.g., reactors and the corresponding separation train), or the entire plant.

unit test Special operating procedure. The unit is operated at prescribed conditions. Special measurements may be made to supplement routine ones. One of the principal goals is to establish nearly constant material and energy balances to provide a firmer foundation for model development.

validation Procedure for screening measurements to determine whether they are consistent with known unit characteristics. Measurements are compared to other measurements, expected operating limits, actual equipment status, and equipment performance characteristics. It is a useful tool to eliminate potentially distorting measurements from further consideration.

INTRODUCTION TO ANALYSIS OF PLANT PERFORMANCE

MOTIVATION

The goal of plant-performance analysis is to develop an accurate understanding of plant operations. This understanding can be used to:

- Identify problems in the current operation.
- Identify deteriorating performance in instruments, energy usage, equipment, or catalysts.
- Identify better operating regions leading to improved product or operating efficiency.
- Identify a better model leading to better designs.

The results of plant-performance analysis ultimately lead to a more efficient, safe, profitable operation.

FOCUS

Section 30 is written for engineers responsible for day-to-day interpretations of plant operation, those responsible for developing unit (plant) tests, and those responsible for analyzing plant data. The content focuses on aspects of troubleshooting, fault detection, parameter estimation, and model discrimination. In order to reach reliable conclusions, methods of identification, validation, reconciliation, rectification and interpretation are included. The emphasis is on guidelines that assist in avoiding many of the pitfalls of plant-performance analysis. While there are numerous mathematical and statistical methods in the technical literature, most of them apply only to restricted plant situations atypical of normal operations or to situations where enormous amounts of measurements are handled on a routine basis. Typical plant measurements are incomplete, their statistical distributions are unknown, the plant fluctuations are too great, and/or the volume of data makes the methods intractable. The numerical methods are useful to provide some insight, and an overview is presented. However, because of the limitations to measurement and numerical methods, the engineering judgment of plant-performance analysts is critical. Analysts must develop an accurate understanding of plant operations in order to draw valid conclusions about current operation, alternative operating regimes, and proposed designs founded upon the current plant configuration.

OVERVIEW

Historical Definition Plant-performance analysis has been defined as the reconciliation, rectification, and interpretation of plant measurements to develop an adequate understanding of plant operation. Measurements taken from the operating plant are the foundation for the analysis. The measurements are reconciled to meet the constraints on the process, such as material balances, energy balances, and phase relations. The measurements are rectified to identify and eliminate those measurements that contain bias (i.e., systematic errors) sufficiently large to distort conclusions. The data are interpreted to troubleshoot, develop plant models, or estimate values for significant operating parameters. Ultimately, the results are used to discriminate among causes for deterioration of performance, operating regions, models, and possible operating decisions. The purpose of plant-performance analysis is to understand plant operations such that relational or physical models of the plant can be developed. The intended results are better profits, better control, safer operation, and better subsequent designs.

Plant-Performance Triangle This view of plant-performance analysis is depicted in Fig. 30-1 as a plant-performance triangle. Figure 30-2 provides a key to the symbols used.

The three vertices are the operating plant, the plant data, and the plant model. The plant produces a product. The data and their uncertainties provide the history of plant operation. The model along with values of the model parameters can be used for troubleshooting, fault detection, design, and/or plant control.

The vertices are connected with lines indicating information flow. Measurements from the plant flow to plant data, where raw measurements are converted to typical engineering units. The plant data information flows via reconciliation, rectification, and interpretation to the plant model. The results of the model (i.e., troubleshooting, model building, or parameter estimation) are then used to improve plant operation through remedial action, control, and design.

Unit (Plant) Data Measurements supporting plant-performance analysis come from daily operating logs, specific plant tests, automatic data acquisition, and specific measurement requirements. Examples of these data include temperatures, pressures, flows, compositions, elapsed time, and charge volume. The data are all subject to random errors from a variety of sources ranging from plant fluctuations and sampling technique through instrument calibration to laboratory methodology. The random errors define the precision in the data.

The measurements are also subject to systematic errors ranging from sensor position, sampling methods, and instrument degradation

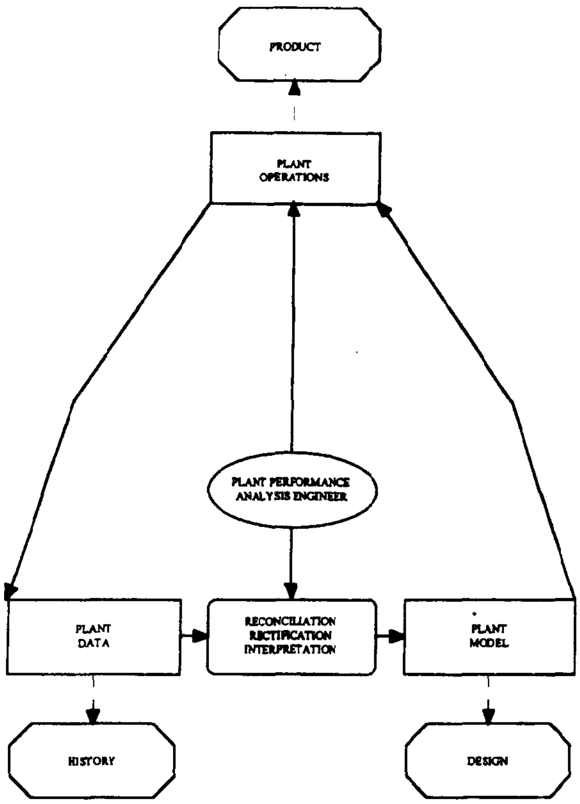

FIG. 30-1 Simplified plant performance analysis triangle.

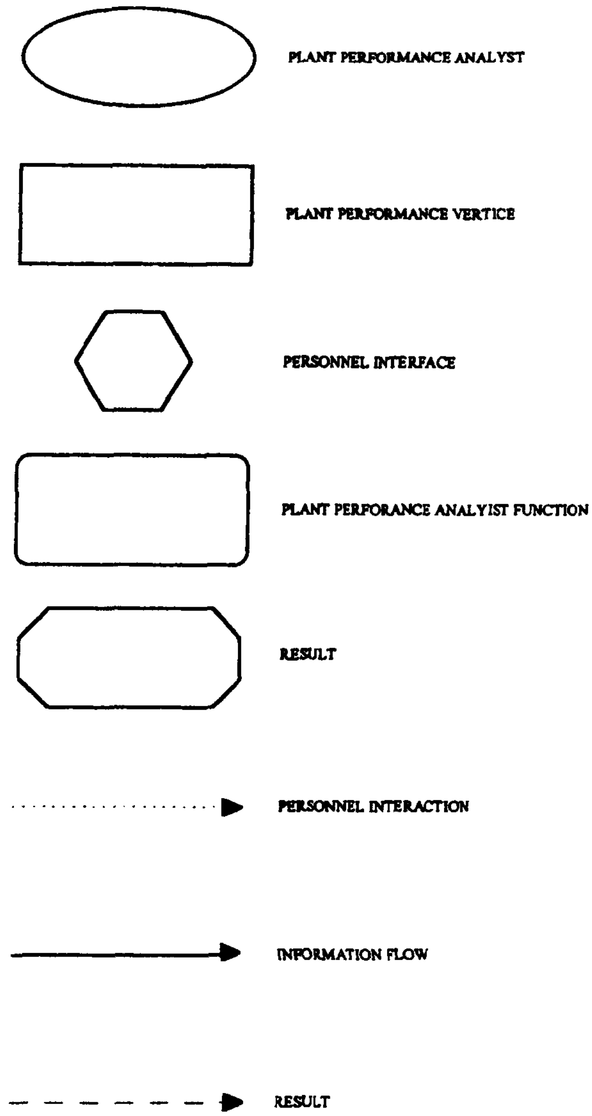

FIG. 30-2 Symbol key used in plant performance triangle.

to miscalibration in the field and laboratory. The systematic errors define the accuracy in the data.

These measurements with their inherent errors are the bases for numerous fault detection, control, and operating and design decisions. The random and systematic errors corrupt the decisions, amplifying their uncertainty and, in some cases, resulting in substantially wrong decisions.

Role of Plant-Performance Analysts In this simplified representation, the principal role of analysts is to recognize these uncertainties; to accommodate them in the analysis; and to develop more confident control, operating, or design decisions. The analysts recognize and quantify these uncertainties through repeated measurements and effective communication with equipment and laboratory technicians. They validate the data comparing them to known process and equipment information. They accommodate these errors through reconciliation—adjusting the measurements to close the process constraints. Example constraints include process constraints such as material balances, energy balances, equilibrium relations (occasionally), elapsed time, and so on; and equipment constraints or boundaries that define the limitations of equipment operation. The reconciliation literature focuses primarily on process constraints, but it is important to include equipment constraints and boundaries to ensure correct measurement adjustment.

During reconciliation, measurements in which the analysts have a high degree of confidence are adjusted little, if at all, to meet the constraints, while adjustments for less reliable measurements are greater. Correct reconciliation minimizes the impact of measurement error and results in adjusted measurements that represent plant operation better than the raw ones. Traditionally, analysts have adjusted the measurements intuitively, relying on their experience and engineering judgment. The purpose of mathematical and statistical algorithms developed over the past several years is to perform these adjustments automatically. However, algorithmic adjustment is subject to many of the same pitfalls that exist for intuitive adjustment. Both intuitive and algorithmic adjustment require correct estimates for uncertainty in the measurements. Both methods also require a correct implicit model of the plant. Without correct measurement error estimates and constraints, reconciliation will add bias to the adjusted measurements. For example, an unrecognized leak or vent invalidates the material-balance constraints developed from the implicit plant model, and either intuitive or algorithmic adjustment of data to meet invalid constraints adds systematic error to the adjusted measurements. Even when reconciliation is done algorithmically, the experience and judgment of the analysts are crucial.

The primary assumption in reconciliation is that the measurements are subject only to random errors. This is rarely the case. Misplaced sensors, poor sampling methodology, miscalibrations, and the like add systematic error to the measurements. If the systematic errors in the measurements are large and not accounted for, all reconciled measurements will be biased. During the measurement adjustment, the systematic errors will be imposed on other measurements, resulting in systematic error throughout the adjusted measurements.

Rectification accounts for systematic measurement error. During rectification, measurements that are systematically in error are identified and discarded. Rectification can be done either cyclically or simultaneously with reconciliation, and either intuitively or algorithmically. Simple methods such as data validation and complicated methods using various statistical tests can be used to identify the presence of large systematic (gross) errors in the measurements. Coupled with successive elimination and addition, the measurements with the errors can be identified and discarded. No method is completely reliable. Plant-performance analysts must recognize that rectification is approximate, at best. Frequently, systematic errors go unnoticed, and some bias is likely in the adjusted measurements.

The result of the reconciliation/rectification process is a set of adjusted measurements that are intended to represent actual plant operation. These measurements form the basis of the troubleshooting, control, operating, and design decisions. In order for these decisions to be made, the adjusted measurements must be interpreted. Interpretation typically involves some form of parameter estimation. That is, significant parameters—tray efficiency in a descriptive distillation model or linear model parameters in a relational model—are estimated. The model of the process coupled with the parameter estimates is used to control the process, adjust operation, explore other operating regimes, identify deteriorating plant and instrument performance or to design a new process. The adjusted measurements can also be interpreted to build a model and discriminate among many possible models. The parameter estimation and model building process is based on some form of regression or optimization analysis such that the model is developed to best represent the adjusted measurements. As with reconciliation and rectification, unknown or inaccurate knowledge of the adjusted measurement uncertainties will translate into models and parameter estimates with magnified uncertainty. Further, other errors such as those incorporated into the database will corrupt the comparison between the model and adjusted measurements. Consequently, parameters that appear to be fundamental to the unit (e.g., tray efficiency) actually compensate for other uncertainties (e.g., phase equilibria uncertainty in this case).

Extended Plant-Performance Triangle The historical representation of plant-performance analysis in Fig. 30-1 misses one of the principal aspects: identification. Identification establishes troubleshooting hypotheses and measurements that will support the level of confidence required in the resultant model (i.e., which measurements will be most beneficial). Unfortunately, the relative impact of the measurements on the desired end use of the analysis is frequently overlooked. The most important technical step in the analysis procedures is to identify which measurements should be made. This is one of the roles of the plant-performance engineer. Figure 30-3 includes identification in the plant-performance triangle.

The typically recorded measurements in either daily operations or specific plant-performance tests are not optimal. The sampling locations were not selected with troubleshooting, control, operations, or model building as the focus. Even if the designers analyzed possible sample locations to determine which might maximize the information contained in measurements, it is likely that the actual operation is different from that envisioned by the designers or control engineers. More often, the sample locations are based on historic rules of thumb whose origins were likely based on convenience. Thus, for a given measurement, the amount of information leading to accurate parameter estimates is limited. Greater model accuracy can be achieved if locations are selected with the end use of the information well defined. It is necessary to define the intended end-use of the measurements and then to identify measurement positions to maximize the value in testing hypotheses and developing model parameter estimates.

END USE

The goal of plant-performance analysis is to improve understanding, efficiency, quality, and safety of operating plants. The end use must be established to focus the analysis. Figure 30-3 shows the three principal categories of end use improvements. The criteria for accuracy may vary among the categories requiring different numbers and levels of accuracy in the measurements.

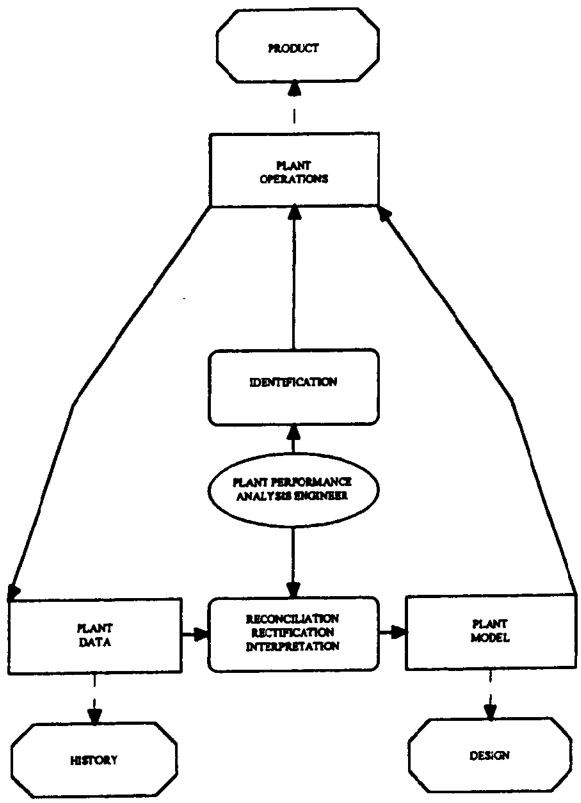

FIG. 30-3 Extended plant performance triangle.

Plant Operation The purpose is to maintain and improve performance (i.e., product quality, rate, efficiency, safety, and profits). Examples include identification of plant conditions that limit performance (troubleshooting, debottlenecking) and exploration of new operating regions.

History The history of a plant forms the basis for fault detection. Fault detection is a monitoring activity to identify deteriorating operations, such as deteriorating instrument readings, catalyst usage, and energy performance. The plant data form a database of historical performance that can be used to identify problems as they form. Monitoring of the measurements and estimated model parameters are typical fault-detection activities.

Design In this context, *design* embodies all aspects requiring a model of the plant operations. Examples can include troubleshooting, fault detection, control corrections, and design development.

TECHNICAL BARRIERS TO ACCURATE UNDERSTANDING

Limited Contained Information Data supporting the plant-performance analysis can come from daily operating logs, automatic or manual, or from formal plant tests. Daily logs consist of those measurements that the process and control designers and, subsequently, the plant engineers deem to be important in judging daily plant operation. No special operations (e.g., accumulating a constant-composition feed stock) are prerequisite for acquiring plant data of this caliber. While these data were intended to give sensitive insight into plant-performance, oftentimes they are recorded based on history and not formal analysis (i.e., their value has not been established or identified with respect to their end use). This presents the first technical hurdle—using data with limited contained information.

Formal unit (plant) tests (e.g., those developed for commissioning) usually last over a period of hours to weeks. The intent is to have the plant lined out in a representative operating regime. Feed stocks are typically accumulated in advance to ensure steady-state or controlled operation. Plant personnel are notified about the importance of the test so that they pay special attention to the operation, including charging rates, operating conditions, cycle times, and the like. Laboratory resources are dedicated beyond those normally required. A formal unit (plant) test requires significant coordination and investment. While it may give an indication of the plant capability, it is not representative of normal operation. During a unit (plant) test, greater attention and more personnel are dedicated to operation and data acquisition. Excursions in operating conditions are minimized. The data-acquisition effort should focus on sensitive measurements, providing insight beyond that gleaned from daily operations. However, oftentimes, little forethought is given to the end use of the information and the conclusions that will be drawn from it. Therefore, these additional data are not typically in the most sensitive regions of space and time. These data, too, contain less than optimal information.

There are significant technical barriers to accurate understanding from either source.

Limited Data First, plant data are limited. Unfortunately, those easiest to obtain are not necessarily the most useful. In many cases, the measurements that are absolutely required for accurate model development are unavailable. For those that are available, the sensitivity of the parameter estimate, model evaluation, and/or subsequent conclusion to a particular measurement may be very low. Design or control engineers seldom look at model development as the primary reason for placing sensors. Further, because equipment is frequently not operated in the intended region, the sensitive locations in space and time have shifted. Finally, because the cost-effectiveness of measurements can be difficult to justify, many plants are underinstrumented.

Plant Fluctuations Second, the plant is subject to constant fluctuations. These can be random around a certain operating mean; drift as feed stock, atmospheric, and other conditions change; or step change due to feed or other changes. While these fluctuations may be minimized during a formal unit (plant) test, nevertheless they are present. Given that each piece of equipment has time constants, usually unknown, these fluctuations propagate throughout the process, introducing error to assumed constraints such as material and energy balances.

Random Measurement Error Third, the measurements contain significant random errors. These errors may be due to sampling technique, instrument calibrations, and/or analysis methods. The error-probability-distribution functions are masked by fluctuations in the plant and cost of the measurements. Consequently, it is difficult to know whether, during reconciliation, 5 percent, 10 percent, or even 20 percent adjustments are acceptable to close the constraints.

Systematic Measurement Error Fourth, measurements are subject to unknown systematic errors. These result from worn instruments (e.g., eroded orifice plates, improper sampling, and other causes). While many of these might be identifiable, others require confidence in all other measurements and, occasionally, the model in order to identify and evaluate. Therefore, many systematic errors go unnoticed.

Systematic Operating Errors Fifth, systematic operating errors may be unknown at the time of measurements. While not intended as part of daily operations, leaky or open valves frequently result in bypasses, leaks, and alternative feeds that will add hidden bias. Consequently, constraints assumed to hold and used to reconcile the data, identify systematic errors, estimate parameters, and build models are in error. The constraint bias propagates to the resultant models.

Unknown Statistical Distributions Sixth, despite these problems, it is necessary that these data be used to control the plant and develop models to improve the operation. Sophisticated numerical and statistical methods have been developed to account for random errors, identify and eliminate gross errors, and develop parameter estimates. These methods require good estimates of the underlying uncertainties (e.g., probability distributions for each of the measurements). Because the probability distributions are usually unknown, their estimates are usually poor and biased. The bias is carried through to the resulting conclusions and decisions.

PERSONNEL BARRIERS TO ACCURATE UNDERSTANDING

Because the technical barriers previously outlined increase uncertainty in the data, plant-performance analysts must approach the data analysis with an unprejudiced eye. Significant technical judgment is required to evaluate each measurement and its uncertainty with respect to the intended purpose, the model development, and the conclusions. If there is any bias on the analysts' part, it is likely that this bias will be built into the subsequent model and parameter estimates. Since engineers rely upon the model to extrapolate from current operation, the bias can be amplified and lead to decisions that are inaccurate, unwarranted, and potentially dangerous.

To minimize prejudice, analysts must identify and deal effectively with personnel barriers to accurate understanding. One type of personnel barrier is the endemic mythologies that have been developed to justify decisions and explain day-to-day operation in the plant. These mythologies develop because time, technical expertise, or engineers' and operators' skills do not warrant more sophisticated or technical solutions.

Operators Operators develop mythologies in response to the pressure placed upon them for successful production quality and rates. These help them make decisions that, while not always technically supported, are generally in the correct direction. When they are not, convincing plant personnel of the deficiency in their decision structures is a difficult task.

Design and Control Engineers Equally important are the mythologies developed by the design or control engineers. Their models of plant performance are more technically sound, but may be no more accurate than the operators' mythology. Consequently, the mythology passed along by the design and control engineers can also add bias to the foundation upon which the analyst relies.

Finally, with the current developments in control technology, there is a reliance by the operating engineer on, what is in most cases, an approximate model. While the control and design engineers might fully recognize the limitations inherent in projecting beyond the narrow confines of current operation, the operating engineer will frequently believe that the control model is accurate. This leads to bias in the operation and subsequent decisions regarding performance.

Analysts The above is a formidable barrier. Analysts must use limited and uncertain measurements to operate and control the plant and understand the internal process. Multiple interpretations can result from analyzing limited, sparse, suboptimal data. Both intuitive and complex algorithmic analysis methods add bias. Expert and artificial intelligence systems may ultimately be developed to recognize and handle all of these limitations during the model development. However, the current state-of-the-art requires the intervention of skilled analysts to draw accurate conclusions about plant operation.

The critical role of analysts introduces a potential for bias that overrides all others—the analysts' evaluation of the plant information. Analysts must recognize that the operators' methods, designers' models, and control engineers' models have merit but must also beware they can be misleading. If the analysts are not familiar with the unit, the explanations are seductive, particularly since there is the motivation to avoid antagonizing the operators and other engineers.

Analysts must recognize that the end use as well as the uncertainty determines the value of measurements. While the operators may pay the most attention to one set of measurements in making their decisions, another set may be the proper focus for model development and parameter estimation. The predilection is to focus on those measurements that the operators believe in or that the designers/controllers originally believed in. While these may not be misleading, they are usually not optimal, and analysts must consciously expand their vision to include others.

In most situations, the plant was designed to be controlled and operated in a certain regime. It is likely that this has changed due to differences between the design basis and actual operation, due to operating experience and wholesale changes in purpose. Further, when developing sample, control, and measurement points, the designers/controllers may have had a model in mind for the operation. It is likely that that model is not accurate. Alternatively, they may have only used rules of thumb. Focusing only on previously selected points is limiting.

Each of the above can reduce analysts' opportunity for full understanding of the plant. Analysts must recognize that the plant operates by well-defined but not always obvious rules. It is important to identify these fundamental rules. If the analyst uses incorrect rules, the results will be further biased.

For the plant-performance analysis to be effective, the identified variables must be measured, the laboratory analysis must be correct, the simulation programs must accurately model the plant and the control recommendations must be implemented. In many settings, these aspects are not performed by plant-performance analysts. Analysts may be viewed as outsiders and operators are reluctant to modify their time-tested decision process. Laboratories geared to focusing on feed stock and product quality view unit (plant) tests as an overload. Simulation programs are not easily modified and proposed changes may not receive high priority attention. Control engineers may view modifications as an invasion of their responsibility. The plant-performance analysis milieu is much more complicated than that presented in Fig. 30-3 because of the personnel and communication barriers to implementation.

Figure 30-4 presents a more complete representation of plant-performance analysis. The information flow always faces barriers of personnel interactions. The operator must be convinced that the proposed changes and measurements will work using his/her language. The laboratory personnel must be convinced that the measurements are necessary, occasionally convinced that greater accuracy is required and that methods used are not giving results needed. Again, communication in their language must be effective. The software interaction is typically direct. However, the general nature of commercial simulators limits their effectiveness in particular situations. Occasionally, modifications are required. The software engineer is not familiar with the process and likely cannot be made aware because of proprietary considerations. This impedes communication. Finally, control engineers have been successful in establishing a control scheme which for all appearances works. Modifying the performance implies that they have not been as successful as appearances might indicate. While in all of these situations, teamwork should override these personnel considerations, it often doesn't. Consequently, communication is the paramount skill for plant-performance analysts.

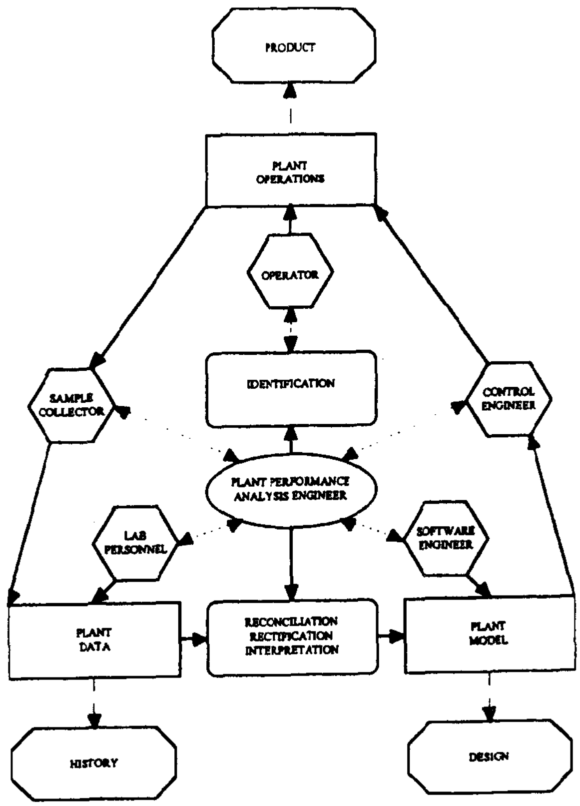

FIG. 30-4 Complete plant performance triangle including personnel interaction.

OVERALL GUIDELINES

There are four overall guidelines that analysts should keep in mind. They must recognize the difficulties associated with the limited number and accuracy of the data, overcome the plant operation mythologies, overcome the designers' and controllers' biases and, finally, override the analysts' own prejudices. The following four overall guidelines assist in overcoming the hurdles to proper plant performance.

First, any analysis must be coupled with a technically correct interpretation of the equipment performance soundly rooted in the fundamentals of mass, heat, and momentum transfer; rate processes; and thermodynamics. Pseudotechnical explanations must not be substituted for sound fundamentals. Even when the development of a relational model is the goal of the analysis, the fundamentals must be at the forefront.

Second, any analysis must recognize the nonlinearities of equipment capability. Model development must recognize that equipment fundamentals will affect conclusions and extrapolations. These boundaries and nonlinearities of equipment performance overlay the chemical engineering fundamentals and temper the conclusions.

Third, any analysis must recognize that the measurements have significant uncertainty, random and systematic. These affect any conclusions drawn and models developed. Multiple interpretations of the same set of measurements, describing them equally well, can lead to markedly different conclusions and, more significantly, extrapolations.

Fourth, communication is paramount, since successful analysis requires that those responsible for measurement, control, and operation are convinced that the conclusions drawn are technically correct and the recommended changes will enhance their performance. This is the most significant guideline in implementing the results of the analysis.

Analysis of plant performance has been practiced by countless engineers since the beginning of chemical-related processing. Nevertheless, there is no body of knowledge that has been assembled called "analysis of plant performance." The guidelines given herein are effective in plant-performance applications. There are many more practiced by others that are also effective and should be employed whenever the challenges arise. Therefore, the material discussed in this section is the initial point for analysis and should not be considered all-inclusive. The particular equipment, operations, and problems associated with any plant spawn a myriad of effective methods to approach analysis of plant performance. They should not be ignored in preference to material in this section but should be added to these to improve the accuracy of conclusions and the efficiency of approach.

PLANT-ANALYSIS PREPARATION

MOTIVATION

These are a few of the reasons to justify analysis of plant performance. Units come on-line too slowly or with extreme difficulty because heat exchangers cannot add or remove heat, venting is inadequate, or towers do not produce quality product. Units come on-line and do not meet nameplate capacity and/or quality. Unit efficiency, quality, and/or yield are below expectations because energy or catalyst usage appears too high, product compositions are below that required, or raw material usage is excessive. Unit safety is questioned because operation appears too close to equipment control limitations. Unit environmental specifications are unfulfilled. Unit operations have deteriorated from historical norms. Alternate feed stocks are available, but their advantages and disadvantages if fed to the unit are unknown. Product demand exceeds the apparent capacity of the unit requiring modifications in operating conditions, in equipment configuration, or in equipment size. Unit operation is stable, and understanding of the operation is desired.

Troubleshooting start-up, quality and capacity problems, detecting faults in deteriorating effectiveness or efficiency performance, unit modeling to examine alternate feed stocks and operating conditions, and debottlenecking to expand operations are all aspects of analysis of plant performance. Conclusions drawn from the analyses lead to piping and procedure modifications, altered operating conditions including setpoint modifications and improved designs. Analyzing plant performance and drawing accurate conclusions is one of the most difficult and challenging responsibilities of the chemical engineer (Gans, M., D. Kohan, and B. Palmer, "Systematize Troubleshooting Techniques," *Chemical Engineering Progress*, April 25–29, 1991). Measurements and data are incomplete and inaccurate. Identical symptoms come from different causes. Aspects of unit response are not readily quantified and modeled, requiring inductive, investigative reasoning. According to Gans et al. (1991), 75 percent of all plant problems are due to unidentified, inefficient plant performance ultimately traced to simple equipment problems and limitations. Another 20 percent are due to inadequate design such as those encountered in startup and quality/quantity limitations. The remainder is due to a process failure. The goal of the plant-performance analyst is to identify correctly the problems and the opportunities for changes and to quantify the potential improvements.

The opportunities leading to false conclusions and inadequate recommendations are extreme. The probability of successful completion of analysis of plant performance is greatly enhanced if the preparatory work is complete. Analysts must define the detail of study required. Analysts must understand the operation of the unit. This includes the chemical engineering fundamentals and the operator's perspective and control response. Analysts must understand historical unit performance, developing a model commensurate with the measurements available and the detail of study required. Should a unit test, short-cut or exhaustive, be required, the unit personnel must understand the goals and their responsibilities. The laboratory must be prepared to handle the overload of samples that may be necessary and be able to produce data of required quality. Personnel and the supporting supplies must be available to make measurements, gather samples, and solve problems during the course of the test.

The purpose of this section is to provide guidelines for this preparation. General aspects are covered. Preparations for the specific units can be drawn from these. Topics include analyst, model, plant, and laboratory preparation. Since no individual analyst can be responsible for all of these activities, communication with other personnel is paramount for the success of the analysis.

ANALYST PREPARATION

Analysts must have a strong foundation in plant operations and in the unit under study. The hurdles thrown at analysts increase the probability that the conclusions drawn will be incorrect. A lack of understanding in the operation of the unit increases the likelihood that the conclusions will be inaccurate. An understanding of the chemical engineering fundamentals, the equipment flowsheets, the equipment plot, the operators' understanding and interpretations, and the operators' control decisions is essential to minimize the likelihood for drawing false conclusions. Reaching this understanding prior to undertaking a unit test and the measurement interpretation will increase the success and efficiency of the analysis.

The analyst must necessarily rely on the expertise and efforts of others to operate, gather, and analyze samples and record (automatically or manually) readings. Communication of the goals, measurement requirements, and outcome to all involved is critical. It is imperative that all involved understand their responsibilities, the use of the information that they gather, and the goals of the test.

Measurement locations and methods may be different from those used daily. Analysts and the sample-gatherers must be intimately familiar with the locations, difficulties, and methods. Analysts must ensure that the methods are safe, that the locations are as indicated on the flow sheets, and that the sample-gatherers will be able to safely obtain the necessary samples.

Process Familiarization The analysts' first step in preparation for analyzing plant performance is to become completely familiar with the process. Analysts should review:

- Process flow diagrams (PFDs)
- Operating instructions and time-sequence diagrams
- Piping and instrumentation diagrams (P&IDs)
- Unit installation
- Operator perspectives, foci, and responses

The review should emphasize developing an understanding of the processing sequence, the equipment, the equipment plot, the operating conditions, instrument and sample locations, the control decisions, and the operators' perspectives. While the preparation effort may be less for those who have been responsible for the unit for a long period of time, the purpose of the test requires that the types and locations of the measurements be different from those typically recorded and typically used. The condition of these locations must be inspected. Operating specifications may be different. Therefore, refreshment is always necessary.

The intensity of the situation requiring the analysis may not allow analysts to develop a formal preparatory review of the unit as described below. Analysts must recognize that the incomplete preparation may result in a less efficient analysis of plant performance.

PFDs (process flow diagrams) display the processing sequence for the unit, the principal pieces of equipment in the unit, and the operating conditions and control scheme. The equipment sequence should represent the sequence found in the unit. The operating conditions shown on the flow sheet may be those envisioned by the designer and may not properly reflect the current conditions. These should be verified during the subsequent discussions with operators and studied through review of the shift and daily logs. Where differences are substantial, these need to be understood, as they may indicate that operating philosophy has changed significantly from that proposed by the designers. It is particularly important to verify that the control scheme represents the current control philosophy. The purpose of each piece of equipment must be understood. This understanding should include understanding of key components, temperature specifications, elapsed time constraints, and the like. The basis of the operating conditions must be understood with respect to these constraints. The PFD review is completed by developing a material balance of sufficient detail for analysts to understand the reactions and separations.

Operating instructions and time-sequence diagrams provide insight into the basis for the operating conditions. They will also provide a foundation for the subsequent discussion with operators. The time sequence diagrams may provide insight into any difficulties that will arise during the unit test.

P&IDs (piping and instrumentation diagrams) should identify instruments, sample locations, the presence of sample valves, nozzle blinding, and control points. Of particular importance are the bypasses and alternate feed locations. The isolation valves in these lines may leak and can distort the interpretation of the measurements.

Understanding the positions of sample and other measurement locations within the equipment is also important. The presence or absence of isolation valves needs to be identified. While isolation valves may be too large for effective sampling, their absence will require that pipe fitters add them such that sample valves can be connected. This must be done in advance of any test. If analysts assume that samples are from a liquid stream when they are vapor or that temperature measurements are within a bed instead of outside it, interpretation of results could be corrupted. Analysts should also develop an understanding of control transmitters and stations. The connection between these two may be difficult to identify at this level in fully computer-controlled units.

Unit layout as installed is the next step of preparation. This may take some effort if analysts have not been involved with the unit prior to the plant-performance analysis. The equipment in the plant should correspond to that shown on the PFDs and P&IDs. Where differences are found, analysts must seek explanations. While a line-by-line trace is not required, details of the equipment installation and condition must be understood. It is particularly useful to correlate the sample and measurement locations and the bypasses shown on the P&IDs to those actually piped in the unit. Gas vents and liquid (particularly water-phase) discharges may have been added to the unit based on operating experience but not shown on the P&IDs. While these flows may ultimately be small within the context of plant-performance analysis, they may have sufficient impact to alter conclusions regarding trace component flows, particularly those that have a tendency to build in a process.

Discussion with operators provide substantial insight. The purpose of the discussion should be to develop an understanding of operators' perspectives of the unit, their foci for the operation, and their decision sequence in response to deviations and off-specification products. Two additional, albeit nontechnical, goals of this discussion are to establish rapport with the operators and to learn their language. The operators will ultimately be required to implement recommendations developed by analysts. Their confidence is essential to increase the likelihood of success. The following topics should be included in the discussion.

The operators have been given instructions on unit operation. Most of these are written and should have been studied prior to the meeting. Others may be verbal or implied. While this is not optimal, verbal instructions and operating experience are still part of every unit. It is not unusual that different shifts will have different operation methods. While none of the shift operations may be incorrect, they do lead to variability in operation and different performance. "What-if" questions posed to the operators can lead to insight into operator response. This will lead to analysts gaining better understanding of the unit (Block, S.R., "Improve Quality with Statistical Process Control," *Chemical Engineering Progress*, November 1990, 38–43). The discussion with the operators must provide insight into their view of the unit operation, their focus on the operation, and their understanding of equipment limitations.

One topic of discussion is the measurements to which the operators pay the most attention (their foci). Of the myriad of measurements, there is a limited set that they find most important. These are the measurements that they use to make the short-cycle decisions. The important points to glean are the reasons they focus on these, the values and trends that they expect, and their responses to the deviations from these.

With respect to their response, the discussion should emphasize why these are important and why they adjust certain control settings. Among the deviations on which analysts should focus the discussion are the high and low alarm settings. Some alarms will require rapid response. Alarms may give insight into equipment-operation boundaries as well as process constraints.

Operators typically have long cycle measurements upon which they focus. These may be part of morning reports giving production rates, compositions, yields, and so on. They may also have some recorded measurements that they examine once per shift. Analysts should understand the importance that the operators place on these measurements and the operators' responses to them.

Analysts are typically not totally prepared to discuss the purpose of the impending test at this meeting. Therefore, this topic may be premature. There is typically a sequence of meetings between operators and analysts. The information flow in the first is typically from the operators to analysts as analysts develop their understanding and learn to communicate in the operators' language. After the analysts study the process further based on the first meeting and preliminary simulations of the unit, another meeting is useful to test the analysts' understanding and communication methods. A third meeting to discuss the impending test purpose, focus, measurements, and procedures completes this phase of the preparation.

Data Acquisition As part of the understanding, the measurements that can be taken must be understood. A useful procedure to prepare for this is to develop a tag sheet for the process (Lieberman, N.P., *Troubleshooting Refinery Processes*, PennWell Books, Tulsa, 1981, 360 pp). An example of a simplified sheet is given in Fig. 30-5.

This sheet will be used ultimately to record readings during the

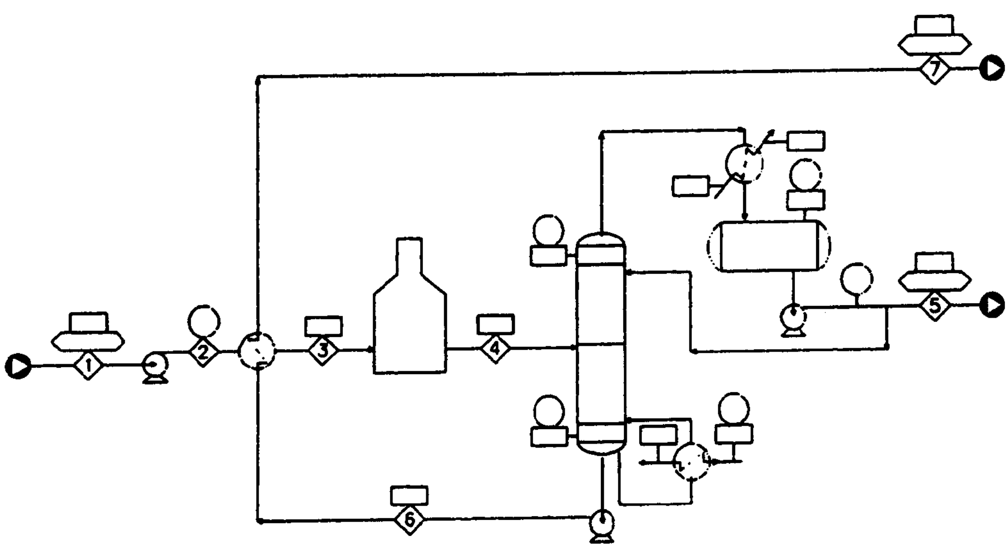

FIG. 30-5 Simplified tag-sheet for a distillation process.

plant test. It will help to develop a consistent set of measurements for the plant and help validate the measurements (identify inconsistencies). At this stage, however, it gives the analyst a visual representation of what measurements can be made. If there are sample locations, these must be added. Also, differential pressure measurements, additional flows, and utilities can be added as the unit instrumentation allows and as identified as being important during the identification step. Since identification has not been completed at this point, the measurements shown on these sheets are the ones already available on the board and in the field. The tag sheet also provides a visual point for discussion with the operators to confirm that certain measurements are made or can be made.

As part of this step, the analyst needs to develop an understanding of the uncertainty in the measurements and typical fluctuations experienced in daily operation. The uncertainties are functions of the instruments and their condition. Qualitatively, dial thermometers are less certain than thermocouples. On-line analyzers tend to be less accurate than lab analyses (assuming that the sample-gathering methodology is correct). Readings using different pressure gauges are less reliable than readings using a single pressure gauge. These random errors may be negligible in a unit that exhibits large fluctuations. The relative importance of plant fluctuations and random measurement error should be established. Multiple, rapid readings, control samples, or confirming measurements with other instruments will help establish the measurement uncertainty. Operating data will provide insight into the plant fluctuations, which can then be compared to the instrument uncertainty.

Operators frequently have insight into which instruments are accurate and which are not. If those instruments subsequently prove critical, recalibration must be done prior to the unit test. Preliminary analysis of daily measurements and practice measurements will help to identify which are suspect and require instrument recalibration prior to the unit test.

Analysts should discuss sample-collection methods with those responsible. Frequently, the methods result in biased data due to venting, failure to blow down the sample lines, and contamination. These are limitations that must either be corrected or accepted and understood. Sampling must be conducted within the safety procedures established for the unit. Since samples may be hot, toxic, or reactive in the presence of oxygen, the sample gatherers must be aware of and implement the safety procedures of the unit.

Material Balance Constraint There are two types of constraints for the unit. These are the process constraints and the equipment constraints. In each of these, there are equality constraints such as material balances and inequality constraints such as temperature limits. Analysts must understand the process and equipment constraints as part of the preparation for the unit analysis.

The most important of the process constraints is the material balance. No test or analysis can be completed with any degree of certainty without an accurate material balance. The material balance developed during this preparation stage provides the foundation for the analysts' understanding of the unit and provides an organizational tool for measurement identification. Analysts should develop a material balance for the process based on typical operating measurements. This can be compared to the design material balance. Estimates of tower splits, reactor conversions, elapsed times, and stream divisions help to identify the operating intent of the unit. Analysts must focus on trace as well as major components. The trace components will typically provide the most insight into the operation of the unit, particularly the separation trains.

During this preparation stage, analysts will frequently find that there is insufficient quantity or quality of measurements to close the material balance. Analysts should make every effort to measure all stream flows and compositions for the actual test. They should not rely upon closing material balances by back-calculating missing streams. The material balance closure will provide a check on the validity of the measurements. This preparatory material balance will help to identify additional measurements and schedule the installation of the additional instruments.

A typical material-balance table listing the principal components or boiling ranges in the process as a function of the stream location should be the result of this preliminary analysis. An example shown as a spreadsheet is given in the validation discussion (Fig. 30-18).

Energy Balance Many of the principal operating problems found in a plant result from energy-transfer problems such as fouled or blanketed exchangers, coked furnaces, and exchanger leaks. Consequently, developing a preliminary energy balance is a necessary part of developing an understanding of the unit. A useful result of the energy-balance analysis is the identification of redundant measurements that provide methods to obtain two estimates for unit performance. For example, reflux-flow and steam-flow measurements provide two routes to identifying heat input to a tower. These redundant measurements are very useful; both should be taken to provide the redundancy, and one or the other should not be ignored.

The material balance table can be supplemented with temperatures, pressures, phases, and stream enthalpies (or internal energies). Utility flows and conditions should be added to the process information.

Other Process Constraints Typical of these constraints are composition requirements, process temperature limits, desired recoveries, and yields. These are frequently the focus of operators. Violation of these constraints and an inability to set operating conditions that meet these constraints are frequently the motivation for the unit analysis.

Equipment Constraints These are the physical constraints for individual pieces of equipment within a unit. Examples of these are flooding and weeping limits in distillation towers, specific pump curves, heat exchanger areas and configurations, and reactor volume limits. Equipment constraints may be imposed when the operation of two pieces of equipment within the unit work together to maintain safety, efficiency, or quality. An example of this is the temperature constraint imposed on reactors beyond which heat removal is less than heat generation, leading to the potential of a runaway. While this temperature could be interpreted as a process constraint, it is due to the equipment limitations that the temperature is set.

Developing an understanding of these constraints provides further insight into unit operation.

Database The database consists of physical property constants and correlations, pure component and mixture, that are necessary for the proper understanding of the operation of the unit. Examples of the former are molecular weights, boiling curves, and critical properties. Example pure-property correlations are densities versus temperature, vapor pressures versus temperature, and enthalpies versus temperature and pressure. Example mixture-property correlations are phase equilibria versus composition, temperature, and pressure; kinetic rate constants versus temperature; and interfacial tension versus composition and temperature. While the material balance can be developed without most of these, the energy balance and any subsequent model cannot. Therefore, an accurate database is critical to accurate understanding of plant operation. Very often, unit model parameters will interact with database parameters. The most notable example is the distillation tower efficiency and the phase equilibria constants. If the database is inaccurate, the efficiency estimate will also be inaccurate. Therefore, whenever the goal of the unit analysis is to develop a model for operation and design, care must be taken to minimize errors in the database that can affect the accuracy of the model parameters. Inaccurate models cannot be used for sensitivity studies or extrapolation to other operating conditions.

Analysts should not rely on databases developed by others unless citations and regression results are available. Many improper conclusions have been drawn when analysts have relied upon the databases supplied with commercial simulators. While they may be accurate in the temperature, pressure, or composition range upon which they were developed, there is no guarantee that they are accurate for the unit conditions in question. Pure component and mixture correlations should be developed for the conditions experienced in the plant. The set of database parameters must be internally consistent (e.g., mixture-phase equilibria parameters based on the pure-component vapor pressures that will be used in the analysis). This ensures a consistent set of database parameters.

It is not unusual for 30–40 percent of the process design effort to be spent in developing a new database. The amount of time required at this stage in the analysis of plant performance for analysis of the unit should be equivalent. The amount of effort devoted to database development becomes more intensive as the interaction between the model parameters and the database increases.

PLANT MODEL PREPARATION

Focus For the purposes of this discussion, a model is a mathematical representation of the unit. The purpose of the model is to tie operating specifications and unit input to the products. A model can be used for troubleshooting, fault detection, control, and design. Development and refinement of the unit model is one of the principal results of analysis of plant performance. There are two broad model classifications.

The first is the relational model. Examples are linear (i.e., models linear in the parameters and neural network models). The model output is related to the input and specifications using empirical relations bearing no physical relation to the actual chemical process. These models give trends in the output as the input and specifications change. Actual unit performance and model predictions may not be very close. Relational models are useful as interpolating tools.

The second classification is the physical model. Examples are the rigorous modules found in chemical-process simulators. In sequential modular simulators, distillation and kinetic reactors are two important examples. Compared to relational models, physical models purport to represent the actual material, energy, equilibrium, and rate processes present in the unit. They rarely, however, include any equipment constraints as part of the model. Despite their complexity, adjustable parameters bearing some relation to theory (e.g., tray efficiency) are required such that the output is properly related to the input and specifications. These models provide more accurate predictions of output based on input and specifications. However, the interactions between the model parameters and database parameters compromise the relationships between input and output. The nonlinearities of equipment performance are not included and, consequently, significant extrapolations result in large errors. Despite their greater complexity, they should be considered to be approximate as well.

Preliminary models are required to identify significant measurements and the complexity of model required and to test the analysis methods that will be used during the unit analysis. Effort must be devoted during the preparation stage to develop these preliminary models.

It must be recognized that model building is not the only outcome of analysis of plant performance. Many troubleshooting activities do not require a formal mathematical model. Even in these circumstances, analysts have developed through preliminary effort or experience a mental model of the relation between specifications, input, and output that provides a framework for their understanding of the underlying chemical engineering. These mental models generally take longer to develop but can be more accurate than mathematical models.

Intended Use The intended use of the model sets the sophistication required. Relational models are adequate for control within narrow bands of setpoints. Physical models are required for fault detection and design. Even when relational models are used, they are frequently developed by repeated simulations using physical models. Further, artificial neural-network models used in analysis of plant performance including gross error detection are in their infancy. Readers are referred to the work of Himmelblau for these developments. [For example, see Terry and Himmelblau (1993) cited in the reference list.] Process simulators are in wide use and readily available to engineers. Consequently, the emphasis of this section is to develop a preliminary physical model representing the unit.

Required Sensitivity This is difficult to establish *a priori*. It is important to recognize that no matter the sophistication, the model will not be an absolute representation of the unit. The confidence in the model is compromised by the parameter estimates that, in theory, represent a limitation in the equipment performance but actually embody a host of limitations. Three principal limitations affecting the accuracy of model parameters are:

- Interaction between database and model parameters
- Interaction between measurement error and model parameters
- Interaction between model and model parameters

Three examples are discussed.

Tray efficiency is one example of the first interaction. Figure 30-6 is a representation of a distillation tray.

Defining tray efficiency as the difference between the actual and the equilibrium vaporization, the efficiency is:

$$\theta_{i,j} = \frac{y_{i,j} - x_{i,j}}{y^*_{i,j} - x_{i,j}}$$

where $$y^*_{i,j} = K_{i,j} x_{i,j}$$

Tray efficiency $\theta_{i,j}$ is supposed to represent a measure of the deviation from equilibrium-stage mass transfer assuming backmixed trays. However, the estimate of tray efficiency requires accurate knowledge of the equilibrium vaporization constant. Any deviations between the actual equilibrium relation and that predicted by the database will be embodied in the tray efficiency estimate. It is a tender trap to accept tray efficiency as a true measure of the mass transfer limitations when, in fact, it embodies the uncertainties in the database as well.

As another example of the first interaction, a potential parameter in the analysis of the CSTR is estimating the actual reactor volume. CSTR shown in Fig. 30-7. The steady-state material balance for this CSTR having a single reaction can be represented as:

$$0 = X_{i,1} - X_{i,2} - V_r k f(\bar{X}_2, S_2, \rho_2)$$

where X_i is the flow of component i, V_r is the reactor volume, k is the rate constant at the reactor temperature, $\bar{X}_2$ is the vector of component flows in stream 2, S_2 is the stream-2 flow, and ρ_2 is the stream-2 density. Any effort to estimate the reactor volume and therefore also the volume efficiency of the reactor depends upon the database estimate of the rate constant. Any errors in the rate constant will result in errors in the reactor volume estimate. Extrapolations to other operating conditions will likely be erroneous. Estimating the rate constant based on reactor volume will have the same difficulties.

The second interaction results in compromised accuracy in the parameter estimate due to the physical limitations of the process as

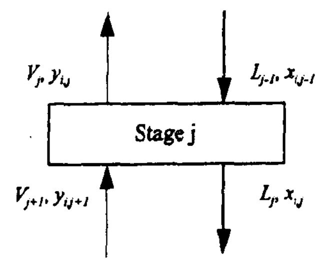

FIG. 30-6 Representation of a distillation tray numbering from the top of the column.

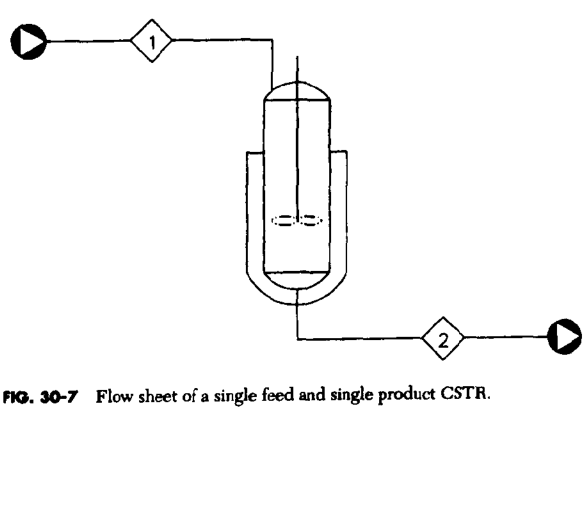

FIG. 30-7 Flow sheet of a single feed and single product CSTR.

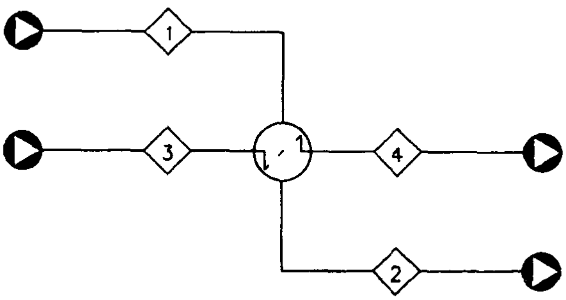

FIG. 30-8 *PFD of Shell and tube heat exchanger.*

embodied in the measurement uncertainties. Figure 30-8 shows a simple shell and tube heat exchanger. Many plant problems trace back to heat-transfer-equipment problems. Analysts may then be interested in estimating the heat-transfer coefficient for the heat exchanger to compare to design operation. However, this estimation is compromised when stream temperature changes are small, amplifying the effect of errors in the heat-transfer estimation. For example, the heat transfer could be calculated from the energy balance for Stream 1.

$$Q = S_1 C_p (T_2 - T_1)$$

The error in estimating the temperature difference is

$$\sigma_{\Delta T} = \sqrt{2}\sigma_T$$

The percentage error in the temperature difference translates directly to the percentage error in the estimate Q. As temperature-measurement error increases, so does the heat transfer coefficient error.

The third interaction compromising the parameter estimate is due to bias in the model. If noncondensables blanket a section of the exchanger such that no heat transfer occurs in that section, the estimated heat-transfer coefficient based on a model assuming all of the area is available will be erroneous.

The first two examples show that the interaction of the model parameters and database parameters can lead to inaccurate estimates of the model parameters. Any use of the model outside the operating conditions (temperature, pressures, compositions, etc.) upon which the estimates are based will lead to errors in the extrapolation. These model parameters are effectively no more than adjustable parameters such as those obtained in linear regression analysis. More complicated models may have more subtle interactions. Despite the parameter ties to theory, they embody not only the uncertainties in the plant data but also the uncertainties in the database.

The third example shows how the uncertainties in plant measurements compromise the model parameter estimates. Minimal temperature differences, very low conversions, and limited separations are all instances where errors in the measurements will have a greater impact on the parameter estimate.

The fourth example shows how improper model development will lead to erroneous parameter estimates. Assuming that the equipment performs in one regime and developing a model based on that assumption could lead to erroneous values of model parameters. While these values may imply model error, more often the estimates appear reasonable, giving no indication that the model does not represent the unit. More complicated examples like the kind given by Sprague and Roy (1990) emphasize the importance of the accuracy of the underlying model in parameter estimation, troubleshooting, and fault detection. In these situations, the model may describe the current operation reasonably well but will not actually describe the unit operation at other operating conditions.

Preliminary Analysis The purpose of the preliminary analyses is to develop estimates for the model parameter values and to establish the model sensitivity to the underlying database and plant and model uncertainties. This will establish whether the unit test will actually achieve the desired results.

The model parameter estimation follows the methods given in the interpretation subsection of this chapter. Analysts acquire plant measurements, adjust them to close the important constraints including the material and energy balances and then through repeated simulations, adjust parameter values to obtain a best description of the adjusted measurements. Not only does this preliminary analysis provide insight into the suitability of the model but also it tests the analysis procedures. The primary emphasis at this stage should be on developing preliminary parameter estimates with less emphasis on rigorously developing the measurement error analysis.

Once the model parameters have been estimated, analysts should perform a sensitivity analysis to establish the uniqueness of the parameters and the model. Figure 30-9 presents a procedure for performing this sensitivity analysis. If the model will ultimately be used for exploration of other operating conditions, analysts should use the results of the sensitivity analysis to establish the error in extrapolation that will result from database/model interactions, database uncertainties, plant fluctuations, and alternative models. These sensitivity analyses and subsequent extrapolations will assist analysts in determining whether the results of the unit test will lead to results suitable for the intended purpose.

PLANT PREPARATION

Intent Plant personnel, supplies, and budget are required to successfully complete a unit test. Piping modifications, sample collection, altered operating conditions, and operation during the test require advance planning and scheduling. Analysts must ensure that these are accomplished prior to the actual test. Some or all of the following may be necessary for a successful unit test.

Communication Analysts will require the cooperation of the

- Unit operators
- Unit supervisors
- Plant management
- Maintenance personnel
- Laboratory personnel

Operators are primarily concerned with stable operation and may be leery of altering the operation; they may fear that operation will drift into a region that cannot be controlled. Supervision may be reluctant despite their recognizing that a problem exists: Any deficiencies with the operation or operating decisions is their responsibility. Permission for conducting the test from the supervisor and the operators will be required. Management cooperation will be required, particularly if capital is ultimately needed. Maintenance will be called upon to make modifications to sample locations and perform a sequential pressure measurement. The laboratory personnel, discussed in detail in the next subsection, may view the unit test as an overload to available resources. These concerns must be addressed to ensure accurate sample interpretation.

Permission Analysts must have the permission of the operators and the supervisors to conduct even the most straightforward tests. While this is part of the analysts' preparation, it is important for all involved to know that analysts have that permission.

Schedule Complex tests should be done over a period of days. This provides the opportunity for the unit to be nearly steady. The advantages are that confirming measurements can be made. Scheduling a multiday test should be done when there is a likelihood that the feed stock supply and conditions will be nearly constant. The cooperation of upstream units will be required. The multiday test also requires that the downstream units can take the unit products.

The schedule should be set well in advance so that support services can provide the necessary personnel and supplies.

Simpler tests will not require this amount of time. However, they should be scheduled to minimize disruption to normal operations.

Piping Modifications One result of the inspection of the sample locations is a list of sample locations that will require modifications. The mechanical department will be required to make these modifications before the unit test is run. It is likely that the locations that are not typically used will be plugged with debris. The plugs will have to be drilled out before the test begins. Drilling out plugs presents a safety hazard, and those involved must be aware of this and follow the plant safety protocols.

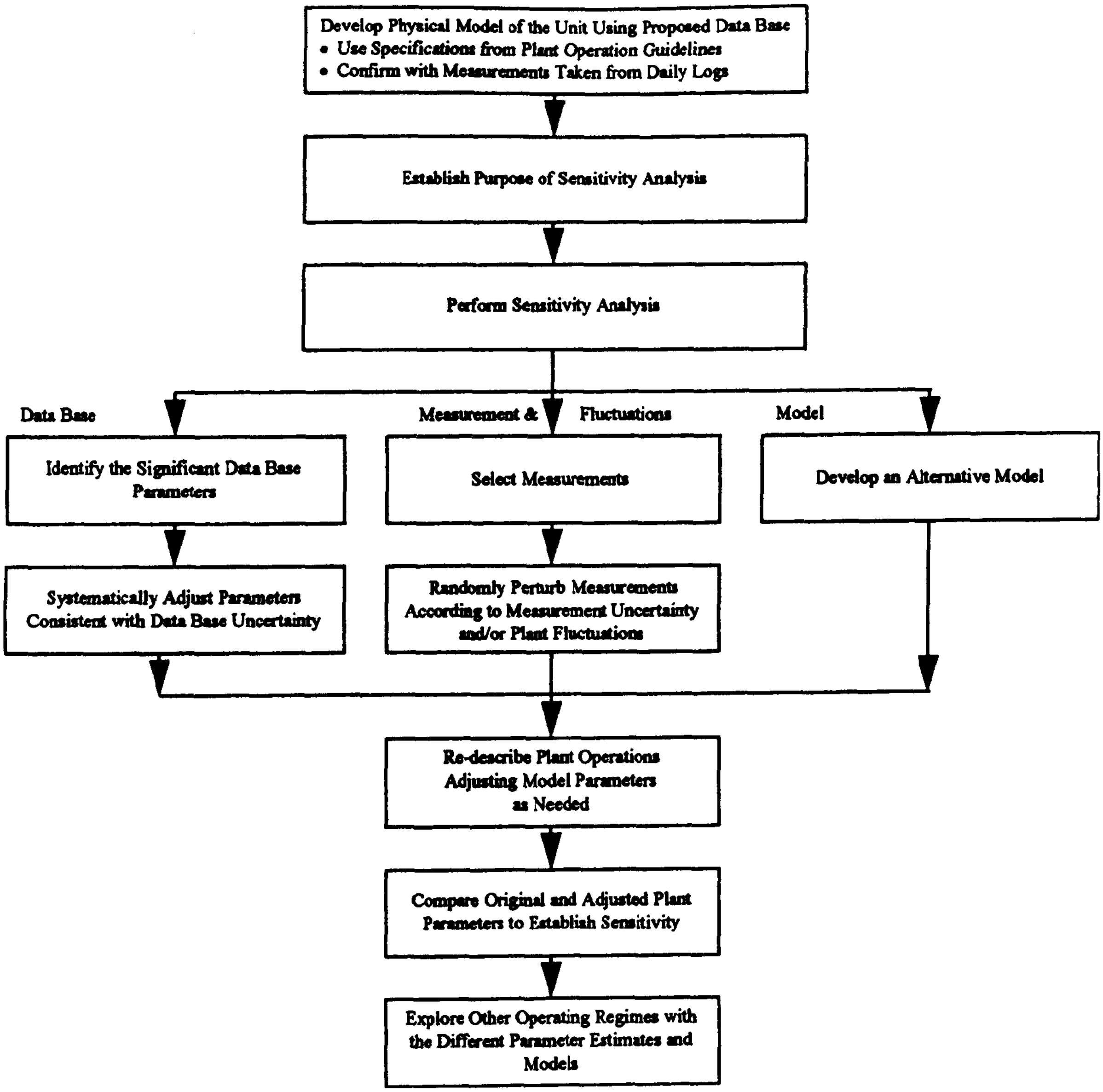

FIG. 30-9 Logic diagram for plant sensitivity analysis.

Instrumentation Calibration may be required for the instruments installed in the field. This is typically the job of an instrument mechanic. Orifice plates should be inspected for physical condition and suitability. Where necessary, they should be replaced. Pressure and flow instruments should be zeroed. A preliminary material balance developed as part of the preliminary test will assist in identifying flow meters that provide erroneous measurements and indicating missing flow-measurement points.

When doing a hydraulic test, a single pressure gauge should be used and moved from location to location. This gauge must be obtained in advance. The locations where this pressure will be measured should be tagged to assist the pipe fitter who will be responsible for moving the gauge from location to location. A walk-through with the pipe fitter responsible can be instructive for both the analysts and the fitter.

Thermocouples tend to be reliable, but dial thermometers may need to be pulled and verified for accuracy.

Sample Containers More sample containers will be required for a complex test than are typically used for normal operation. The number and type of sample containers must be gathered in advance, recognizing the number of measurements that will be required. The sample containers should be tagged for the sample location, type, and conditions.

Field Measurement Conditions Those gathering samples must be aware of the temperature, pressure, flammability, and toxic characteristics of the samples for which they will be responsible. This is particularly important when samples are taken from unfamiliar locations. Sample ports will have to be blown down to obtain representative samples. Liquid samples will have to be vented. Temperatures above

330 K (140° F) can cause burns. Pressures above atmospheric will result in flashing upon pressure reduction during venting. Venting to unplug the sample port and the sample bomb must be done properly to minimize exposure. A walk-through may be useful so that sample-gatherers are familiar with the actual location for the sample.

Operating Guidelines The test protocol should be developed in consultation with the principal operators and supervisor. Their cooperation and understanding are required for the test to be successful. Once the protocol is approved, analysts should distribute an approved one-page summary of the test protocol to the operators. This should include a concise statement of the purpose of the test, the duration of the test, the operating conditions, and the measurements to be made. The supervisor for the unit should initial the test protocol. Attached to this statement should be the tag sheet that will be used to record measurements.

Upstream and Downstream Units Upstream and downstream units should be notified of the impending test. If the unit test will last over a period of days, analysts should discuss this with the upstream unit to ensure that they are not scheduling activities that could disrupt feed to the unit under study. Analysts should seek the cooperation of the upstream units by requesting as consistent feed as possible. The downstream units should also be notified to ensure that they will be able to absorb the product from the unit under study. For both units, measurements from their instruments will be useful to confirm those for the unit under study. If this is the case, analysts must work with those operators and supervisors to ensure that the measurements are made.

Preliminary Test Operation of the unit should be set at the test protocol conditions. A preliminary set of samples should be taken to identify problems with instruments, measurements, and sample locations. This preliminary set of measurements should also be analyzed in the same manner that the full-test results will be analyzed to ensure that the measurements will lead to the desired results. Modifications to the test protocol can be made prior to exerting the effort and resources necessary for the complete test.

LABORATORY PREPARATION

Communication Laboratory services are typically dedicated to supporting the daily operation of the unit under study as well as other units in the plant. Their purpose is the routine confirmation that the unit is running properly and the determination of the quality of feed stocks. Laboratory staffing is normally set based on these routine service requirements. Consequently, whenever a plant test is conducted to address deterioration in efficiency, yield, or specifications or to develop a unit model, the additional samples required to support the test, place laboratory services in overload (Gans, M., and B. Palmer, "Take Charge of Your Plant Laboratory," *Chemical Engineering Progress*, September 1993, 26–33). If the laboratory cannot handle the analysis quickly, the likelihood of the samples reacting, leaking, or being lost markedly increases with subsequent deterioration in the accuracy of the conclusions to be drawn from the test. Therefore, adequate laboratory personnel must be accounted for early in the preparation process.

Plant-performance analysts must understand:

- Laboratory limitations
- Laboratory organization
- Laboratory measurement uncertainties
- Measurement cost
- Additional personnel requirements

The laboratory supervision and personnel must supply this information so that analysts gain this understanding.

Laboratory supervision and personnel must understand:

- Type of samples required
- Level of detail, accuracy, and precision of the samples
- Flammability, toxicity, and conditions of samples
- Anticipated schedule and duration of the test
- Justification for the overload assignments

Analysts provide this information.

The laboratory may need time to prepare for the unit test. This must be accounted for when the test is scheduled. The analysis of samples required for the unit test may focus on different composition ranges and different components than those done on a routine basis. Laboratory personnel may need to modify their methods or instruments to attain the required level of accuracy and detail. The modification, testing, and verification of the methods are essential parts of the preparation process. A practice run of gathering samples will help identify any deficiencies in the sample handling, storage, and analyses.

Without forethought, planning, and team-building, the sample analyses during the unit test may be delayed, lost, or inaccurate. The laboratory is an essential part of the unit test and must be recognized as such.

Confidence The accuracy of the conclusions drawn from any unit test depends upon the accuracy of the laboratory analyses. Plant-performance analysts must have confidence in these analyses including understanding the methodology and the limitations. This confidence is established through discussion, analyses of known mixtures, and analysis of past laboratory results. This confidence is established during the preparation stage.

Discussing the laboratory procedures with the personnel is paramount. Routine laboratory results may focus on certain components or composition ranges in the sample. The routine analyses narrow the laboratory personnel's outlook. The succinct and often misleading daily logs are the result of this focus. Analysts who have little daily interaction with the laboratory and plant may interpret daily results differently than intended. A typical example is laboratory analyses of complex streams where components are often grouped and identified as a single component. Consequently, important trace components are unanalyzed or masked. The impending plant test may require that these components be identified and quantified. The masking in the routine results can only be identified through discussion.

Even within a single sample analysis, it is likely that some of the reported concentrations are known with greater accuracy than others. Laboratory personnel will know which concentrations can be relied upon and which should be questioned. The plant-performance analyst should know at this stage which of the concentrations are of greatest importance and direct the discussion to those components.

Should the additional component compositions be required to fully understand the unit operation, the laboratory may have to develop new analysis procedures. These must be tested and practiced to establish reliability and minimize bias. Analysts must submit known samples to verify the accuracy.

Known samples should also be run to verify the accuracy and precision of the routine methods to be used during the unit test. Poor quality will manifest itself as poor precision, measurements inconsistent with plant experience or laboratory history, and disagreement among methods. Plotting of laboratory analysis trends will help to determine whether calibrations are drifting with time or changing significantly. Repeated laboratory analyses will establish the confidence that can be placed in the results.

If the random errors are higher than can be tolerated to meet the goals of the test, the errors can be compensated for with replicate measurements and a commensurate increase in the laboratory resources. Measurement bias can be identified through submission and analysis of known samples. Establishing and justifying the precision and accuracy required by the laboratory is a necessary part of establishing confidence.

Sampling Despite all of the preparation inside the laboratory, by far the greatest impact on successful measurements is the accuracy of the sampling methods. The number of sample points for a unit test are typically greater than the number required for routine sampling. It is likely that some of the sample locations, characteristics, and properties are unfamiliar to the sample-gatherers responsible for the routine ones. This unfamiliarity could lead to improper sampling, such that samples are not representative of the unit, and accidents, such that the sample gatherers are placed at risk. Part of the preparation process is to reduce this unfamiliarity to ensure safety and accuracy. The safety of the sample-gatherers is paramount and should not be compromised. Proper sampling methods accounting for volatility, flash points, toxicity, corrosivity, and reactivity should be written down for each plant and unit within the plant. The methodology must be understood and practiced.