Pioneer Plants Study User's Manual

R. E. Horvath

35th Year Rand

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PREFACE

This manual is the latest of a series of reports growing out of Rand's Pioneer Plants Study, which began in 1978. The research on which the manual is based is summarized in R-2569-DOE, *Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants*, by E. W. Merrow, K. E. Phillips, and C. W. Myers, September 1981. The research was conducted for the U.S. Department of Energy under contract DE-AC01-79PE70078; the Office of Defense Waste and Byproducts of the Department of Energy supported this effort.

The Pioneer Plants Study sought a better understanding of the reasons for inaccurate estimates of capital costs and performance difficulties for first-of-a-kind process plants. It found that cost growth was generally higher for plants that introduced new technology and for plants that were not well defined. Similarly, poorer plant performance was found to be associated with new technology. The purpose of the present manual is to explain in detail what information a potential user of the Pioneer Plants Study needs to apply the results of that study correctly.

SUMMARY

This manual supplies the material needed to apply the results of the Pioneer Plants Study analysis. It is a companion piece to *Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants*. Members of both private industry and government could find this manual a useful tool in predicting the cost growth and performance of first-of-a-kind process plants.

The Pioneer Plants Study was a statistical analysis of 44 pioneer process plants that varied greatly in their individual characteristics. Despite the diversity, clear patterns emerged with respect to cost and performance. In particular, we found that capital costs are normally underestimated for pioneer process plants, and that this misestimation is strongly related to the degree of technical innovation in the plant and the level of project information. By project information we mean information specific to that particular project—such as the site and environmental regulations—rather than to the technology. We also found that plant performance, as expressed as a percent of design capacity, is generally overestimated, and is strongly related to the technological innovation of the plant. Furthermore, we learned that both these misestimations can be corrected somewhat by information available early on in a project's life: the percent of investment in new equipment, the degree of impurity problems in R&D, plant complexity, project definition, the level of process development, the completeness of the estimate, the number of new steps, knowledge of heat and mass balance equations, the degree of waste handling problems in R&D, and whether the plant handles solids.

The results of the Pioneer Plants Study are summarized by two equations, one for cost misestimation and one for plant performance. This manual defines each of the above areas of information and demonstrates how they can be quantified for insertion into the equations. We use an actual waste facility as an example. Sufficient instructions are given to permit the user to repeat the procedure using a plant of his or her choice. The information required can be obtained through interviews with the project manager for that particular plant. The results of the equations are expressed in terms of a confidence interval. An example of a sensitivity analysis shows the reader how to cope with uncertainty about the equation inputs.

ACKNOWLEDGMENTS

I gratefully acknowledge the assistance of my Rand colleagues who carefully reviewed the draft versions of this manual to ensure accuracy. In particular, I thank Christopher Myers and Mary Vaiana. Myers thoroughly checked the technical information in the manual, and Vaiana patiently reorganized the chapters so that the manual would be of help to a user of the Pioneer Plants Study. I am also grateful to Susan Bodilly, Edward Merrow, and John Turner, who offered many helpful suggestions for improvement. Any remaining errors are my own.

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I. INTRODUCTION

THE AUDIENCE FOR THIS MANUAL

This manual is written for potential users of the Pioneer Plants Study.[1] As a report on research results, that document was intended primarily for policymakers; it focused on a conceptual discussion of cost and performance misestimation problems, the search for variables that explained those problems, and the data base used in the analysis. The goal of this manual is to enable an interested reader to gather the necessary project information, place a quantitative value on the terms of the Pioneer Plants Study equations, and estimate the expected cost growth and performance for a particular process plant project. It focuses on the variables that demonstrated an association with cost and performance misestimation, and leads the reader through an illustrative application of the Pioneer Plants Study results.

The audience for this manual includes diverse groups from both government and the private sector. Government analysts can use the manual to provide suggestions to policymakers by informing them about the implications of misestimation errors in cost growth and plant performance for specific sets of plants. Cost estimators in the private sector can use the manual to increase the accuracy of the plant cost and performance estimates that enter into their firms' decisions about investing in process plants.

In general, however, it will not be possible for a single individual in the government to use this manual to apply the results of the Pioneer Plants Study. The approach we suggest is to form an interdisciplinary team of government people to discuss the information required, collect the data, and then assign values to the equation inputs. Such a team would consist of an engineer (preferably a chemical engineer), an economist or cost analyst, and someone with skills in several fields. The engineer is needed for technical interpretation, the cost analyst for the cost figures and analysis, and the remaining person for synthesizing the diverse elements. The team will also find it necessary to contact a person who is knowledgeable about the development of the specific technology being examined.

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[1]See E. W. Merrow, K. E. Phillips, and C. W. Myers, *Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants,* The Rand Corporation, R-2569-DOE, September 1981.

This manual can profitably be used only after a thorough reading of the main report, *Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants*. It does not explain any of the statistical nuances of that study. To meet the needs of the manual's varied audience, we have avoided technical terms wherever possible and have provided examples of the information that must be gathered to apply the cost estimation error and plant performance equations of the Pioneer Plants Study.

BACKGROUND OF THE PIONEER PLANTS STUDY

The Pioneer Plants Study, begun in late 1978 and finished in late 1981, explored the phenomena of cost growth and performance shortfalls in first-of-a-kind process plants. Its results were based on a statistical analysis of 44 chemical process plants, which were characterized by over 900 data items. We solicited plants from a wide range of companies that represented a cross-section of firms in the process industries. A total of 34 companies in the chemical, oil, minerals, and architectural design-services industries provided the data. Most of the 44 plants were new at the time of the study, having started production between 1975 and 1981 at a total capital investment of $7.5 billion in 1980 dollars. All were built in the United States or Canada between 1966 and 1981. Most plants were represented by two or more cost estimates, ranging from early, conceptual estimates to ones prepared in late engineering and early construction. We arrived at the following major conclusions from that study:

- Capital costs are repeatedly underestimated for first-of-a-kind chemical process facilities. Furthermore, their performance typically falls short of what was predicted by designers and assumed in financial analyses.
- Greater than expected capital costs and performance shortfalls that are not anticipated by conventional estimating techniques can be explained by the characteristics of the particular technology and the amount of information incorporated into estimates at various points in project development.
- Most important from a planning viewpoint, the factors that account for poor cost estimates and poor performance can largely be identified early in the development of the technology, long before major expenditures have been made for detailed engineering and construction. If carefully applied, the statistical models developed here can provide reasonable, early predictions of plant cost and performance for a spec-

trum of advanced process plants, including energy process plants.

The results of the Pioneer Plants Study are summarized in two equations, one on cost misestimation and one on plant performance. The equations were derived using "multiple regression," a mathematical technique that shows how well certain items explain a phenomenon. In the Pioneer Plants Study, we statistically examined the relationship between cost misestimation and plant performance, using a variety of characteristics of the plants in our data base. We tested combinations of characteristics (or variables) until we found the set that made the most sense and gave us the best estimation of the actual values for cost growth and performance. It is important to understand that the variables do not explain cost growth or performance in any direct sense, because any given variable may incorporate the effects of several other factors.[2] But these variables, measured in the ways we will explain in this manual, do the best job of prediction. The user of this manual can use those same variables to predict cost misestimation performance for his plant as long as the values for those variables fall within the universe of the Pioneer Plants Study data base.

In the Pioneer Plants analysis, we define the terms "cost misestimation" and "plant performance" as follows. Cost misestimation is the phenomenon of inaccurate capital cost estimates for process plants. We found an almost universal tendency to understate the ultimate capital costs of a plant. Plant performance refers to the closeness of the match between a plant's designed production and its actual capacity after start-up. Our analysis addresses only those factors affecting estimation accuracy and plant performance that are internal to a project.

We distinguish between external factors that increase the costs of a project and those internal factors that affect the accuracy of estimates independently of all else. External factors that may increase plant cost are changes in scope, unanticipated inflation or escalation, unanticipated regulatory changes, strikes, bad weather, and management practices. Factors that may affect estimation accuracy are process characteristics and knowledge, the extent to which the project is defined, and incentives for accurate estimation. The Pioneer Plants Study examined only the internal factors, and found that they ac-

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[2]We note that our statistical analysis does not imply causation. By that we mean that the variables we show to be *related* to cost misestimation and performance shortfalls are not necessarily the *causes* of those phenomena. No statistical technique can guarantee causation.

counted for approximately three-quarters of the cost growth in the data base.

Based on preliminary work on the Pioneer Plants Study, we formulated two hypotheses about the sources of cost growth and performance shortfalls.[3] The first was that the more a plant's technology departed from previously established commercial systems, the larger would be the misestimation error and the poorer would be the plant's performance. The second was that cost misestimation, measured as the gap between any estimate and actual costs, would decline as the completeness of the plant definition increased. Although we also sought to test other possibilities suggested by members of industry and by the literature, the amount of unproven technology and the level of project definition were the two primary factors that guided our structuring of the data base and analysis. The Pioneer Plants Study provided quantitative support to these widely held but qualitative hypotheses.

The Pioneer Plants data base contains information on 44 commercial-scale chemical process plants, and represents a wide range of generic processes, cost growth, and plant performance. This variety enabled us to statistically examine broad problem areas and permitted us to draw inferences beyond the limitations of a single process. Most plants in the data base can be placed in one of the following generic product categories: olefins and olefin derivatives, aromatics and aromatic derivatives, refinery products and by-products, chlorine-based chemicals, and minerals processing. The choice of what plants to include was ultimately left to the participating companies, whom we provided with seven criteria to guide their choices. They were asked to select:

- Plants that involve some degree or kind of technical change from prior plants.
- Medium-sized to large plants in terms of annual output—100 million pounds per year or more.
- Plants constructed in the U.S. and Canada from 1965 onward.
- Green-field, co-located, or add-on units but not revamps of an existing plant.
- Plants for which reliable data are available.
- No plant chosen solely because significant deviations from cost or expected performance occurred.

[3]E. W. Merrow, S. W. Chapel, and C. Worthing, *A Review of Cost Estimation in New Technologies: Implications for Energy Process Plants*, The Rand Corporation, R-2481-DOE, July 1979.

Taken as a whole, the sample includes plants that introduce more technical advances than average and have somewhat larger production capacities. Compared with process plants in general, the sample overrepresents solids and liquids handling at the expense of gas processing.

Cost Misestimation and Plant Performance

For each plant in the data base, we collected the actual capital costs and at least one cost estimate. We then defined cost estimation error as the estimated capital cost in constant dollars divided by the actual capital cost in constant dollars, and expressed that figure as a decimal. The reciprocal of cost estimation error is cost growth. If, for example, a facility is estimated to cost $50 million dollars, but is actually built for $72.5 million (in constant dollars), then the cost estimation error is 50/72.5, or 0.69. The cost growth is simply 1/0.69, which equals 1.45. We can then say that the plant experienced a cost growth of 45 percent.

We also collected data on plant performance, defined as the average percent of design capacity realized per calendar day during months 7 through 12 after start-up. Design capacity is simply the amount of product to be produced for some period of time, and is often expressed as pounds per year. If we knew that a plant was designed to produce 100 million pounds per year, but actually produced 35 million pounds during months 7 through 12 after start-up, we would say that the plant was operating at 70 percent design capacity (35/50 million pounds per half year = 0.70).

The Variables that Explain Cost Misestimation and Plant Performance

The Pioneer Plants Study showed that cost misestimation can be explained by a combination of variables that characterize the technology and the amount of project information about the proposed plant. Plant performance can be explained by a set of technical variables alone. What we mean by technical and project information variables is shown conceptually in Fig. 1.1, a diagrammatic representation of the cost misestimation and plant performance equations. The technical variables capture how much innovation is incorporated into the plant. The project information variables capture the stage of the project's development.

The variables collected in the Pioneer Plants Study were chosen after discussions with industry. These variables describe virtually

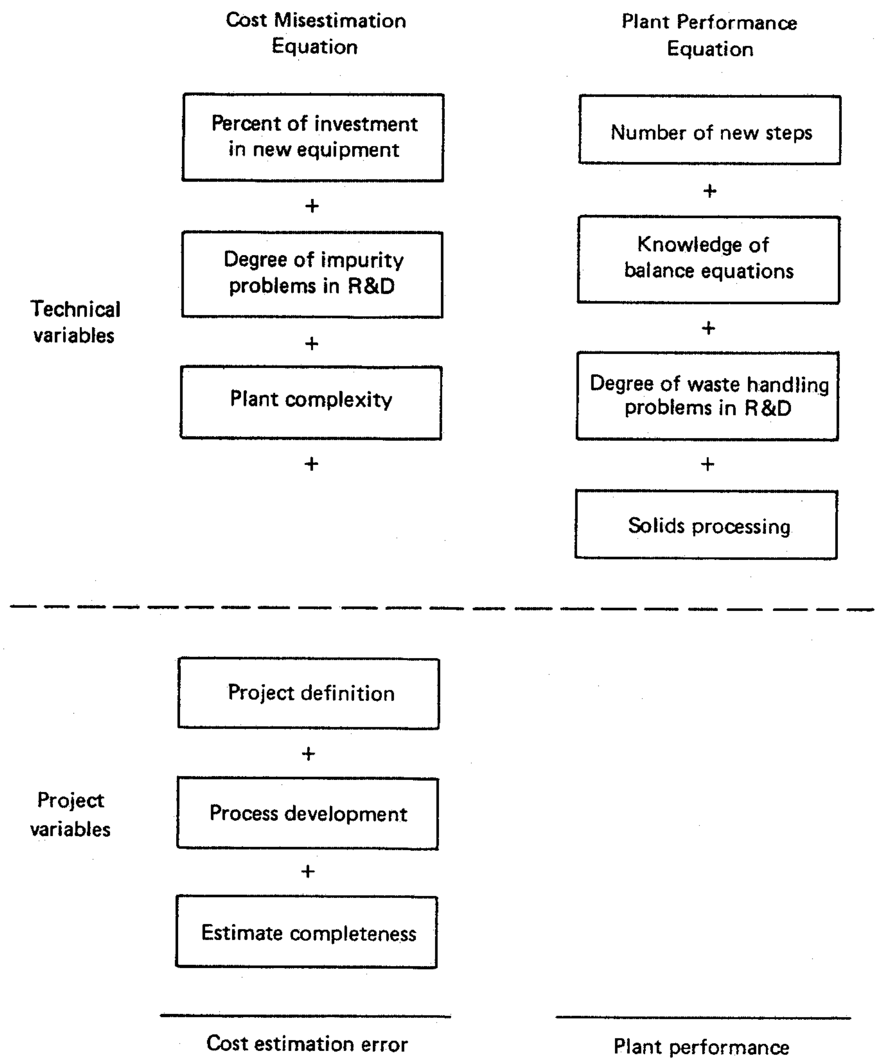

Fig. 1.1—Conceptual diagram of cost estimation error and performance equations

every aspect of a project, including its technical characteristics and the technical problems encountered during various development stages, detailed cost estimation histories, key beginning dates, lengths of time spent for each major project stage, environmental and regulatory issues affecting the project, actual project costs, start-up problems, and performance records. Of these many variables, only six are used in the cost estimation error equation, and four in the performance equation. The choice of including a particular variable in the equations was guided by the technical reasonableness of linking that variable to either cost estimation error or plant performance, and how well the variable fit in the equation statistically.

The cost estimation error equation consists of six variables, three technical and three related to project definition:

- PCTNEW is the percent of estimated capital cost incorporating new technology. This variable, derived from the NEWSTEPS variable (see the plant performance variables), measures the portion of capital cost to be spent on new technology.
- IMPURITIES is an assessment, on a scale of 0 to 5, of the difficulties with process stream impurities encountered during process development. In particular, IMPURITIES measures the extent to which impurity buildup was a significant source of design and development problems.
- COMPLEXITY is the count of the number of continuously linked process steps or block units in the plant. More complex plants are slightly more difficult to estimate accurately than less complex plants.
- PROJECT DEFINITION is a numerical rating from 2 to 8 that measures the extent to which the cost estimate uses site-specific information, and the level of detailed engineering accomplished by the date of the cost estimate.
- PROCESS DEVELOPMENT is scored as either 0 or 1, and represents the stage of the process's technical development. 0 indicates that the process is fairly well understood, while 1 indicates that significant R&D issues remain. This variable captures the level of technical knowledge of the process, and is used in conjunction with PROJECT DEFINITION.
- INCLUSIVENESS represents the completeness of a cost estimate—its thoroughness of detail.

The plant performance equation consists of four variables, all of them technical:

- NEWSTEPS is the number of process step blocks in the plant that are new in commercial use at the time of the cost estimate. The "in commercial use" qualification means that the step must have been used in a plant whose purpose was to produce a product commercially, rather than to serve for testing or development. This variable acts as a gauge for the innovativeness of the technology.
- BALANCE EQUATIONS is the percentage of heat and mass (material) balance equations that are based on actual data from existing (or prior) commercial plants. This variable is a measure of the level of technical innovation, and indicates the amount of process understanding that comes from commercial experience as opposed to theory or developmental units.
- WASTE is a 0 to 5 subjective index of design difficulty encountered with waste handling. This variable is probably affected by regulatory requirements.
- SOLIDS takes on a value of either 0 or 1: 1 if the plant handles solids either as a feedstock, intermediate material, or as a product, and 0 otherwise. This variable accounts for the difficulty encountered when processing solid materials.

CONFIDENCE IN THE MODEL AND THE CONFIDENCE INTERVAL

Both the cost estimation error equation and the performance equation are statistical models, whose users must be aware of what constitutes accuracy in such models. Simply put, there are two concerns about a model's accuracy. The first deals with the appropriateness of the model and the confidence with which it may be applied to any particular instance. The second deals with confidence that the model's result will be reasonably close to the true value.

Confidence in the Model

Our confidence that a particular plant fits our two models depends entirely on how well that plant fits into our data base. Briefly, the Pioneer Plants Study can be applied to any plant that meets the following criteria:

- The plant consists of at least one chemical conversion (a chemical conversion involves changes in the molecular form of a material). Examples of chemical process steps are reactors, distillation columns, dryers, gasification units, and ion exchangers.

- The process steps in the plant are continuously linked as opposed to a batch process.
- The plant is to be built in North America.
- A legitimate, good-faith cost estimate exists.

The plants in our data base met those criteria. To determine whether a particular plant resembles those in the data base, the user will ensure that the values of the plant's variables are within the ranges of those in the data base (they are presented in the following sections).

By way of example, one may or may not apply the Pioneer Plants Study to the following lists:

Criteria apply to:	Criteria do not apply to:
Chemical plants	Fossil power plants
Petrochemical plants	Nuclear power plants
Metallurgical plants	Simple storage facilities
Refineries	Solar technologies
Synthetic fuels plants	Pipelines
Nuclear reprocessing plants	

Confidence Interval

Because of the statistical nature of the cost estimation error and plant performance equations, there is an inherent uncertainty in the results, even when the values assigned to the variables have no error in them and the plant is similar to those in our data base. This uncertainty is customarily expressed in the form of a confidence interval. The fundamental idea behind a confidence interval is that we can have more confidence in the accuracy of our statistical results the closer a particular plant's variables are to the averages of the variables in the Pioneer Plants data base. Conversely, the results of our models have less accuracy when the variables deviate from the means of the data base variables. This accuracy is usually expressed as a confidence interval around the result given by the model. In this manual we use a confidence interval of one standard deviation, or roughly 68 percent.[4] Applying the Pioneer Plants Study results in this way means that the true cost estimation error for a particular plant has a 68 percent chance of lying within the range specified by the results. The same is true for the plant performance results.

Unfortunately, the mathematics needed to calculate the confidence interval for a given set of variable values are not easy to explain or perform. However, we have calculated an approximation for the exact confidence interval that will suffice for most situations. The approximation is validly applied whenever the values are within two standard deviations of the Pioneer Plants Study means. For that reason, we will give the Pioneer Plants Study means in the variable discussions. In Sec. V we will demonstrate with an example how the confidence interval works.

ORGANIZATION OF THE MANUAL

This manual is organized to be as clear a guide as possible for someone who is trying to apply the results of the Pioneer Plants Study. Section II describes the best sources for the information the user will require, and provides two tables that summarize that information. Section III describes what technical information is needed and how to interpret it. The first three technical variables, COMPLEXITY, NEWSTEPS, and PCTNEW, should be collected in the order shown because each depends on the one preceding. The rest of the technical variables may be collected in any order. Use of each variable is illustrated by means of an actual waste processing facility in the northwest United States. We use this facility throughout the manual as an example. Section IV describes what project information is needed and again provides examples using the same facility. Finally, Sec. V ties all the examples together to demonstrate the use of the cost estimation error and performance equations.

Our Example Facility was built to solidify liquid wastes for storage on site. Replacing an obsolete waste facility, the new facility incorporates innovative technology, including remote handling, new materials of construction, and new equipment designs. The basic design was established by June 1974, and the final design by January 1976. Initial engineering was completed by July 1976, and detailed engineering by January 1978. Construction began in October 1976 and

[4]A standard deviation is a measure of dispersion or spread of any set of numerical values around their average. One standard deviation means that 68 percent of all the numerical values fall within the range of plus or minus one standard deviation around the average.

was completed in late 1981. The total actual cost of the plant was $115 million in mid-1980 dollars. As of this writing (summer of 1982), the plant is undergoing start-up.[5]

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[5]The facility converts liquid wastes into a solid form whose storage is both safer and more economical. The method that is used to make the conversion is called fluidized-bed calcination. "Fluidized-bed" refers to the fact that the chief reaction takes place in a vessel in which granular solids are suspended by whirling air. This suspended mass of particles is called a "bed," which is heated by the combustion of kerosene and oxygen. The liquid waste is sprayed into the vessel and reacts with the hot, whirling granular solids. This reaction is called calcining, which in general means to heat materials to a high temperature but without fusing in order to drive off volatile matter or effect changes. In this facility, calcination results in the decomposition of the liquid feed, which leaves the solid bed particles with a coating of dissolved solids. The combustion and decomposition gases and water vapor leave the calciner (as the reactor vessel is called) for further treatment: scrubbing and separating, wet cleanup, and dry cleanup. The harmless off-gas that results is then released to the atmosphere. The solid wastes produced are transported along an underground, pneumatic tube from the calciner vessel to underground solid waste storage bins. The bins are stainless steel, cylindrical tanks encased in concrete. The heat from the hot, solid waste is dissipated by natural convection. There is zero discharge of liquids during the process, because all liquid wastes generated by the facility during either operation or decontamination activities are recycled as feed solution.

II. WHOM TO ASK FOR COST ESTIMATE AND PERFORMANCE INFORMATION

The person most likely to be able to supply the necessary information is the project manager, who is the person responsible for the overall design, construction, and sometimes the start-up of a plant. Every plant constructed has such a person in charge, and that person's title is almost always "project manager." The project manager always has a team to work with, whose composition varies from firm to firm. Each team member is responsible for a specific portion of the project, such as engineering design, process design, finance, research and development (R&D), and operations. Sometimes two or more of these areas are combined under one heading (engineering design and process design might be combined under technical design, for example), and sometimes the areas of responsibility are not clearly delineated. None of the information required for the Pioneer Plants Study is so detailed that it must come from someone below the level of the project manager's team, and in general the project manager will be able to answer all technical questions.

If the project manager is unavailable, the vice president (or equivalent) over the project manager is the next person to contact. Quite often the vice president must make presentations to the Board of Directors (or the operating committee) regarding the plant, and he or she is therefore knowledgeable about many of the technical details. If a specific question cannot be answered, the vice president can supply the name of someone who can.

Each firm usually has what is termed a "project advocate" who is unabashedly in favor of the plant's construction. The placement of this person in the firm may be just about anywhere, but he or she is usually well placed (has exposure at the Board level). Although the project advocate is a willing source of information, care must be taken that his or her data are not biased by the advocacy position. Since "project advocate" is not an official position, there is no easy way to discern if your contact is so predisposed. The project advocate is rarely the project manager, but he or she may be the vice president in charge of the project manager. If you suspect that your contact is such an advocate and is coloring his or her responses, it is best to talk to other knowledgeable people (on the project manager's team, for example) to gain other points of view.

We note here that the results of the Pioneer Plants Study are only as accurate as the information supplied. While it is possible on occasion to verify some of the information from other sources, it is generally not possible to check each and every detail. There is no way to guarantee that all information received is accurate. You must always bear in mind the possibility that the information might be biased and that the results must be adjusted accordingly. This adjustment simply involves substituting another value for the suspect one and recalculating the results.

THE COST ESTIMATE AND THE ACTUAL COST OF THE PLANT

Because the cost estimation error equation uses a plant cost estimate as a base, it is important that you understand what should be included in the cost estimate, and exactly what the cost estimation error equation produces as a result. The cost estimate must not include inflation or escalation. That is, the estimate must be in "build today, operate today" dollars. It should include any contingencies that the estimators incorporated to cover uncertainties.

The cost predicted by the cost estimation error equation excludes any changes in scope,[1] inflation, unanticipated regulatory changes, or *force majeure* events—items that are beyond the ability of a cost estimator to predict.

Consider our illustrative waste facility. Its final design was agreed upon by June 1974, after which the contractor began preparing an estimate that would be completed in 1975. We refer to this estimate as the "1975 cost estimate." The estimated capital cost in 1975 dollars was $52.1 million, which included direct and indirect field cost, detailed engineering, and contingency, but not escalation. That is, it was a complete capital cost estimate presented in "build today, operate today" dollars, which meant that no inflation was assumed to occur. When a cost estimate includes escalation (read "inflation"), it must be adjusted to "build today, operate today" dollars before being applied to the cost estimation error equation. Any well-documented cost estimate will specify how the escalation was calculated, and from that information it is a straightforward task to remove the escalation to produce a "build today, operate today" estimate. Because the Example Facility's 1975 cost estimate was already expressed in "build

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[1]By scope changes we mean changes in plant design capacity, changes in the product slate, or other discretionary changes that took place after the cost estimate was made, and that were therefore not reflected in the cost estimate. We do not include as scope changes modifications to plant design found to be necessary to make the plant operate.

today, operate today" dollars, it was unnecessary for us to make any further adjustment.

COLLECTING THE DATA FOR THE EQUATIONS

The information that must be collected is outlined in Tables 2.1 and 2.2. Each blank in Table 2.1 is to be completed or calculated for the cost estimation error equation. Similarly, Table 2.2 is to be filled out for the plant performance equation. The following two sections will define each variable and then, using the Example Facility, show how the information is recorded in Tables 2.1 and 2.2.

Table 2.1

BLANK WORKSHEET FOR COST ESTIMATION ERROR CALCULATION

A. Variable Name	B. Assigned Value		C. Multiplied by		D. Equals
1. COMPLEXITY	______	x	.011	=	______
2. PCTNEW	______	x	.003	=	______
3. IMPURITIES	______	x	.021	=	______
4. PROJECT DEFINITION	______	x	.040	=	______
5. PROCESS DEVELOPMENT	__ x [.]	x	.024	=	______
6. Subtotal					______
7. INCLUSIVENESS	______	x	.0011	=	______
8. Subtract line 7 from line 6					______
9. A constant					1.122
10. Put the number from line 8 here					______
11. Subtract line 10 from line 9 (COST ESTIMATION ERROR)					______
12. Capital cost estimate for plant					$____M
13. Divide line 12 by line 11 (EXPECTED CAPITAL COST)					$____M

Table 2.2

BLANK WORKSHEET FOR PLANT PERFORMANCE CALCULATION

	A. Variable Name	B. Assigned Value		C. Multiplied by		D. Equals
1.	NEWSTEPS	______	x	9.69	=	______
2.	WASTE	______	x	4.12	=	______
3.	SOLIDS	______	x	17.9	=	______
4.	Subtotal				=	______
5.	BALANCE EQUATIONS	______	x	.33	=	______

6. Subtract line 5 from line 4 .... ______

7. A constant 85.8

8. Put the number from line 6 here .... ______

9. Subtract line 8 from line 7 (PLANT PERFORMANCE) ... ______ percent

III. TECHNICAL INFORMATION

This section discusses the technical information required to apply the cost estimation error and plant performance equations from the Pioneer Plants Study. The section is organized in the order in which one may collect the information, but the order is critical only for the first three variables—COMPLEXITY, NEWSTEPS, and PCTNEW. For each variable we note whether the information being discussed is needed for the cost estimation error equation, or the plant performance equation, or both. The variables discussed are COMPLEXITY, NEWSTEPS, PCTNEW, IMPURITIES, WASTE, BALANCE EQUATIONS, and SOLIDS.

COMPLEXITY (COST EQUATION)

The definition of COMPLEXITY is the count of the number of continuously linked process steps or block units in the plant. The values for COMPLEXITY in the Pioneer Plants Study range from 1 to 11, with an average of 5.5. This variable is used in the cost estimation error equation and is needed before either NEWSTEPS or PCTNEW can be calculated. Its purpose is to account for the fact that more complex plants are slightly more difficult to estimate accurately.

Working Definition

The plant's block units are defined as the continuously linked process steps that are integral parts of the chemical process. These block units, also known as "subsystems," are found on the plant block diagram instead of the more detailed process flow sheets. The block units are functional area groupings of major equipment. In general, all process steps are included that act either chemically or physically on the material being processed. In deciding whether to include a step in the count, the single most important criterion is how necessary that step is to the overall plant process: If that step fails and cannot be bypassed to keep the plant running, then that step should be included in the block count of the process. We exclude subsystems that produce power or utilities: steam plants, electrical power plants, air separators, refrigeration units, water pumping stations, and all piping or networks that distribute any of those items. We also exclude pumps, on-line heaters, surge tanks, and duplicate parallel trains, as well as straightforward storage facilities for liquids, such as tanks or ponds, or for solids. Because a storage facility generally involves no chemical or physical conversion of processed material, it should normally be excluded from the count. But if removal from a storage facility requires reheating, stirring, or separation, for example, the unit would be counted.

Example Facility

The Example Facility has a total of eight process block units for its COMPLEXITY count: the feed system, the calciner, the quencher, the scrubber separator, wet cleanup, dry cleanup, solids storage, and the decontamination facility.

The information needed to construct the block count can be obtained from a process flow sheet. The process flow sheet is a detailed diagram of the process that includes schematic drawings of each piece of major equipment, as well as numbers describing the material and heat flow. Because of the material and heat flow numbers, this process flow sheet is often proprietary, and therefore difficult to obtain. More accessible is something called a "simplified process flow sheet," which omits proprietary material and heat numbers. These major equipment items are then grouped to form the block diagram of the process.

Figure 3.1 depicts a simplified process flow sheet for the Example Facility. Although it is not necessary to understand the workings of this facility in order to use our definition of COMPLEXITY, it may be useful to summarize them here.

The feed system injects the raw waste liquid solution into the main reactor vessel (the calciner) along with kerosene and oxygen. The mixture of kerosene, oxygen, and liquid wastes is heated in the reactor until it burns. The wastes solidify and are stored underground. The gases are cooled in the quencher and then scrubbed so that they are partially cleaned up. The gases are then cleaned up further before being released to the atmosphere. The decontamination facility is a necessary part of this plant because of the radioactive nature of the wastes.

The major equipment in Fig. 3.1 can be combined to form the block diagram of Fig. 3.2 in the following way. The feed system of Fig. 3.1 comprises the waste solution tank and the injection equipment that feeds into the calciner. The calciner comprises the calciner vessel and the high-efficiency cyclone (the calciner vessel and the cyclone physically touch each other). The quencher comprises the quench tank and

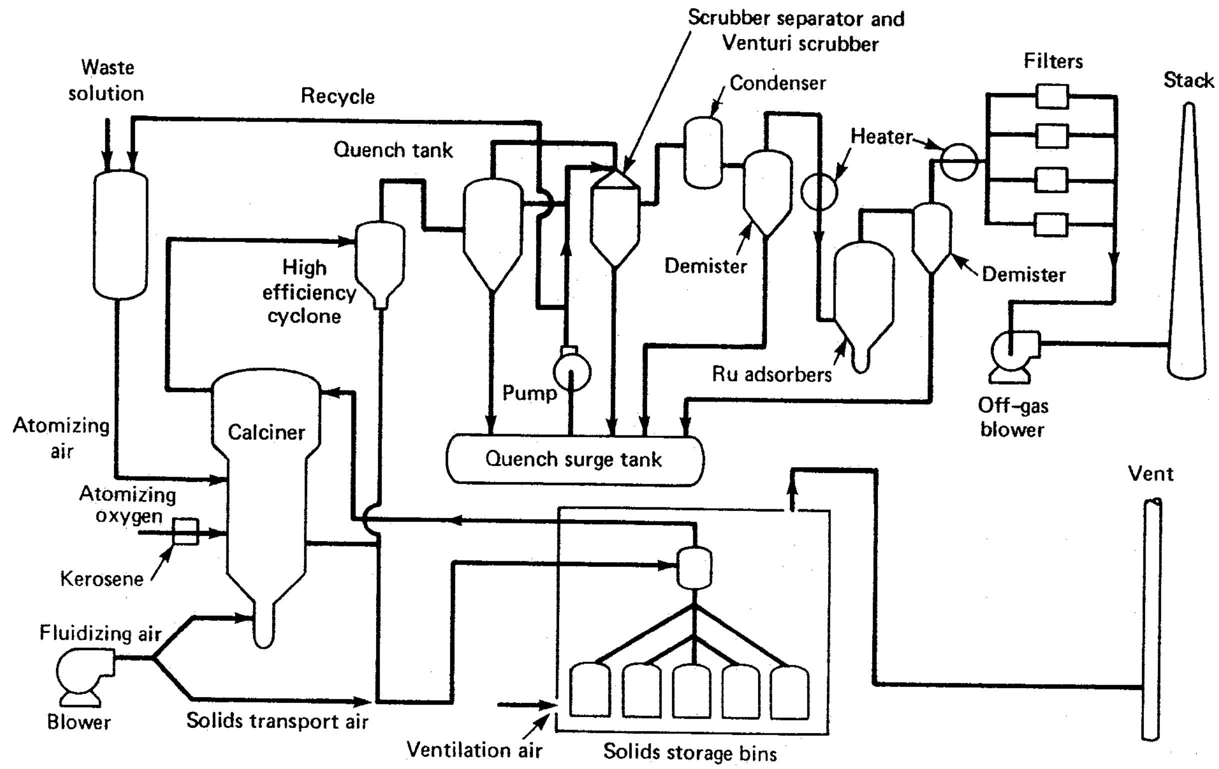

Fig. 3.1—Simplified process flow diagram of the Example Facility

the quench surge tank (the surge tank temporarily stores the recycled liquid until it is ready to be pumped up to the scrubber separator). The scrubber separator removes particles from the off-gas. The wet cleanup system consists of the condenser, demister, and the ruthenium adsorbers, while the dry cleanup system consists of the filters, off-gas blower, and stack. The solids storage in the block diagram corresponds to the solids storage bins in Fig. 3.1. The solids storage is counted as a step because it is monitored, not simply left alone. The decontamination facility is not shown in the simplified process diagram. We must include it in the block diagram (Fig. 3.2), however, because it is linked to each of the other process steps, and therefore is an integral part of the process stream. To keep Fig. 3.2 simple, we drew the decontamination facility as a separate block unit.

A natural question to ask is, How does one go about converting the major equipment items of the simplified process diagram into a block diagram? Ordinarily, you would not do so yourself. If one of the engineers responsible for the plant in question is not available, then a process engineer must be found to perform the groupings. It is not necessary for that engineer to be intimately familiar with the process, as long as he or she has the simplified process diagram to work from. If for some reason there is some uncertainty as to whether certain equipment ought to be grouped together, you may perform a sensitivity analysis by grouping the items two different ways and checking to see how the cost estimation error changes.[1] Because of the way the COMPLEXITY variable works in the equation, you are likely to see that the two ways of grouping do not make much difference in the size of the cost estimation error.

Summary of the Variable COMPLEXITY

COMPLEXITY is the block count of the process steps in the plant. It ranged from 1 to 11—with an average of 5.5—in the Pioneer Plants Study data base. Counting the blocks on the block diagram yields the value for COMPLEXITY. For the Example Facility, this gives a value of 8 (see Fig. 3.2). If the block diagram is not readily available, it can be drawn from the simplified process diagram, which shows the process flow for all the major equipment items. To derive the block diagram, one groups the major equipment items into sensible blocks. While there is no cut-and-dried way to make this grouping, any process engineer would be able to do so. In grouping the major equip-

[1]A "sensitivity analysis" is one in which the inputs are varied to see how they affect the result. An example is presented in Sec. V.

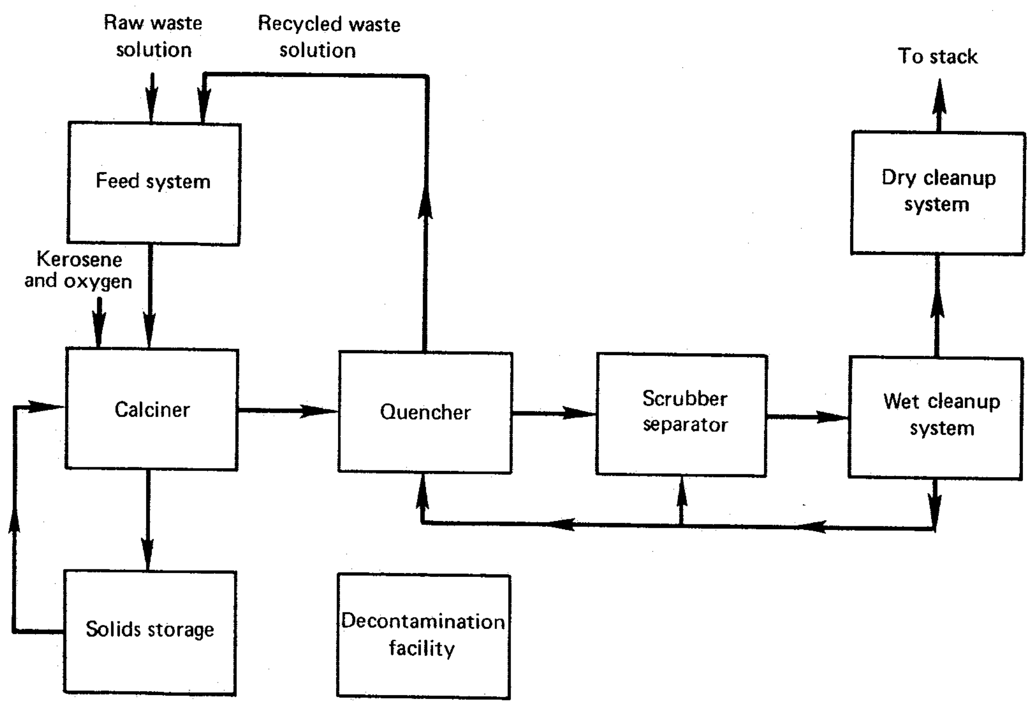

Fig. 3.2—Block diagram for the Example Facility

ment, one ignores pumps, on-line heaters, liquid storage and surge tanks, utilities and power generation, and duplicate parallel trains. All other chemical and physical process steps are counted.

Table 3.1 shows how the COMPLEXITY is recorded on the worksheet for the cost estimation error equation.

Table 3.1

COMPLEXITY: Partially Filled Worksheet for Cost Estimation Error Calculation

A. Variable Name	B. Assigned Value		C. Multiplied by		D. Equals
1. COMPLEXITY	8	x	.011	=	.088
2. PCTNEW	______	x	.003	=	______
3. IMPURITIES	______	x	.021	=	______
4. PROJECT DEFINITION	______	x	.040	=	______
5. PROCESS DEVELOPMENT	__ x [ ]	x	.024	=	______
6. Subtotal					______
7. INCLUSIVENESS	______	x	.0011	=	______
8. Subtract line 7 from line 6					______
9. A constant					1.122
10. Put the number from line 8 here					______
11. Subtract line 10 from line 9 (COST ESTIMATION ERROR)					______
12. Capital cost estimate for plant					$____M
13. Divide line 12 by line 11 (EXPECTED CAPITAL COST)					$____M

NEWSTEPS (PERFORMANCE EQUATION; NEEDED FOR THE COST EQUATION)

The definition of NEWSTEPS is the block count of all process steps in the plant that are new in commercial use at the time of the cost estimate. The value for NEWSTEPS in the Pioneer Plants Study ranged from 0 to 7, with an average of 1.7. This variable is used directly in the plant performance equation, and is an element in developing the variable called PCTNEW. NEWSTEPS acts as a gauge for the newness of the technology, and was shown in the Pioneer Plants Study to be strongly related to poor plant performance.

Working Definition

As the name implies, NEWSTEPS is the number of new process steps. One new element in a step makes the entire step count as new; several new elements in the step are still counted as only one new step. The word "new" is not used loosely here, but is given the following definition. A piece of equipment is considered new if any of the following is true:

- A new design is necessary for the unit at that scale, or new materials of construction are required.
- The unit is to be used under operating conditions that have not been tried with that design and at that scale.
- The chemistry to take place has not been demonstrated in commercial use with that piece of equipment.
- The combination of feedstock and equipment has not been tried before in commercial use.

"In commercial use" means that the equipment was used in a plant built for the purpose of producing product sold to generate income. When such a use occurs for the first time, the process or equipment is *new* in commercial use. A facility (bench or laboratory, process development unit, component test facility, a pilot plant, or a demonstration plant) constructed to generate process information is *not* a commercial facility. The acid test of "newness" is whether the technology has been used in a facility to generate process information or profits. Sometimes a prior facility was built for both purposes; in such a case the current use of the technology should be considered new if a reasonable business risk to use the technology in a commercial facility would not have been taken without the prior facility being built first.

Most engineers and plant managers tend to downplay the extent to which their project is new, largely to avoid being perceived as pushing the state of the art too much. Consequently, their definition of "new" is much narrower than the one we have given above. Nevertheless, we have found that our broader definition of "new" helps to explain the phenomena of cost estimation error and plant performance.

Some of the above four criteria deserve further elaborating. "Materials of construction" are simply the materials from which the equipment is designed. Thus, an off-the-shelf piece of equipment that is being built with Inconel 650 instead of the standard stainless steel would be considered new. "Operating conditions" refer to the physical environment that the equipment is expected to operate under, such as pressure and temperature. If a reactor is to be used under operating conditions, such as temperature and pressure, that were not specifically considered in the original design, that reactor is new for our purposes. "New chemistry" refers to the chemical reaction itself. "Feedstock" is the raw material supplied to the processing plant. The above four criteria can be summarized by the following: A process step is new if the equipment involved is to be used in commercially undemonstrated operating conditions, newly designed or built with undemonstrated materials of construction, used with undemonstrated chemistry, or used with a new feedstock in commercial use. The importance of the technology being demonstrated in commercial use cannot be overemphasized. A reactor vessel is considered new if it is to contain a chemical reaction that has only been demonstrated in a test facility of some kind. Therefore, a piece of equipment that is being scaled up for commercial use is also new.

Example Facility

The Example Facility embodies new technology in several different ways, in a total of three new steps (see Table 3.2).

The three steps we are counting in our assessment of a value for NEWSTEPS are the calciner, the dry cleanup step, and the decontamination facility. The calciner is considered new for two reasons: It is 20 percent larger than the calciner in the prior demonstration facility, and it contains new materials of construction for the insulation. The 20 percent scale-up would in itself be enough to put the calciner in the "new step" category, even though 20 percent is not an inordinate scale, and even though the calciner in the old facility is in commercial use. The reason that the scale is sufficient to classify the calciner as new is that the calciner in the old facility was needed to test the calciner design. Good business judgment required that the design be tested before being used in a commercial facility.

Table 3.2

UNDEMONSTRATED TECHNOLOGY IN THE EXAMPLE FACILITY

Equipment	Innovation	Process Block
Calciner	20 percent larger	Calciner
Insulation	New stainless removal insulation for calciner	Calciner
Blowers in off-gas compressors	New design and required chrome shafts	Dry cleanup system
Filters	Square pressure vessels (new design)	Dry cleanup system
Decontamination facility	New design	Decontamination
Remote handling equipment	New design	Not applicable (general plant equipment)

The dry cleanup step is considered new because the off-gas blowers and the filters are new. Note that if any piece of major equipment is new within a block step, the whole block step is counted as new. For example, Table 3.2 shows that the off-gas blowers and the filters, which both belong to the dry cleanup block step, are both innovative designs. Thus the dry cleanup step counts as a new step even though the stack, which comprises the remainder of that step, is not new in this application.

The decontamination facility is considered new because of its new design. Note that Table 3.2 has listed an item called "remote handling equipment." This equipment was required because of the contaminated nature of the feedstock, but is also to be used for routine maintenance. As such it is not a process step unto itself ("new" or otherwise), and is therefore not attached to any particular piece of major equipment. We include the remote handling equipment in Table 3.2 because it will be necessary during the calculation of the next variable, PCTNEW.

Other Comments on NEWSTEPS

When querying the project manager or his surrogate on NEWSTEPS, it may be necessary to try different wording of "new equipment" before he understands what you are looking for. Some suggested alternate wordings are:

- What major equipment is undemonstrated in commercial use,
- Do any steps employ new materials of construction,
- Which steps are being designed from scratch,
- Which items are being scaled up,
- Are any feedstocks being used in this configuration for the first time, or,
- Are any of the operating conditions here new in this configuration?

Summary of the Variable NEWSTEPS

NEWSTEPS is the block count of the number of process steps that are new in commercial use. This variable is used in the plant performance equation. The range in the Pioneer Plants Study was 0 to 7, with an average value of 1.7. The value for the Example Facility is 3. A step is considered new if the equipment involved is to be used under commercially undemonstrated operating conditions, newly designed or built with undemonstrated materials of construction, used with undemonstrated chemistry, or be used with a new feedstock. The value for NEWSTEPS may not exceed the value for the previous variable, COMPLEXITY.

Table 3.3 shows how NEWSTEPS is recorded on the worksheet for the plant performance equation.

PCTNEW (COST EQUATION)

The definition of PCTNEW is the percent of estimated capital cost incorporating new technology. The value for PCTNEW in the Pioneer Plants Study ranges from 0 to 95 percent, with an average of 26 percent. This variable is used directly in the cost growth equation, and is derived from the NEWSTEPS variable. PCTNEW measures the proportion of new technology used in the plant, and was shown in the Pioneer Plants Study to be strongly related to cost estimation error.

Table 3.3

NEWSTEPS: Partially Filled Worksheet for Plant Performance Calculation

	A. Variable Name	B. Assigned Value		C. Multiplied by		D. Equals
1.	NEWSTEPS	3	x	9.69	=	29.1
2.	WASTE	______	x	4.12	=	______
3.	SOLIDS	______	x	17.9	=	______
4.	Subtotal				=	______
5.	BALANCE EQUATIONS	______	x	.33	=	______
6.	Subtract line 5 from line 4					______
7.	A constant					85.8
8.	Put the number from line 6 here					______
9.	Subtract line 8 from line 7 (PLANT PERFORMANCE) ...					______ percent

Working Definition

PCTNEW is the percentage (0 to 100) of the total estimated plant cost associated with new process steps and new equipment when the estimate was made. The value for PCTNEW is calculated by adding together the costs associated with each step counted in the variable NEWSTEPS, adding the costs of any new equipment not associated with a particular step, and then dividing that number by the total estimated capital cost of the plant. Equation 3.1 shows the computational form of this variable.

$$\text{PCTNEW} = \frac{\text{Costs of NEWSTEPS and new equipment}}{\text{Total estimated capital cost of plant}} \times 100 \quad (3.1)$$

The costs associated with NEWSTEPS and new equipment include:

- Capital cost;
- Installation costs;
- Allocated indirect costs, only if these costs are included in the total capital cost of the plant;
- Contingency (allocated, if necessary), only if the contingency is included in the total capital cost of the plant.

The direct cost of each new step is the capital cost of that step. This cost must be expressed in constant ("build today, operate today") dollars. Future escalation allowances are removed or "backed out." Any process allowance for contingency specific to a particular step, as opposed to the entire project, should be included in the calculation.

Installation costs are those expenses incurred during the construction of the process steps. These costs may be accounted for in three ways: first, as part of the capital cost of the new step; second, as a separate line item for each step in the plant; and third, as a total amount for all the process steps. In the case of the third accounting procedure, the installation cost for any given step may be approximated by allocating the total installation cost proportionately according to the capital costs of the steps. The installation costs should be in constant dollars. The sum of the capital cost and the installation cost is called the direct cost.

Indirect costs are those which cannot be logically applied to any particular process step, but rather are tied to the process as a whole and are somewhat akin to overhead. The indirect cost for any given step is calculated by allocating the total indirect cost proportionately according to the capital costs of the individual steps. The indirect costs are to be included in the PCTNEW calculation only if they are included in both the numerator and denominator of Eq. (3.1) (that is, in the cost of the new technology and the total cost estimate of the plant, respectively). If the indirect costs cannot be allocated, they should be subtracted from the total capital cost before using Eq. (3.1). The indirect costs are in constant dollars.

Contingencies are specific provisions for unforeseeable elements of the plant's capital cost. There are as many different kinds of contingencies as there are firms, and there is no standard within the industry as to how to interpret or even define "contingency" unambiguously. If a project contingency (that is, for the whole project) is the only one specified, the contingency for any given step is calculated by allocating the total project contingency according to whatever method was used to derive the contingency. If this method is not known, the project contingency should *not* be allocated to each equipment item and should *not* be included in the calculation of PCTNEW. Contingencies should only be included in the calculation of PCTNEW if they are included in both the numerator and the denominator of Eq. (3.1). Finally, contingencies should be in constant dollars.

Example Facility

First, we calculate the denominator—the capital cost estimate of Eq. (3.1). The 1975 summary cost estimate for the Example Facility is shown in Table 3.4. The costs are shown in 1975 dollars.

Table 3.4

EXAMPLE FACILITY SUMMARY COST ESTIMATE
(In 1975 $ million)

Item		Cost
Design and inspection		7.9
Project management		3.0
Construction		
Land improvements	0.073	
Building	8.8	
Utilities	0.420	
Equipment	15.3	
Demolition	0.055	
Other costs (fees, licenses, etc.)	6.78	
Total construction costs		31.4
Escalation		7.0
Contingency		9.8
Total project cost estimate		59.1

Table 3.4 shows that the total capital cost of the facility is $59.1 million, including escalation and contingency.[2] To be consistent with our data base, we must "back out" the escalation estimate of $7.0

[2]The contingency shown in Table 3.4 represents about 20 percent of the total capital cost without escalation. This level of contingency is normal for a project in its early stages of development. See App. B for a brief discussion of contingencies.

million, leaving a total capital cost estimate of $52.1 million in constant dollars. This figure is the denominator of Eq. (3.1).

The new technology incorporated in the Example Facility was summarized in the previous discussion of NEWSTEPS, and consisted of the calciner, the dry cleanup step, the decontamination facility, and the remote-handling equipment. Although only the first three items are counted in the NEWSTEPS variable, all four are included in the calculation of PCTNEW. The calculation of the numerator for Eq. (3.1) is shown in Table 3.5. Included in Table 3.5 are the direct costs, the allocated indirect costs, and the total cost for each item. Note that the capital and installation costs are listed together under "Direct Cost"; as is often the case, the cost estimators for the Example Facility did not disaggregate the capital cost of an item from its installation cost.

Table 3.5

VALUE OF NEW TECHNOLOGY IN THE EXAMPLE FACILITY
(In 1975 $ million)

Item	Direct Cost (Capital cost + installation)	Indirect	Total
Calciner	$ .91	1.59	2.50
Dry cleanup	1.22	2.15	3.37
Decon facility	4.07	7.27	11.3
Remote handling	1.50	2.69	4.19
Total			$21.4

Table 3.5 shows that $21.4 million of the 1975 capital cost estimate is earmarked for new technology. The direct costs in the table are listed as line items in the Example Facility's cost estimate. The estimated indirect costs were allocated proportionately using the total estimated direct cost as a basis.

Before illustrating how the numbers in the "Total" column were calculated, we first must discuss the indirect costs. For our purposes, indirect costs are those costs that are integrally related to the process, but cannot be tied to any particular process step. For the Example

Facility, these items (from Table 3.4) are design and inspection, building, utilities, and contingency. (The building for the Example Facility actually houses the process and must be specially designed to contain the radiation. For most process plant projects the building is simply an administrative building and not a part of the process itself. In such a case, the building costs would not be counted as an indirect cost for our purposes.) The items not included under "Indirect" are project management, land improvements, demolition, and other. These items are project-related rather than process-related, and are therefore excluded. Table 3.6 summarizes the indirect costs for the Example Facility.

Table 3.6

INDIRECT COSTS FOR EXAMPLE FACILITY
(In 1975 $ million)

Design and Inspection	$ 7.9
Building	8.8
Utilities	0.42
Contingency	9.8
Total	$26.9

To illustrate how the right-most numbers in Table 3.5 were calculated, consider the calciner. The cost of the calciner vessel, including installation, was approximately $0.91 million in 1975 dollars (no escalation), which represents about 5.9 percent ($0.91/15.3 \times 100$) of the total equipment costs (see Table 3.4). Multiplying this 5.9 percent by the total indirect costs ($26.9 million) gives $1.59 million, which is listed in Table 3.4 as the amount of the indirect cost allocated to the calciner unit. The rest of the numbers under "Indirect" were calculated in a similar manner.

The value of PCTNEW is obtained by dividing $21.4 million by $52.1 million and multiplying by 100:

$$21.4/52.1 \times 100 = 41 \text{ percent for the Example Facility} .$$

Summary of the Variable PCTNEW

PCTNEW is the percent of estimated capital cost incorporating new technology. This variable is used in the cost estimation error equation. Its range in the Pioneer Plants Study is 0 to 95 percent, with an average of 25.6 percent. The value for the Example Facility is 41 percent. The cost of new technology includes the capital cost, installation cost, indirect costs, and any contingency—if that contingency is also included in the total plant capital cost estimate. "New technology" includes all new process steps in the plant (as defined in the section on NEWSTEPS) as well as any new equipment not associated with any particular process step.

Table 3.7 shows how the value for PCTNEW is recorded for the cost estimation error equation.

IMPURITIES (COST EQUATION)

The definition of IMPURITIES is a 0 to 5 subjective ranking of the difficulties with process stream impurities encountered during process development. The average value of the IMPURITIES variable in the Pioneer Plants Study is 2.0. This variable is used in the cost estimation error equation. The IMPURITIES variable measures, on a 0 (no problem or not applicable) to 5 (severe problem) scale, the extent to which impurity buildup was a significant source of design and development problems.

Working Definition

The IMPURITIES variable measures the extent to which one particular problem (process impurities) was encountered during process development, out of the many potential difficulties that may result from the technological innovation being developed. Tests done in the laboratory (often called "bench tests" or "bench scale runs") and tests done in the field (using pilot plants, process development units, or component test facilities) can sometimes indicate whether the process reaction leaves undesired trace elements or other impurities. These impurities are the product of the innovative nature of the reaction or component design being developed. They are undesirable because they may interfere with recycle process streams (streams that feed materials from one place in the plant to a point earlier in the plant), intermediate process streams (streams in the middle of the plant that lead from one step to the next), or the proper operation of the catalyst.

Table 3.7

PCTNEW: PARTIALLY FILLED WORKSHEET FOR COST ESTIMATION ERROR CALCULATION

	A. Variable Name	B. Assigned Value				C. Multiplied by		D. Equals
1.	COMPLEXITY	8	x			.011	=	.088
2.	PCTNEW	41	x			.003	=	.123
3.	IMPURITIES	______	x			.021	=	______
4.	PROJECT DEFINITION	______	x			.040	=	______
5.	PROCESS DEVELOPMENT	__	x [	]	x	.024	=	______
6.	Subtotal							______
7.	INCLUSIVENESS	______	x			.0011	=	______
8.	Subtract line 7 from line 6							______
9.	A constant							1.122
10.	Put the number from line 8 here							______
11.	Subtract line 10 from line 9 (COST ESTIMATION ERROR)							______
12.	Capital cost estimate for plant							$____M
13.	Divide line 12 by line 11 (EXPECTED CAPITAL COST)							$____M

Although impurities exist in intermediate process streams, they are particularly a problem for processes that involve catalysis or extensive recycle in which the buildup of impurities can cause corrosion. "Catalysis" refers to chemical processes in which chemical reaction rates (that is, how fast the reaction occurs) are affected by a substance that may or may not change during the reaction. A substance so used is called a catalyst. Normally, a catalyst is used to speed up a chemical reaction. Catalysts are often sensitive to impurities in the process stream, which can coat or chemically alter the catalyst's form (called poisoning) to such an extent that it is unable to perform its function in the chemical reaction. Because catalysis is often used at critical points in the process (such as in the primary reactor), catalytic poisoning can be serious. Either a new form of the catalyst must be found, the impurities must be cleaned up before the catalytic reaction, or the catalytic process step must be redesigned. All of these solutions can be costly. Sometimes the impurity problem occurs within extensive recycle streams in which trace elements (chemical elements present in minute quantities) accumulate or build up over time. Often this build-up forms a corrosive material that then damages tubing, valves, or some other piece of equipment. Again, this damage can be expensive to correct, especially if it becomes necessary to redesign that portion of the plant.

The value assigned to the IMPURITIES variable ranges from 0 to 5 according to the following guidelines:[3]

0. No problem or not applicable: no recycle streams and no catalytic reactions; absolutely no problems encountered during process development; generally applies only to standard technology that is using the same feedstock that it used in the past.
1. No real impurity problems encountered during development of the process, but the design includes at least one recycle stream or at least one catalytic reaction; this value is generally applied to designs that contain small, innovative wrinkles on what is otherwise standard technology.
2. Mild impurity problems (that is, problems easily solved) were encountered during the process development in one or more of the development facilities: bench scale reactions, process development units, component test facilities, pilot plants, or semiworks facilities.
3. For the most part, mild impurity problems were encountered during the process development in one or more of the development facilities (see 2); performance of the development facility is not affected; but at least one significant problem developed that required a slight redesign of a recycle stream (or its related equipment) or of a catalytic process step.
4. At least one major impurity problem encountered during the process development in one or more of the development facilities (see 2); performance of the development facility af-

[3]We note here that the guidelines were suggested to respondents only when they asked for them. Many respondents simply rated the impurities problem on a scale of 0 (not applicable) to 5 (major source of difficulties), without receiving further guidance. We suggest that the same approach be taken for a user of this manual.

fected adversely, but not substantially; some redesign is necessary to prevent the problem from occurring in the commercial unit.

5. At least one major impurity problem encountered during the process development in one or more of the development facilities (see 2); performance of the development facility affected adversely, possibly to the point of unscheduled shutdown; a significant redesign effort is necessary to prevent the problem from occurring in the commercial unit.

Note that an impurity-related problem can be rated as severe (toward the high end of the scale) even though it had been solved in the development facility and had been taken into account with respect to the design of the commercial unit. Furthermore, it does not matter whether the problem occurred early or late in the process development. We found in the Pioneer Plants Study that problems tended to resurface in commercial units, even though those same problems had been detected and fixed in development facilities. There are two reasons for this resurfacing of problems. The first is that the accommodation made to the commercial design is a fix in theory only, and proves ineffective when the full-scale plant is built. When a fix *is* effective—a cleanup step or redesign—it can be expensive, thus contributing to the cost growth. The second reason is that the impact of a problem on the commercial unit is often underestimated at the time the problem is detected. Consequently, little or no effort is made to correct the commercial design so that the problem will not reoccur. Again, correction during construction or later can be expensive.

Example Facility

The old waste facility, which preceded our Example Facility and acted as a development facility, experienced impurity-related problems. The value of the IMPURITIES variable for the Example Facility is 4, which indicates fairly severe problems. Impurity buildup in the old plant had caused corrosion problems in some of the vessels; the problems were solved by shutting down the plant and performing maintenance. Because the degraded performance of the old plant was not severe, however, the value for IMPURITIES is 4 instead of 5.

In the 1975 design for the Example Facility, corrective action had not been taken for the corrosion noted in the old facility. However, during the engineering work for the 1978 design, the engineers decided to use Nitronic 50 (a material of construction) in the design of those vessels that had corrosion problems. If the Pioneer Plants Study were being applied to the 1978 design, the IMPURITIES variable would still rate a 4, regardless of the fact that the problem had been noted and accounted for in the new design. We found during our work on the Pioneer Plants Study that problems that occurred during process development were related to cost growth even though apparently corrective measures had been taken.

Other Comments on IMPURITIES

Asking questions of a plant expert to assess the IMPURITIES variable can take the form, "What problems have you had during process development with respect to impurities in the process streams?" or "Did impurities cause any catalyst poisoning or other problems?" or "Did you experience impurity problems in any of the recycle streams?" Questions about similar problems during process development should also be asked. We found that a high value for the IMPURITIES variable was generally associated with high values for other process development problems. These other problem areas fell into four categories:

- Temperature tolerances and peaks
- Pressure tolerances and peaks
- Corrosion
- Abrasion

"Temperature tolerances" refers to problems with controlling the temperature inside a vessel or other piece of equipment within a specific temperature range. "Temperature peaks" refers to problems associated with temperatures that are higher than those for which there is prior commercial experience. It also refers to the problem of keeping the temperature uniform throughout a volume, such as a reactor vessel. "Pressure tolerances" and "pressure peaks" are directly analogous to their temperature counterparts. Corrosion refers to the wearing away of a material through a chemical reaction (as opposed to a physical action). Impurities in a process stream can cause corrosion, but corrosion can also be caused or exacerbated by high temperatures because the rate of corrosion tends to increase with rising temperature. Abrasion refers to the wearing away of a material by friction.

The above problem areas can be used as a check on the value assigned to IMPURITIES. If, for example, a development facility experiences severe corrosion problems and suffers from temperature problems within the reactor that cause a partial shutdown of the facility, then one should be suspicious if the value for IMPURITIES is low, say a 0 or a 1. If there are severe problems with temperature, pressure, corrosion, or abrasion, then problems with impurities are also likely. This correlation is especially high between impurities and corrosion. This does not mean that someone who ranks impurities high and corrosion low is wrong. Rather, one should be suspicious of such a case and probably push for more information about the types of difficulties encountered during process development.

Summary of the Variable IMPURITIES

IMPURITIES is a ranking on a scale of 0 to 5 of the extent to which problems with impurities were experienced during the development of a process. This variable is used in the cost estimation error equation. The range in the Pioneer Plants Study was 0 to 5 with an average of 2.0. The value for the Example Facility is 4. Impurity problems are most likely to occur in normal process streams, recycle streams, and steps involving catalysis. A value close to 5 indicates that the impurity problems encountered were severe enough to seriously degrade the development facility's performance. Problems with impurities often occur not in isolation, but rather in conjunction with problems of temperature, pressure, corrosion, and abrasion.

Table 3.8 shows how the value for IMPURITIES is recorded for the cost estimation error equation.

WASTE (PERFORMANCE EQUATION)

The definition of WASTE is the amount of design difficulty encountered with waste handling. The value for WASTE in the Pioneer Plants Study ranges from 0 to 5, with an average of 2.0. This variable is used in the plant performance equation, and suggests that regulatory requirements may affect plant performance.

Working Definition

The variable WASTE is a subjective ranking on a 0 to 5 scale of how difficult it was to design the waste handling portion of the plant. A 0 indicates that there was no difficulty at all and a 5 indicates that there were significant problems. The scale is similar to that for IMPURITIES. Although subjective, we have found that the scale is easily applied, and that engineers generally agree within one point on the scale.

Table 3.8

IMPURITIES: PARTIALLY FILLED WORKSHEET FOR COST ESTIMATION ERROR CALCULATION

A. Variable Name	B. Assigned Value		C. Multiplied by		D. Equals
1. COMPLEXITY	8	x	.011	=	.088
2. PCTNEW	41	x	.003	=	.123
3. IMPURITIES	4	x	.021	=	.084
4. PROJECT DEFINITION	______	x	.040	=	______
5. PROCESS DEVELOPMENT	__ x [ ]	x	.024	=	______
6. Subtotal					______
7. INCLUSIVENESS	______	x	.0011	=	______
8. Subtract line 7 from line 6					______
9. A constant					1.122
10. Put the number from line 8 here					______
11. Subtract line 10 from line 9 (COST ESTIMATION ERROR)					______
12. Capital cost estimate for plant					$____M
13. Divide line 12 by line 11 (EXPECTED CAPITAL COST)					$____M

The 0 to 5 scale does not have a rigid set of criteria by which to assign the ranking for a particular plant. We offer the following as a guideline:[4]

0. Absolutely no problems were encountered with the design of the waste handling; the waste handling process steps are

[4]As we noted for the variable IMPURITIES, these guidelines were offered only in the rare case when they were asked for. Most respondents simply rated the WASTE variable on a scale of 0 (not applicable) to 5 (major source of difficulties), without receiving further guidance. We suggest that the same approach be taken for a user of this manual.

completely standard, and the wastes they are handling are well known and have been handled many times in other plants in the United States or Canada.

1. No problems were encountered; the design is standard, and the wastes are only slightly different from the wastes the design was originally intended for.
2. A minor problem was encountered for one of the following reasons:
   a. The steps were standard but included an innovative wrinkle in the technology.
   b. The wastes they are being employed to handle are quite a bit different from the wastes for which the steps were originally designed, and minor design changes were therefore required.
   c. Regulatory changes required some minor design changes.
3. A number of minor problems were encountered, for the reasons given in 2.
4. Major problems were encountered, (if, for example, the amount of time or the level of engineering effort had to be increased to complete the design) for any of the following reasons:
   a. The steps were new in commercial use.
   b. Major design changes were required to handle the particular wastes.
   c. Regulatory changes required major design changes.
5. Major problems were encountered that also affected the design of the other parts of the plant; the reasons for the design changes may be any of those given in 4.

The waste handling design problems do not have to be technical; for example, the spent shale from oil shale technologies is roughly 25 percent larger than the original shale. The waste handling problem with spent shale may have more to do with where to put the shale and how to get it there, rather than with any chemical or physical processing. The design problems may also have to do with additional tests on the wastes to determine whether any design changes will be required.

When the waste handling design problems are technical, they sometimes are noted from the running of pilot plants or other development facilities. These units suggest problems, such as an unexpectedly corrosive waste product, for which fixes must be designed. Computer simulations, when they are sophisticated enough, also may suggest whether a proposed design is adequate to handle the product waste.

Example Facility

The Example Facility is an unusual example for the WASTE variable because its *product* is waste. Most process plants produce waste in addition to their products. The value for WASTE in the Example Facility is 2 because a minor problem was encountered during the development of the facility. That problem had to do with the abrasive quality of the powdery waste and the effect of that abrasion on the design of about a dozen elbow joints (joints in piping that allow the pipe to bend at a right angle). The design solution, which we will not detail here, was straightforward and presented no serious difficulty.

No other problems were associated with the waste handling steps of the Example Facility, largely because the old facility had been operating satisfactorily much longer than it had been originally designed for, and the waste problems were well understood.

Other Comments on WASTE

If a technology is being used for the first time in the United States or Canada, the WASTE variable will probably fall at the higher end of the 0 to 5 scale. The reason is that because both the United States and Canada have strong environmental regulations, the transfer of a technology from abroad is likely to call for new waste handling techniques.

If the heat and mass balance equations (discussed below) are not well known, it is again likely that the WASTE variable will fall higher on the scale. The reason is that waste streams are part of the heat and mass balance equations, and to the extent that these equations are unknown or suspect, the WASTE variable would be assigned a high value to reflect the necessary new design work.

When the wastes being handled are solid (instead of liquid or gas), there is reason to suspect that the WASTE variable will be higher, not lower. The reason is that solid wastes in general are little understood, and it may be necessary to do a careful redesign of the waste handling steps.

Summary of the Variable WASTE

WASTE is a 0 to 5 ranking of the severity of problems encountered in development with waste handling. This variable is used in the performance equation. The range in the Pioneer Plants Study was 0 to 5 (by definition) with an average value of 2. The value for the Example Facility is 2. WASTE is correlated positively with the first-time use of a technology in the United States or Canada, and with the extent to which the heat and mass balance equations are unknown. Waste handling design problems can arise from technological innovation, changes in environmental regulations, or difficulties with other aspects of the project.

Table 3.9 shows how to record the value of WASTE for the plant performance equation.

Table 3.9

WASTE: PARTIALLY FILLED WORKSHEET FOR PLANT PERFORMANCE CALCULATION

A. Variable Name	B. Assigned Value		C. Multiplied by		D. Equals	
1. NEWSTEPS	3	x	9.69	=	29.1	
2. WASTE	2	x	4.12	=	8.2	
3. SOLIDS	______	x	17.9	=	______	
4. Subtotal				=	______	
5. BALANCE EQUATIONS	______	x	.33	=	______	
6. Subtract line 5 from line 4					______	
7. A constant					85.8	
8. Put the number from line 6 here					______	
9. Subtract line 8 from line 7 (PLANT PERFORMANCE) ...					______	percent

SOLIDS (PERFORMANCE EQUATION)

The SOLIDS variable classifies a plant as solids-handling, which we define as handling solids as a feedstock, intermediate material, or as a product. The value for SOLIDS is either 0 or 1: 0 if the plant does not handle solids, and 1 if it does. There were 15 solids-handling plants among the 44 plants in the Pioneer Plants Study. This variable is used in the plant performance equation. In a crude way, SOLIDS takes into account but does not explain the general difficulty of processing solid materials.

Working Definition

Any plant that handles or processes a solid material along the main process stream, including the waste step, is considered a solids-handling plant for our purposes. All synthetic fuel plants using coal or shale as a feedstock are solids-handling plants, as are chemical plants that start with liquids and gases but produce a solid chemical as a product. A plant whose sole solid is a catalyst would not be classified as a solids-handling plant.

Example Facility

Because the Example Facility starts with a liquid feedstock (radioactive waste) and produces a solid waste, SOLIDS takes on a value of 1.

Other Comments on SOLIDS

We found that, other things being equal, solids-handling plants suffered from much poorer performance than either liquids- or gas-handling plants. The solids-handling plants in the data base tend to have more new steps and a smaller percentage of known heat and mass balance equations. If a plant is a solids-handling plant, therefore, a user of the Pioneer Plants Study should be especially thorough about the variables NEWSTEPS and BALANCE EQUATIONS, and should be suspicious if the value assigned to NEWSTEPS is low, or if the value assigned to BALANCE EQUATIONS is high.

Summary of SOLIDS

SOLIDS has a value of 1 if the plant processes solid materials, and 0 if it processes only gases and liquids. This variable is used in the plant performance equation. The Example Facility is a solids-handling plant because its product is a solid. Solids-handling plants tend to be those with higher values of NEWSTEPS, WASTE, and BALANCE EQUATIONS.

Table 3.10 shows how to record the value of SOLIDS for the plant performance equation.

Table 3.10

SOLIDS: PARTIALLY FILLED WORKSHEET FOR PLANT PERFORMANCE CALCULATION

	A. Variable Name	B. Assigned Value		C. Multiplied by		D. Equals
1.	NEWSTEPS	3	x	9.69	=	29.1
2.	WASTE	2	x	4.12	=	8.2
3.	SOLIDS	1	x	17.9	=	17.9
4.	Subtotal				=	______
5.	BALANCE EQUATIONS	______	x	.33	=	______
6.	Subtract line 5 from line 4					______
7.	A constant					85.8
8.	Put the number from line 6 here					______
9.	Subtract line 8 from line 7 (PLANT PERFORMANCE) ...					______ percent

BALANCE EQUATIONS (PERFORMANCE EQUATION)

The definition of BALANCE EQUATIONS is the percentage of heat and mass (material) balance equations that were known from commercial experience at the time of the initial capital cost estimate. The values for BALANCE EQUATIONS in the Pioneer Plants Study range from 0 to 100 percent with an average of 54 percent. This variable is used in the plant performance equation, and is another measure of innovation. While we cannot be certain, it is likely that the variable BALANCE EQUATIONS picks up the effect of the location of the innovative technology in the plant, as well as the effect of instrumentation from prior solids facilities that provides theoretic knowledge of the behavior of solids.

Working Definition

The heat and mass balance equations are the basic equations that govern flows in the plant. They are necessary for estimating the size of all equipment and for determining the needs for energy in and out of the plant at different points. They are most accurate when based on prior experience with commercial-scale equipment that is the same as the equipment to be used in the proposed plant—a successful gasifier, for example, that is also to be used in a proposed synthetic fuels plant.

Such experience is often not available, especially for innovative plants; if so, the heat and mass balance equations for the gasifier must be calculated on the basis of some other information. This information may be generated from theory, from tables based on empirical research, from a full-scale test facility in which the gasifier has been installed, from a scaled-down version of the gasifier in a pilot plant or other development unit, or from a computer program that models how the gasifier will work in the proposed plant. None of those sources is as valuable as commercial experience, of course.

BALANCE EQUATIONS is estimated solely on the basis of prior commercial experience with identical equipment. Thus, a value of 80 percent for BALANCE EQUATIONS means that 80 percent of the heat and mass balance equations were calculated on the basis of prior commercial experience, and 20 percent were calculated on the basis of analogies with full-scale test facilities, smaller-scale plants or development units, or computer models, or from theory.

A process engineer familiar with the plant in question usually estimates BALANCE EQUATIONS off the top of his head rather than going through each equation (of which there may be thousands) and counting up those based on prior commercial experience. While this simple estimation method is highly subjective, we have found that it is highly reliable in explaining plant performance, even though the process engineers we queried were not given clear instructions on how to make their estimates.

Example Facility

At the time the initial estimate was made (1975), the value of BALANCE EQUATIONS for the Example Facility was about 90 percent. That figure is generally much lower for plants with as much innovation (three new steps) as the Example Facility. The reason BALANCE

EQUATIONS had a high value for this facility was that the innovation of the new process steps and their placement in the plant stream permitted a calculation of the balance equations from prior commercial experience. Let us examine these new steps one at a time in this light. The calciner vessel, while new at this scale, was based on a calciner vessel in the old waste facility that was 80 percent of the full-scale commercial size. The other new aspect of the calciner vessel was a removable insulation lining, which does not significantly affect the heat and mass balance equations. The second and third new steps were the decontamination facility and the dry cleanup step. While the uncertainty of these steps certainly affected the balance equations, the effect was not great. The reason is that these steps were located at the back end (the last part) of the plant. Thus any uncertainties in the calculation of the balance equations for these steps did not propagate downstream in the calculation of the other steps' equations.

Other Comments on BALANCE EQUATIONS

The variable BALANCE EQUATIONS *probably* measures three items we were not able to address explicitly: (1) where in the plant stream the new units were located, (2) the level of innovation of the new steps, and (3) innovation that did not get counted in our block count of new steps.

To give an example of (1), suppose that the calciner step were being used for the first time in the Example Facility, and that the earlier plant had not used such a vessel. Because the calciner is located in the front end of the plant, it could be difficult to calculate the balance equations for the remainder of the plant. The balance equations build on one another, and errors may be passed along during the calculation of the balance equations downstream. While it does not follow that none of the downstream balance equations could be calculated, assumptions would have to be made about the materials and energy flows from the calciner step, and those assumptions might or might not prove correct. There is no hard and fast rule, but we suspect that a plant with a highly innovative step at the front end will probably have a value for BALANCE EQUATIONS no higher than 60 or 70 percent.

The calciner vessel is also an example of (2) above. Because of the limited innovation of that vessel, the heat and mass balance equations at that step did not suffer from a loss in accuracy. Greater innovation of the calciner vessel would have lowered the overall balance equations of the plant.

It sometimes happens that innovation in a plant does not get fully accounted for in our block count (see the variables COMPLEXITY and NEWSTEPS). A general example of this is a new type of valve that is scattered throughout the plant. Because the valves are between the individual process steps, they are not counted by the NEWSTEPS variable. But the uncertainty of the valves would be picked up in the calculation of BALANCE EQUATIONS, which would reflect the uncertain performance of the valve. Note that in such cases it makes sense that the performance of the plant is affected, rather than the cost growth, because the costs of non-process-step equipment are generally small relative to the cost of the entire plant.

Summary of the Variable BALANCE EQUATIONS

BALANCE EQUATIONS is the percentage of the plant's heat and mass balance equations known from prior commercial experience. This variable is used in the plant performance equation. The range in the Pioneer Plants Study was 0 to 100 with an average of 54 percent. The value for the Example Facility is 90 percent. This variable is estimated on the basis of what is known about the process from prior commercial experience, rather than from small development facilities or from computer models. BALANCE EQUATIONS probably picks up the effect of the location of the innovative steps in the plant, their degree of innovation, and innovation of non-process-step equipment.

Table 3.11 shows how to record the value of BALANCE EQUATIONS in the plant performance equation. The rest of the worksheet will be filled out in Sec. V of this manual. The next section discusses the project-related variables.

Table 3.11

BALANCE EQUATIONS: PARTIALLY FILLED WORKSHEET FOR PLANT PERFORMANCE CALCULATION

	A. Variable Name	B. Assigned Value		C. Multiplied by		D. Equals
1.	NEWSTEPS	3	x	9.69	=	29.1
2.	WASTE	2	x	4.12	=	8.2
3.	SOLIDS	1	x	17.9	=	17.9
4.	Subtotal				=	______
5.	BALANCE EQUATIONS	90	x	.33	=	29.7

6. Subtract line 5 from line 4 .... ______

7. A constant 85.8

8. Put the number from line 6 here .... ______

9. Subtract line 8 from line 7 (PLANT PERFORMANCE) ... ______ percent

IV. PROJECT-RELATED INFORMATION

Three variables remain to be discussed, all of them concerned with how well the project has been defined. The format of this section resembles that of Sec. III, which dealt with the technology-related variables: We supply a formal and working definition of each variable, followed by the value of that variable for the Example Facility, and then a summary of the variable. The three variables discussed in this chapter are PROJECT DEFINITION, PROCESS DEVELOPMENT, and INCLUSIVENESS. Again, the project manager will be able to provide information to permit the users of this manual to assign values to the variables. Those values can and do change during a project's development. As a project becomes better defined, these variables reflect the improved level of information available to be included by the estimator.

PROJECT DEFINITION (COST EQUATION)

PROJECT DEFINITION is a numerical rating from 2 to 8 that measures the extent to which the cost estimate uses site-specific information and the level of detailed engineering accomplished by the date of the cost estimate. Unlike the other variables, PROJECT DEFINITION is a composite variable, which means it has more than one component. Its two components—site information and engineering level—are equally valued in assigning a numerical rating to PROJECT DEFINITION. The values for PROJECT DEFINITION in the Pioneer Plants Study range from 2 to 8 with an average of 3.25. This variable is used in the cost estimation error equation, and is a gauge for how well a project is defined with respect to site-related and engineering-related information.

Working Definition

PROJECT DEFINITION is a composite of the level of engineering and the amount of site information. The site information is further broken down into four components, which are averaged together. Thus, PROJECT DEFINITION is composed of five separate values, four site-related and one engineering-related, combined in the following manner:

$$\text{PROJECT DEFINITION} = [(\text{site1} + \text{site2} + \text{site3} + \text{site4})/4)] + \text{Engineering Level} \tag{4.1}$$

We will discuss each one of these and provide a means for assigning a numerical value for each.

Definition of Site1, Site2, Site3, and Site4. "Site1" is a quantitative assessment of the extent to which the on-site and off-site unit configurations were included in the cost estimate. On-site and off-site unit configurations are simply the physical layouts of the process steps themselves as well as the auxiliary facilities, such as roads, fences, administration buildings, impoundment dikes, storage facilities, and utilities. Such configurations can be done definitively only after a site has been chosen, because the qualities of a site affect the configurations. For example, the engineers may organize plant layout to take advantage of the grade of a specific site.

"Site2" is a quantitative assessment of the extent to which soils and hydrology data are included in the estimate. The "soils data" refer to a set of information that describes the site technically, and include such items as the grade of the site and how much weight the soil can bear. The "hydrology data" refer to the distribution and circulation of water in and on the site, and allow the engineers to plan the placement of the various plant structures. Taken together, the soils and hydrology data provide an overall picture of the site, including its qualities and its limitations as a place for the proposed plant.

"Site3" is a quantitative assessment of the extent to which health and safety requirements are incorporated into the cost estimate. Have all such local, state, and federal government requirements been identified and incorporated for the site in question? For example, have local worker safety, equipment safety, and OSHA standards been recognized for the site? Have those requirements or standards been accounted for in the cost estimate?

"Site4" is a quantitative assessment of the extent to which environmental requirements are incorporated in the cost estimate. Have the state, local, and federal environmental standards been identified and incorporated for the site in question? Are the applicable solid waste disposal standards known and accounted for in the current plant design? Have all Environmental Protection Agency (EPA) requirements been recognized and their costs included in the current cost estimate? Knowledge of generic requirements, such as those from the national Clean Air Act standards, is necessary but not sufficient. Local requirements for the actual site must also be known and accounted for in the plant design and cost estimate.

Evaluating Site1, Site2, Site3, and Site4. In general, the more information known about each of the "site" variables, the lower the cost estimation error. Each of the four site variables is assigned a value based on the same set of criteria. Table 4.1 displays how the quantitative assignment is made for the above four site variables.

Table 4.1

HOW SITE1, SITE2, SITE3, AND SITE4 ARE ASSESSED

```
Site1, Site2, Site3, or Site4 are assigned a value of

  1 if the work is definitive and completed
  2 if the work is preliminary or limited in scope
  3 if the work is assumed or implicit in the estimate
  4 if the item is not used in the estimate
```

Each site variable is assigned a 1, 2, 3, or 4, depending on whether it meets the criteria summarized in Table 4.1. Site1, site2, site3, and site4 may or may not have the same numerical value. That is, a cost estimate could conceivably be based on a site for which the health and safety regulations are thoroughly known and accounted for, but for which no soils or hydrology work has been done. In such a case, site3 would be assigned a value of 1, while site2 would be assigned a value of 4.

A value of 1 ("definitive and completed work") means that there is no reasonable chance that any more work will be required. A value of 1 for site1, for example, would indicate that a definite site has been chosen, that all the necessary descriptors affecting the plant configuration have been identified, and that the layouts of the process units and the off-site units have been drawn up with no expectation of change. Note that it is not possible to assign a value of 1 to any of the site variables unless the exact final site has been chosen.

A value of 2 ("preliminary or limited in scope") means that some or even most of the work has been performed, but that there is a reasonable chance that more remains. A value of 2 for site3, for example, would indicate that many of the local, state, and federal health and safety regulations are known for the site in question, but not all of them. Or a value of 2 might indicate that *all* of the appropriate health and safety regulations are known, but that not all of them are completely reflected in the cost estimate, and that later cost estimates will be changed to reflect these regulations. In general, a value of 2 means that some work on the actual site has been completed, but not all.

A value of 3 ("assumed or implicit") means that assumptions were made about the site, and that these assumptions were used to construct the cost estimate. A value of 3 for site4, for example, means that the local and state environmental requirements are not exactly known for the site, but that the federal regulations are understood. A value of 3 could also mean that the site has not yet been chosen, and that the engineers are making assumptions about what the site might look like and then basing their cost estimate on that hypothetical site. Also, it might mean that the engineers are basing their cost estimate on a real site, using data collected about that site, but that the plant will be built somewhere else. In general, a value of 3 indicates that a number of assumptions are made about the site in order to put together a cost estimate.

A value of 4 ("not used in the estimate") means that this category was not considered during cost estimation. A value of 4 for site2, for example, means that no soils or hydrology data at all were used to put together the current plant design or cost estimate. This category is generally reserved for the earliest of estimates for which there is little information.

Definition of "Engineering Level." "Engineering Level" is a quantitative assessment of the level of engineering on which the current cost estimate is based. The level can range from completed design specification to little or no engineering completed. The word "engineering" as we are using it here refers to both detailed engineering—the actual designs that permit construction to take place—and the preliminary engineering that is accomplished before detailed engineering.

Evaluating "Engineering Level." "Engineering Level" is assigned a quantitative value based on a four-point scale. (See Table 4.2.) It is given a value of 1 if design specification is completed, that is, when all the engineering that needs to be done for the plant is finished. This engineering may be performed by either the plant owner or by an architectural/engineering firm that is hired. The product of this detailed engineering effort is a set of drawings and specifications from which manufacture and fabrication of the individual process units may begin. Construction does not have to be postponed until detailed design engineering is complete. In some cases construction may begin when detailed engineering is 30 percent complete.[1]

[1]All percent figures given for Engineering Levels 1 through 4 are approximate and were not part of the original question to respondents. We present them here as a crude

Table 4.2

How Engineering Level Is Assessed

Engineering Level is assigned a value of

1 if there is a design specification (engineering completed)

2 if the work to date is characterized by a study design of moderate or extensive basis

3 if the work to date is characterized by a study design of limited basis

4 if the work to date is a screening study

A value of 2 indicates that the detailed engineering is between 50 percent and 100 percent complete. This level of engineering effort is what we mean by a design study of moderate or extensive basis. Construction may have already begun at this stage of engineering completeness.

A value of 3 indicates that the detailed engineering is less than 50 percent complete. This level of engineering effort is what we mean by a design study of limited basis. Construction probably will not have started. If no detailed engineering has been begun, the preliminary engineering—that which is required for detailed engineering—must be completed for a plant to receive a value of 3 for "Engineering Level."

A value of 4 indicates that the design work to date is basically a screening study. This level of engineering includes little (a few percent), if any, detailed engineering. Plants at this stage of engineering are still being examined for worthiness and possibly still being compared with alternative plant designs. This level often describes plants that are still in the project definition stage of their development.

guideline for the user's understanding. We suggest that the user not give the percentages to a respondent unless necessary for explanatory reasons.

Example Facility

The value for PROJECT DEFINITION for the Example Facility is 5.25 for the 1975 cost estimate. (Remember that the scale ranges from a low of 2, indicating a very well-defined plant, to an 8, indicating a virtually undefined plant.) Table 4.3 displays the values for the elements of PROJECT DEFINITION for the Example Facility. The numbers shown for unit configurations, soils and hydrology, environmental requirements, and health and safety requirements are taken from Table 4.1. The number shown for the level of engineering is taken from Table 4.2. The 5.25 is found by inserting the numbers in Table 4.3 into Eq. (4.1).

Table 4.3

EXAMPLE FACILITY VALUES FOR THE PROJECT DEFINITION VARIABLE

Component	Value[a]
Site1--unit configurations	1
Site2--soils and hydrology	1
Site3--health and safety requirements	1
Site4--environmental requirements	2
Engineering level	4

[a]Replicating Eq. (4.1) using these values:
(1 + 1 + 1 + 2)/4 + 4 = 5/4 + 4 = 1.25 + 4 = 5.25

Note that the site-related information was rather well developed for the 1975 estimate, at which time work had not yet begun on the detailed engineering. The only item that was not thoroughly understood was the earthquake requirement. The on-site and off-site unit configurations were complete and definitive, and the value assigned to site1 is a 1. The soils and hydrology data had been collected several years earlier, as were the health and safety requirements, and each of those is also assigned a value of 1. Most of the environmental requirements were also understood. The earthquake standards promulgated up to 1975 were understood as well, but the sponsors of the Example Facility knew that new and probably somewhat stricter regulations were in the offing. Because the work accomplished at that time was preliminary, a value of 2 is assigned to site4.

The level of engineering is assigned a value of 4 because detailed engineering had not yet begun when the 1975 estimate was prepared. At that time the project was undergoing project definition, and engineering performed was of the kind needed to ensure that the project was sound.

To some readers it might seem incongruous that site work would have been so well understood when virtually no engineering had been completed. Indeed, this is not typically the case. The reason for this apparent discrepancy is that the site chosen was literally next door to the old waste facility. In addition, there were other recently built facilities within yards of the Example Facility's site. When these facilities were constructed, the same site information was collected. Thus, the sponsors of the Example Facility started with a site that was well understood from previous efforts.

Summary of Project Definition

PROJECT DEFINITION, used in the cost estimation error equation, is made up of two components, site information and engineering information. The "site information" component is further broken down into four elements: on-site and off-site unit configurations, soils and hydrology, health and safety requirements, and environmental standards. To arrive at the value for PROJECT DEFINITION, these elements are assigned a value on a 1 to 4 scale, averaged together, and then added to the value assigned to the level of engineering. The range in the Pioneer Plants Study was 2 to 8, with 2 indicating complete definition, and 8 indicating least definition. The average value in that study was 3.81. The value for the Example Facility is 5.25. This facility had an unusually well-defined site because of prior work on other nearby facilities. The engineering that had been done was typical of that performed for screening studies. Table 4.4 shows how the value of PROJECT DEFINITION is recorded for the cost estimation error equation. Note that the value 5.25 is placed both on line 4 and line 5.

PROCESS DEVELOPMENT (COST EQUATION)

PROCESS DEVELOPMENT is the stage of the process's technical development. Its value in the Pioneer Plants Study is either 0 or 1. A value of 0 indicates that the process is fairly well understood, while 1 indicates that a significant amount of R&D that remains to be done. This variable is used in the cost estimation error equation along with

Table 4.4

PROJECT DEFINITION: PARTIALLY FILLED WORKSHEET FOR COST ESTIMATION ERROR CALCULATION

A. Variable Name	B. Assigned Value		C. Multiplied by		D. Equals
1. COMPLEXITY	8	x	.011	=	.088
2. PCTNEW	41	x	.003	=	.123
3. IMPURITIES	4	x	.021	=	.084
4. PROJECT DEFINITION	5.25	x	.040	=	.210
5. PROCESS DEVELOPMENT	__ x [5.25]	x	.024	=	______
6. Subtotal					______
7. INCLUSIVENESS	______	x	.0011	=	______
8. Subtract line 7 from line 6					______
9. A constant					1.122
10. Put the number from line 8 here					______
11. Subtract line 10 from line 9 (COST ESTIMATION ERROR)					______
12. Capital cost estimate for plant					$____M
13. Divide line 12 by line 11 (EXPECTED CAPITAL COST)					$____M

the PROJECT DEFINITION variable. We found that PROJECT DEFINITION is associated with greater cost growth when process development is incomplete. PROCESS DEVELOPMENT for a given estimate provides a way to capture the stage of the technical knowledge of the process.

Working Definition

The development of a process proceeds from an idea—usually, but not always, formed in a lab—to an R&D procedure that culminates in the use of that process in a first-of-a-kind process plant. The R&D procedure has many stages, among which may be small-scale lab testing, small process-development units, integrated pilot plants, full-scale component test facilities, and small-scale commercial plants. Naturally, the farther along a firm has proceeded toward the commercial plant, the more it should understand about the process itself. PROCESS DEVELOPMENT attempts to take a snapshot of the point at which a particular cost estimate has been made with respect to the understanding of the technical process. Table 4.5 summarizes how PROCESS DEVELOPMENT is assigned 0 or 1, depending on the level of technical understanding.

Table 4.5

HOW THE VARIABLE PROCESS DEVELOPMENT
IS ASSIGNED A VALUE

PROCESS DEVELOPMENT is assigned a 1 if

most process information is obtained from small-scale laboratory experiments and literature

or

a coordinated R&D program is under way.

PROCESS DEVELOPMENT is assigned a 0 if

work is characterized by efforts to minimize the risk for commercial applications

or

major process uncertainties have been resolved and a design specification has been completed.

PROCESS DEVELOPMENT has a value of 1 if the understanding of the process is still in its early stages, marked by small-scale lab experiments, literature searches, or a coordinated R&D program that is still trying to resolve some process uncertainties. Generally, if any part of the process still contains unresolved technical, as opposed to engineering, uncertainties, then PROCESS DEVELOPMENT is assigned a 1. The important distinction between *process* and *engineering* uncertainties is that the latter are commonly resolved during detailed design engineering or even during construction and start-up, whereas process uncertainties, on the other hand, must be resolved before large capital funds are committed to the project.

PROCESS DEVELOPMENT is 0 if the understanding of the process is in its later stages, marked by research efforts that are directly aimed at building a commercial-scale facility. At that point, there is no question in the minds of the engineers that the process chemistry will work as expected; they base their confidence on empirical evidence gathered at a full-scale component test facility (such as those that exist for some gasifiers) or other large-scale pilot plants. The demonstration of the technology, which includes an understanding of the by-products, catalysts, and wastes, is virtually complete, and the only remaining step, assuming economic feasibility, is to build a commercial plant. All major technical process uncertainties have been resolved. A standard, or duplicate, plant would by definition have a value of 0 for this variable.

Example Facility

The Example Facility, while containing a considerable amount of new technology, had no technical process uncertainties at the time of the 1975 estimate. The old waste facility was a demonstration plant that proved the technical feasibility of this particular calcine process. The process worked so well, in fact, that the old facility was used for many years beyond its original plant life. All technical uncertainties with respect to the process, such as those related to the operation of the calciner vessel, were resolved prior to the 1975 cost estimate. The technical uncertainties referred to earlier in the discussion of the variable NEWSTEPS are related to engineering rather than the process itself. With all major process uncertainties resolved and with efforts geared toward the design of a commercial plant, PROCESS DEVELOPMENT is assigned a a value of 0 for the Example Facility.

Summary of the Variable PROCESS DEVELOPMENT

PROCESS DEVELOPMENT is the stage of the process's technical development. This variable is used in the cost estimation error equation, and takes on the values of 0 or 1 only. A value of 0 indicates that the process is well understood and characterized by efforts directed at building a commercial plant; 1 indicates that at least one major process uncertainty is unresolved and that the R&D effort is marked by small-scale experiments. The value of PROCESS DEVELOPMENT for the Example Facility is 0 because the old waste facility provides the necessary testing of the process itself.

Table 4.6 shows how to record the value of PROCESS DEFINITION for the cost estimation error equation.

Table 4.6

PROCESS DEVELOPMENT: PARTIALLY FILLED WORKSHEET FOR COST ESTIMATION ERROR CALCULATION

A. Variable Name	B. Assigned Value		C. Multiplied by		D. Equals
1. COMPLEXITY	8	x	.011	=	.088
2. PCTNEW	41	x	.003	=	.123
3. IMPURITIES	4	x	.021	=	.084
4. PROJECT DEFINITION	5.25	x	.040	=	.210
5. PROCESS DEVELOPMENT	0 x [5.25]	x	.024	=	0.0
6. Subtotal					____
7. INCLUSIVENESS	____	x	.0011	=	____
8. Subtract line 7 from line 6					____
9. A constant					1.122
10. Put the number from line 8 here					____
11. Subtract line 10 from line 9 (COST ESTIMATION ERROR)					____
12. Capital cost estimate for plant					$____M
13. Divide line 12 by line 11 (EXPECTED CAPITAL COST)					$____M

INCLUSIVENESS (COST EQUATION)

INCLUSIVENESS represents the completeness of a cost estimate with respect to three items: land, inventory, and personnel costs. The value for INCLUSIVENESS in the Pioneer Plants Study ranges from 0 to 100 percent with an average of 38 percent. This variable is used in the cost estimation error equation. INCLUSIVENESS estimates the thoroughness or detail of a cost estimate.

Working Definition

INCLUSIVENESS is measured by calculating the percentages of three items included in the scope of the estimate. Estimates that include all three are generally more accurate than those that do not. The three items are:

- Land—land purchase/leases/property rentals
- Inventory—initial plant inventory, warehouse parts/catalysts
- Personnel—preoperating personnel costs

Each item is coded 1 if it is included in the estimate, and 0 if it is not. The values are then added together and averaged. That average is then multiplied by 100 to obtain a percentage. Thus, the variable INCLUSIVENESS may take on one of four values: 0, 33, 67, and 100 percent. The formula for INCLUSIVENESS is

$$\text{INCLUSIVENESS} = (\text{Land} + \text{Inventory} + \text{Personnel})/3 \times 100 \quad (4.2)$$

"Land" refers to the site on which the plant is to be built. If the cost estimate includes the cost of the land, either in the form of a purchase or a lease, then Land is assigned a value of 1. The value is still 1 if the land was purchased prior to the cost estimate and therefore not included as part of the estimate itself. The reason is that there is no chance that land costs will contribute to any cost estimation error (the land has already been bought and the cost is known with certainty). Note that the site need not have been selected, only that there be an explicit cost for the site in the cost estimate. Land is also assigned a value of 1 if such costs are not to be charged to the project's capital cost and therefore are not subject to the cost growth of the estimate. If the cost of the land for the plant has not been included in the cost estimate, and if the land has not already been bought, then Land is assigned a value of 0.

"Inventory" refers to the cost of the initial plant inventory: warehouse parts, catalysts, and so on. The value of Inventory is 1 if an explicit cost is assigned to the initial plant inventory in the plant cost estimate. These inventory items are those needed to get the plant operating. If they are "assumed" into the cost estimate but not specifically included, then Inventory is coded 0. It is also coded 0 when these items are not considered at all in the estimate.

"Personnel" encompasses the preoperating costs of the plant and is also referred to as "initial labor costs," "start-up labor," "initial personnel costs," or something similar. The labor referred to is that needed after construction but before the start of operations. If costs are explicitly included for these items, then Personnel is assigned a value of 1. If they are not included or are simply assumed, Personnel is assigned a value of 0. Note that these costs are not necessarily associated with start-up costs.

The reason the INCLUSIVENESS variable is important seems to be that it compensates somewhat for the variation in the way firms handle project accounts. That is, some firms include the land in their estimates and some do not. From the twenty-odd items collected during the Pioneer Plants Study, the above three proved the most statistically significant in evaluating the cost estimation error of the data base. We suspect that this variable measures the detail of the information included in the estimate, rather than representing the above three categories alone. That is, these three items are simply a proxy for the level of estimate detail.

If there is any doubt that one of the items (Land, Inventory, or Personnel) is included in the cost estimate, then that item should be assigned a value of 0.

Example Facility

The Example Facility's 1975 cost estimate did not have Land, Inventory, or Personnel costs included explicitly. However, as we mentioned earlier, the site had already been purchased when the old waste facility was built. Because the land was already owned by the Example Facility's sponsors, Land is assigned a value of 1. The other items, Inventory and Personnel, are assigned a value of 0. The value of INCLUSIVENESS, then, is 33 percent, and is calculated in the following way:

$$\text{INCLUSIVENESS} = (1 + 0 + 0)/3 \times 100 = 33 \text{ percent} .$$

Summary of the Variable INCLUSIVENESS

INCLUSIVENESS measures the detail of a cost estimate. It is based on whether land, inventory, and personnel costs are included explicitly. This variable is used in the cost estimation error equation. The range in the Pioneer Plants Study is 0 to 100 percent with an average value of 38 percent. The value for the Example Facility is 33 percent. In general, the more of these items that are included, the more accurate is the cost estimate.

Table 4.7 shows how to record the value of INCLUSIVENESS for the cost estimation error equation.

The remainder of Table 4.7, which involves calculations, will be completed in the next section.

Table 4.7

INCLUSIVENESS: Partially Filled Worksheet for Cost Estimation Error Calculation

A. Variable Name	B. Assigned Value		C. Multiplied by		D. Equals
1. COMPLEXITY	8	x	.011	=	.088
2. PCTNEW	41	x	.003	=	.123
3. IMPURITIES	4	x	.021	=	.084
4. PROJECT DEFINITION	5.25	x	.040	=	.210
5. PROCESS DEVELOPMENT	0 x [5.25]	x	.024	=	0.0
6. Subtotal					______
7. INCLUSIVENESS	33	x	.0011	=	.036
8. Subtract line 7 from line 6					______
9. A constant					1.122
10. Put the number from line 8 here					______
11. Subtract line 10 from line 9 (COST ESTIMATION ERROR)					______
12. Capital cost estimate for plant					$____M
13. Divide line 12 by line 11 (EXPECTED CAPITAL COST)					$____M

V. APPLYING THE EQUATIONS TO THE EXAMPLE FACILITY

This section illustrates the use of the cost estimation error and plant performance equations by applying them to an estimate for the Example Facility. We use the values for the variables as discussed in the previous sections.

Section II explained the Example Facility's 1975 cost estimate of $52.1 million in 1975 constant dollars (that is, excluding the $7 million in escalation). Now we will use the $52.1 million figure as the base on which to estimate the cost estimation error. We will also calculate the plant's expected performance in months 7 through 12 after start-up; for this we need no base figure. The confidence intervals for the cost estimation error and the plant performance will also be presented. We will end with an example of an analysis testing the sensitivity of the predicted cost growth and performance to the input values chosen.

APPLYING THE COST ESTIMATION ERROR EQUATION

We will demonstrate how to apply the cost estimation error equation using Table 5.1 as a model. Table 5.1 is duplicated as Table A.1 in App. A, but without the numbers specific to the Example Facility. Thus, Table A.1 can be photocopied and used to apply the cost estimation error equation to another plant.

Variable Values and Application for Cost Estimate Error

Table 5.1 contains the variable names, the values assigned to those variables for the Example Facility, and the arithmetic instructions necessary to fill out the table. We will walk through Table 5.1 to show how the cost estimation error is calculated for the Example Facility.

Note that the value of 5.25 for PROJECT DEFINITION is written down in column B of both line 4 *and* in the brackets on line 5.

Line 6 is the subtotal of column D, lines 1 through 5. This value is 0.505 for the Example Facility.

Table 5.1

WORKSHEET FOR COST ESTIMATION ERROR CALCULATION
(Example Facility)

	A. Variable Name	B. Assigned Value		C. Multiplied by		D. Equals
1.	COMPLEXITY	8	x	.011	=	.088
2.	PCTNEW	41	x	.003	=	.123
3.	IMPURITIES	4	x	.021	=	.084
4.	PROJECT DEFINITION	5.25	x	.040	=	.210
5.	PROCESS DEVELOPMENT	0 x [5.25]	x	.024	=	0.0
6.	Subtotal					.505
7.	INCLUSIVENESS	33	x	.0011	=	.036
8.	Subtract line 7 from line 6					.469
9.	A constant					1.122
10.	Put the number from line 8 here					.469
11.	Subtract line 10 from line 9 (COST ESTIMATION ERROR)					.653
12.	Capital cost estimate for plant					$52.1M
13.	Divide line 12 by line 11 (EXPECTED CAPITAL COST)					$79.8M

The expected cost of the Example Facility is $79.8 million dollars in build-today, operate-today 1975 dollars.

Line 8 is the result of subtracting line 7 from line 6. This value, 0.469, is then placed in line 8 and line 10. Note that line 9 contains a constant, 1.122, which does not change from plant to plant.

Line 11 contains the result of subtracting line 10 from line 9. This value, 0.653, is the cost estimation error for the Example Facility 1975 cost estimate. Line 12 contains the capital cost estimate for the Example Facility in constant, build-today, operate-today 1975 dollars

—$52.1 million. Dividing the 52.1 by the 0.653 yields the estimated capital cost of the plant—$79.8 million—in constant 1975 dollars.[1]

Confidence in Cost Estimation Error

The first section of this manual introduced the notions of confidence in the model and the confidence interval. Let us illustrate these concepts, starting with confidence in the model. Table 5.2 compares the Example Facility's variable values for the cost estimation error equation with the range of those values for the Pioneer Plants data base. (Ignore the data base averages and standard deviations for the moment.)

Table 5.2

COMPARISON OF EXAMPLE FACILITY WITH PIONEER PLANT SAMPLE

		PPS Sample		
Variable	Example Facility	Range	Average	Standard Deviation[a]
COMPLEXITY	8	1-11	5.5	2.7
PCTNEW	41	0-95	25.6	24.0
IMPURITIES	4	0-5	2.0	1.8
INCLUSIVENESS	33	0-100	38	34.0
PROJECT DEFINITION	5.25	2-8	3.8	1.8

NOTE: PROCESS DEVELOPMENT is not included because it can only take on the values 0 and 1.

[a]A standard deviation is a measure of the spread of a variable. For example, a standard deviation of 2.7 for COMPLEXITY indicates that 68 percent of the plants in the data base have a value of COMPLEXITY between (5.5 - 2.7) and (5.5 + 2.7), or between 2.8 and 8.2.

[1]If we inflate the $79.8 million to 1980 dollars using the Chemical Engineering cost index, we get $116 million. The total actual cost of the plant in 1980 dollars is about $125 million. Thus, our $116 million estimate is about 7 percent below the actual cost, and represents a substantial improvement over the original 1975 estimate.

It is evident from Table 5.2 that the variable values for the Example Facility are well within the range of variable values for the Pioneer Plants Study. In fact, the only variable that *can* fall outside the range of the Pioneer Plants Study is COMPLEXITY. The reason is that the definitions of all the other variables preclude the possibility that their values might fall outside the ranges shown for the Pioneer Plants data base. (PCTNEW cannot exceed 95 percent because there must always be some costs that are not associated with new technology.) To determine whether it is appropriate to apply the cost estimation error equation to a particular plant, it is only necessary to check that that plant's COMPLEXITY count is somewhere within the range 1 through 11, inclusive.[2]

Let us now turn to the confidence interval. Refer again to Table 5.2, which contains the averages and standard deviations of the cost estimation error variables in the Pioneer Plants data base. Note that all the Example Facility variables except IMPURITIES are within one standard deviation of the Pioneer Plants Study values, and that IMPURITIES is just outside one standard deviation. When the variable values are roughly within two standard deviations of the Pioneer Plants Study averages, we can say that the confidence interval is no greater than plus or minus 0.09 for the cost estimation error equation.[3] Table 5.3 illustrates the confidence interval around the cost estimation error for the Example Facility.

Table 5.3 shows how to calculate the 68 percent confidence for the cost estimation error. We start with the 0.653 cost estimation error from Table 5.1 and then subtract and add the 0.09 confidence interval to give 0.563 and 0.743, respectively. Dividing these into the capital cost estimate, $52.1 million, yields $92.5 and $70.1 million, respectively, in 1975 dollars. Thus, we would say that the expected capital cost estimate is $79.8 million, with a 68 percent likelihood that it will lie between $70.1 million and $92.5 million.

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[2]What happens if the COMPLEXITY count falls outside the 1-11 range? Strictly speaking, one should not apply the cost estimation model to such a plant. The reason is that we cannot be sure that the same variables are important or that they behave the same way for that plant as they would for the plants in the Pioneer Plants data base. We have no reason to suspect they *would* behave differently; we simply cannot say that they would exhibit the linear behavior of the plants in our data base. Without enlarging the data base and redoing the analysis, it is not possible to ascertain whether the model remains the same.

[3]With the exception of PCTNEW, it is not possible to be much more than 2 standard deviations away from the mean. Should this happen (that is, PCTNEW greater than 73.6), use a confidence interval of 0.10.

Table 5.3

CONFIDENCE INTERVAL FOR THE EXAMPLE FACILITY

Cost estimation error (see Table 5.1)	.653
Revised capital cost estimate (millions)	52.1/.653 = $79.8
High end of cost estimation error	.653 - .09 = .563
Low end of cost estimation error	.653 + .09 = .743
High estimate of final capital cost	$52.1/.563 = $92.5
Low estimate of final capital cost	$52.1/.743 = $70.1

68 percent confidence interval of capital cost = $70.1 to $92.5 million in 1975 dollars, or $102 to $134 million in 1980 dollars

APPLYING THE PLANT PERFORMANCE EQUATION

Table 5.4 demonstrates how to apply the plant performance equation using Table 5.4 as a model. Table 5.4 is duplicated as Table A.2 in App. A, but without the numbers specific to the Example Facility. Table A.2 can be photocopied and used to apply the plant performance equation to another plant.

Variable Values and Application for Plant Performance

Table 5.4 contains the variable names, the value assigned to each variable for the Example Facility, and the arithmetic instructions necessary to fill out the table.

Confidence in Plant Performance

Table 5.5 illustrates how well a particular plant fits into our data base by comparing the Example Facility's variables values for the performance equation with the range of those values for the Pioneer Plants data base. The variable values for the Example Facility are well within the range of the corresponding values in the data base. The only variable that *can* fall outside the data base range is NEWSTEPS because the definitions of the other variables preclude such a possibility. To determine whether it is appropriate to apply the performance equation to a particular plant, it is only necessary to check

Table 5.4

WORKSHEET FOR PLANT PERFORMANCE CALCULATION
(Example Facility)

	A. Variable Name	B. Assigned Value		C. Multiplied by		D. Equals	
1.	NEWSTEPS	3	x	9.69	=	29.1	
2.	WASTE	2	x	4.12	=	8.2	
3.	SOLIDS	1	x	17.9	=	17.9	
4.	Subtotal				=	55.2	
5.	BALANCE EQUATIONS	90	x	.33	=	29.7	
6.	Subtract line 5 from line 4					25.5	
7.	A constant					85.8	
8.	Put the number from line 6 here					25.5	
9.	Subtract line 8 from line 7 (PLANT PERFORMANCE) ...					60.3	percent

Thus, during months 7 through 12 after start-up, the Example Facility is expected to perform at roughly 60 percent of design capacity.

that that plant's NEWSTEPS count is within the range 0 through 7, inclusive.[4]

We will develop the confidence interval around the performance estimate in a way similar to that used for the estimate of the cost estimation error equation. If each variable for the performance equation is within two standard deviations of the corresponding mean in the Pioneer Plants data base, then we can place a 68 percent confidence interval of 10 percent around the result of the performance equation.

Table 5.5 compares the variable values for the Example Facility with the average values for the plants in the Pioneer Plants Study.

[4]Again, one should not, strictly speaking, apply the performance model to a plant whose value for NEWSTEPS falls outside the 0 to 7 range. We do not know whether the model applies to such plants, although we have no reason to believe it does not.

Table 5.5

COMPARISON OF EXAMPLE FACILITY WITH PIONEER PLANT SAMPLE—PERFORMANCE

Variable	Example Facility	PPS Sample Range	PPS Sample Average	PPS Sample Standard Deviation
NEWSTEPS	3	0-7	1.68	1.6
BALANCE EQUATIONS	90	0-100	54.0	37.5
WASTE	2	0-5	2.0	1.6

NOTE: SOLIDS is not included because it can only take on the values 0 or 1. Thirty-five percent of the plants in the sample were solids-handling plants.

All of the Example Facility values are within two standard deviations of the average values for the Pioneer Plants Study. We can therefore say that the confidence interval is not greater than 10 percent for the plant performance estimate. Table 5.6 illustrates the confidence interval for the Example Facility.

Table 5.6

CONFIDENCE INTERVAL FOR THE EXAMPLE FACILITY—PERFORMANCE

Plant Performance estimate (see Table 5.4)	60.3 percent
High end of performance estimate	60.3 + 10 = 70.3
Low end of performance estimate	60.3 - 10 = 50.3

68 percent confidence interval of plant performance =
50 to 70 percent of Example Facility's design capacity

Starting with the plant performance estimate calculated in Table 5.4, we subtract and add 10 percent to 60.3 to obtain the range. Doing so yields a 68 percent confidence interval that the average performance of the Example Facility during months 7 through 12 will be between 50 and 70 percent of design capacity.

Coping with Uncertainty About Input Values

At times a user of this manual may have doubts about the true values of some of the variables, and therefore have the problem of not knowing how good his or her inputs are. These doubts may arise from confusion about how to apply the variable definitions in a particularly unusual case, or because the information needed is not known with certainty. The user can do two things to cope with this situation: (1) do some checks for internal consistency, and (2) perform a sensitivity analysis.

Internal Consistency. Previous sections have mentioned a few internal consistency checks during the discussions of certain variables. We list them here for convenience:

- The value for NEWSTEPS may not exceed the value for COMPLEXITY.
- If the value for BALANCE EQUATIONS is low, the value for WASTE is likely to be high.
- If the value for SOLIDS is 1, the values for WASTE and NEWSTEPS are likely to be high, and the value for BALANCE EQUATIONS is likely to be low.
- If the plant has a highly innovative step in the front of the plant, it is unlikely that the value for BALANCE EQUATIONS will exceed 60 or 70 percent.

Note that except for the first bullet, these are simply guidelines that may have exceptions. Their purpose is to caution the user to be especially thorough in his or her analysis when one of the above conditions applies.

Sensitivity Analysis. When an input variable is not confidently known, the user may feel uncertain about the results of the equations. It is possible to see how serious an error might result from an incorrect input. The first step is to assign a range for the variable value, and then run the equation using first one value and then the other. Based on the outcome of the equations, the user can expand his or her range of expectations about the results.

For example, the value of COMPLEXITY for the Example Facility is 8. This number is derived by grouping the major equipment items into blocks and then counting the blocks. If the grouping is done incorrectly, COMPLEXITY may be misassigned. Let us say that a user doubts the correctness of the value 8 for COMPLEXITY. The user can test for the seriousness of this doubt simply by changing the value for COMPLEXITY to 7, say, in Table 5.1 and recalculating the cost estimation error. Doing so results in a new cost estimation error of 0.664, rather than the 0.653 when COMPLEXITY was 8. This yields a revised capital cost of $78.5 million rather than $79.8. Thus, instead of a single number from the cost estimation equation, we have a range ($78.5 million to $79.8 million). To construct a confidence interval around this range, one would apply the 0.09 adjustment to both ends of the range, resulting in a 68 percent confidence interval of $69.1 to $92.5 million. The same technique may be applied to any other variable in order to inspect its effect on the cost estimation error or plant performance results.

Appendix A

BLANK WORKSHEETS

Table A.1

BLANK WORKSHEET FOR COST ESTIMATION ERROR CALCULATION

A. Variable Name	B. Assigned Value		C. Multiplied by		D. Equals
1. COMPLEXITY	____	x	.011	=	____
2. PCTNEW	____	x	.003	=	____
3. IMPURITIES	____	x	.021	=	____
4. PROJECT DEFINITION	____	x	.040	=	____
5. PROCESS DEVELOPMENT	__ x [ ]	x	.024	=	____
6. Subtotal					____
7. INCLUSIVENESS	____	x	.0011	=	____
8. Subtract line 7 from line 6					____
9. A constant					1.122
10. Put the number from line 8 here					____
11. Subtract line 10 from line 9 (COST ESTIMATION ERROR)					____
12. Capital cost estimate for plant					$____M
13. Divide line 12 by line 11 (EXPECTED CAPITAL COST)					$____M

Table A.2

BLANK WORKSHEET FOR PLANT PERFORMANCE CALCULATION

	A. Variable Name	B. Assigned Value		C. Multiplied by		D. Equals
1.	NEWSTEPS	______	x	9.69	=	______
2.	WASTE	______	x	4.12	=	______
3.	SOLIDS	______	x	17.9	=	______
4.	Subtotal				=	______
5.	BALANCE EQUATIONS	______	x	.33	=	______

6. Subtract line 5 from line 4 .... ______

7. A constant 85.8

8. Put the number from line 6 here .... ______

9. Subtract line 8 from line 7 (PLANT PERFORMANCE) ... ______ percent

Appendix B

CONTINGENCIES IN PROJECT COST ESTIMATES

Contingencies are often not explicitly enumerated in cost estimates. In fact, most participants in the Pioneer Plants Study were not able to tell us how much contingency was included in their estimates. For those that were able, we found the following (see Table B.1).

Table B.1

CONTINGENCIES IN THE PIONEER PLANTS STUDY ESTIMATES

Project Stage	Explicit Average	Contingency Range	Number in Sample	PCTNEW Average	NEWSTEPS Average
Project Definition	20.1	8.6-30	3	13.3	1.0
Early in Engineering	12.9	5.0-25	10	13.8	1.0
Late in Engineering	9.8	3.5-15	7	24.4	1.9
Construction	7.1	2.4-10	8	15.1	1.1

NOTE: Contingency in percent is defined as 100 x Contingency/(Estimate - Contingency).

Because the sample sizes in Table B.1 are small, the reader is cautioned against using the information as a national average of contingencies employed by the processing industry. Note also that the figures shown are for mildly innovative plants, that is, plants for which PCTNEW is under 25 percent. We would expect the contingencies to be somewhat lower for strictly duplicate plants (PCTNEW = 0 percent), and somewhat higher for plants for which PCTNEW is greater than 25 percent. We did not have enough conceptual estimates—estimates made before project definition—to calculate a contingency for that earliest of project stages.

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