Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants

Edward W. Merrow, Kenneth E. Phillips
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Rand

This research was supported by Contract No. DE-AC01-79PE70078 with the U.S. Department of Energy.

Library of Congress Cataloging in Publication Data

Merrow, Edward W.
Understanding cost growth and performance shortfalls in pioneer process plants.

"Prepared for the Department of Energy."
"R-2569-DOE."
1. Energy facilities--Estimates.
2. Chemical plants--Estimates. I. Phillips, Kenneth E. II. Myers, Christopher W., 1954-
III. United States. Dept. of Energy.
IV. Rand Corporation. V. Title.
TJ163.9.M47 660.2'8'0681 81-13788
ISBN 0-8330-0352-6 AACR2

Published by The Rand Corporation

R-2569-DOE

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September 1981

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Rand
SANTA MONICA, CA. 90406

PREFACE

This is the second report from Rand's Pioneer Plants Study, which began in 1978. The study seeks a better understanding of the reasons for inaccurate estimates of capital costs and performance difficulties for first-of-a-kind process plants, especially energy process plants. Armed with a better understanding of the problems, the goal is to provide government and industry with tools to improve assessment of the commercial prospects of developing technologies.

The first report, R-2481-DOE, *A Review of Cost Estimation in New Technologies: Implications for Energy Process Plants,* by E. W. Merrow, S. W. Chapel, and J. C. Worthing, July 1979, documented the problems routinely encountered in projecting realistic costs for advanced technologies. This report presents an analysis of cost estimation and system performance for 44 pioneer process plants built by the private sector in North America over the past fifteen years.

Forthcoming reports will present the results of an effort to develop a simple and useable scale for measuring technical advance in process plants, an application of the study results to selected synthetic fuels projects, and an executive summary.

This study is being conducted for the U.S. Department of Energy under contract DE-AC01-79PE70078 as part of Rand's program of policy research and analysis for DOE. DOE offices supporting the research are Policy and Evaluation, Nuclear Energy, Resource Applications, and Energy Research.

SUMMARY

Misestimation of the capital costs and performance of innovative energy process plants and other chemical process facilities creates fundamental problems for government and industry in planning the development and commercialization of such plants. Misestimation erodes the rationality of R&D allocations, capital expenditure assessments, and comparisons between competing systems. The past decade has witnessed continual upward revisions in the estimated costs of synthetic fuels and other energy process plants—increases far beyond the effects of inflation. Among the few plants that have been completed here and elsewhere, most have experienced reliability problems that have adversely affected their economic viability.

The occurrence of cost misestimation and performance shortfalls does not surprise the few people who have experience with first-of-a-kind technologies. Unlike prior anecdotal accounts of the problems afflicting innovative process plants, however, this report presents an empirical and quantitative analysis of the following questions:

- What factors are responsible for inaccurate cost estimates for process plants?
- How well do pioneer plants perform and what factors are responsible for poor plant performance?
- What are the implications of the answers to the above questions for planning by the process industries and the Department of Energy?

For this study, 34 firms in the process industries provided data to support a statistical analysis of cost estimation error and performance shortfalls in pioneer plants. Detailed proprietary information on 44 process plants sustained the analysis.

The principal conclusions of the analysis are:

- Both performance problems and cost-estimation error, measured as the ratio of the estimated costs at various points in a project's development to the actual cost, were common among the plants examined. Both experiences, however, are associated with characteristics of the project or technology—characteristics that are knowable early in project development.
- Despite widespread belief to the contrary, unanticipated inflation, unanticipated regulatory changes, scope changes, and

other external factors such as bad weather and strikes, are *not* the principal causes of cost underestimation.

- Most of the variation found in cost-estimation error can be explained by (1) the extent to which the plant's technology departs from that of prior plants, (2) the degree of definition of the project's site and related characteristics, and (3) the complexity of the plant.
- Most of the variation in plant performance is explained by the measures of new technology and whether or not a plant processes solid materials.
- The statistical analysis of cost-estimation error—cost growth—enables both government and industry planners to gauge the reliability of a given estimate, and to assess probable ultimate costs of process facilities.
- The performance analysis suggests that the routinely high performance assumed for pioneer process plants when financial analyses are done is unrealistic. Over 50 percent of the plants in our sample failed to achieve their production goals in the second six months after start-up.

The analytic method presented in this study can be useful to industry and the Department of Energy in making decisions about R&D allocations where, otherwise, conventional estimating techniques will routinely overstate any advantages of advanced technology; in making decisions about commercialization; and in making decisions about required subsidies and risks for synthetic fuels and other energy process plants.

ACKNOWLEDGMENTS

The authors owe a considerable debt to several Rand colleagues whose analytic assistance and careful reviews of this report in various stages substantially improved its form and substance. Foremost among these were the other members of the project team: S. W. Chapel, R. E. Horvath, J. R. Nelson, and J. C. Worthing. G. J. Hall's statistical guidance was invaluable. Thanks are due to S. J. Bodilly, T. K. Glennan, and D. Seidman for their helpful comments on a prior draft and to R. L. Perry for his technical review. Special thanks go to W. L. Stanley of Rand's Engineering and Applied Sciences Department, whose technical review significantly improved the substance and exposition of the report. We are indebted to M. E. Vaiana for her assistance in organizing and drafting the report, and to L. Swanson, who typed and prepared the report for publication. We thank W. Harriss for clarifying and polishing our prose.

Too many individuals in the process industries read and commented on the report for us to mention them all. We are deeply indebted to them for taking time from their jobs of estimating, designing, and building process plants to add to our analysis. We feel that we must acknowledge the contributions of John W. Hackney, however, whose own work helped inspire this study and whose aid and suggestions promoted its success.

Any errors that remain probably result from our failure to take good advice and are therefore our responsibility.

SPECIAL ACKNOWLEDGMENT

The quantitative analyses undertaken in this report were made possible only through the participation of many private industry firms. These firms donated their time, effort, and data in helping us assemble the rich and unique data base described in the report. We would especially like to thank the companies for their time and effort in putting their data together and for their helpful comments.

Although the data were collected on a proprietary basis and are protected by formal nondisclosure agreements between the company and The Rand Corporation, 24 of the firms signed letters agreeing to be publicly acknowledged. These are listed below.

Air Products and Chemicals, Inc.
American Cyanamid Company
ARCO/Chemical Company
Atlantic Richfield Company
Celanese Chemical Company, Inc.
CF&I Corporation
Chem Systems, Inc.
Dow Chemical Company
E.I. du Pont de Nemours & Company
Ebasco Services, Inc.
Exxon Research & Engineering Company
Gulf Science & Technology Company
Home Oil Company Ltd.
Kennecott Copper Corporation
Mallinckrodt, Inc.
3M (Minnesota Mining & Manufacturing Company)
Mobil Research and Development Corporation
Oxirane International
The Pritchard Corporation
Rohm & Hass Company
Standard Oil Company Ohio
Sun Oil Company
Suncor, Inc.
Texaco, Inc.

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I. INTRODUCTION

The soundness with which planners assess the anticipated capital costs and performance of advanced energy technologies affects the quality of many fundamental decisions on U.S. energy policy. How serious our energy situation really is depends in considerable measure on whether energy systems now in development can produce significant quantities of needed fuels at prices that will not disrupt the U.S. economy. Similarly, the vigor and dedication with which the nation must pursue mandatory conservation measures (or subsidies to induce conservation) depend partly on the costs of new energy technologies. R&D and capital allocations by both the public and private sectors can be made more reasonably and efficiently if the costs of energy from these new sources can be predicted within usefully narrow bounds.

The nation's most pressing energy need for the foreseeable future will be direct substitutes for imported petroleum. This is true not only because of U.S. vulnerability to the oil cartel, but also because the economy is so heavily invested in equipment requiring light liquid hydrocarbons that any rapid forced transition to other energy forms would pose major, if not catastrophic, dislocations. For this reason, current investment decisions in both government and private industry are focusing on synthetic fuels technologies that produce liquids from coal, shale, biomass, oil sands, and very heavy oils. Reasonable expectations about the cost of these technologies are needed. Important issues hinge on those expectations: Whether substantial quantities of acceptable synthetic fuels can be produced for $30 to $50 per barrel-of-petroleum equivalent, or will cost $80 to $100 per barrel, may affect the health of our economy, our lifestyles, and our foreign policy for the next twenty years and more.

As yet, however, we do not know with even moderate surety what the capital costs, system performance, and therefore product costs, of advanced energy process technologies will be. The history of cost estimates for synthetic fuels and other energy process technologies is not one to inspire corporate and government planners with confidence. Over the past decade, estimated costs have risen continuously and rapidly in constant dollars. The purpose of Rand's Pioneer Plants study was to identify the sources of this "cost growth" and related performance shortfalls, and to devise methods that would yield more realistic expectations of ultimate costs and performance for first-of-a-kind process plants.

The first step in the study was to review what was known about the problem of poor cost estimation and performance for advanced technologies in particular and very large projects in general.[1] The study concluded that:

- Severe underestimation of capital costs is the norm for *all* advanced technologies; the underestimation for energy process technologies mirrored that seen in major weapon systems acquisition, very large advanced construction projects, and major public works activities. A number of advanced technologies brought to project completion had problems with reliability and performance.
- The literature on sources of cost growth and performance shortfalls is extensive, but only for major weapon systems have detailed statistical analyses been performed that successfully isolate factors associated with the problems. As discussed in the first report on this study,[2] the weapon system analyses gave us valuable insight into generic factors to be examined and inspired the methodological approach for this study. As for process plants, the literature and our discussions with industry provided no consensus about the relative contribution of various factors to misestimation of costs and performance shortfalls.
- Because they lacked systematic understanding of these factors, planners dealing with pioneer process plants were severely handicapped. Their best options were either to disregard early cost estimates for advanced technologies and rely on non-economic criteria (such as efficiency or environmental considerations), or to support costly design and engineering work to improve the estimates. Neither option could be very attractive to government and corporate managers, who need good early cost estimates to support planning decisions.

For the analysis described in this report, our approach was to develop a detailed data base of advanced process plant projects undertaken by the chemical, oil, and minerals industries in North America over the past fifteen years. The data base enabled us to test a range of hypotheses suggested by the literature, by the conventional wisdom, and by our own models of the factors affecting cost and performance estimation.

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

[2] Ibid.

We arrived at the following major conclusions:

- Capital costs are repeatedly underestimated for advanced chemical process facilities, just as they are for advanced energy process plants. Furthermore, the performance of advanced process plants constantly falls short of what was predicted by designers and assumed in financial analyses.
- Greater than expected capital costs and performance shortfalls not anticipated by conventional estimating techniques can be explained in terms of 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, much less construction. If applied with appropriate care, the statistical models developed here can provide reasonable, early predictions of plant cost and performance for a spectrum of kinds of advanced process plants, including energy process plants. The analysis also suggests several steps by which planners can improve the quality of cost estimates made early in project development.

Section II below discusses the cost estimating and performance problem and our approach to resolving it. The section also briefly sketches out what a process plant project is, when cost estimates are made, and the purposes they serve. Section III describes the data base assembled for the study. Sections IV and V provide the results of the statistical analyses for cost growth and plant performance, respectively. The final section summarizes the primary lessons for government and industry planners, and suggests how the results of the analysis might be used to improve future decisions on energy policy.

II. THE PROBLEM AND THE APPROACH

The decision to commercialize a new technology depends on a realistic evaluation of its economic viability; and realism calls for reasonably accurate estimates of the capital investment needed to design and construct a plant that will produce the desired product competitively. Earlier research on commercializing first-of-a-kind technologies found repeated failure to anticipate actual costs, and frequent disappointing performance. Early cost estimates for technically advanced plants are characteristically far below actual costs, and troublesome system performance problems are much more likely for advanced systems than for systems with prior commercial experience. Pioneer energy process plants have proven to be no exception. All ten energy process plant projects that we examined in the first phase of this research had to revise their cost estimates (in constant dollars) sharply upward, and of the four plants actually constructed, three performed poorly.[1]

In this section we will first review how a typical process plant project develops, and then discuss our conceptual models of cost growth and performance shortfalls.

AN OVERVIEW OF PROJECT DEVELOPMENT PHASES

To set a context for a discussion of the conceptual models that guided our analysis, we will briefly discuss what a typical pioneer plant project looks like, how it proceeds through various stages, and difficulties that sometimes arise. Our discussion is necessarily an idealization; how projects are assembled varies considerably from company to company, time to time, and project to project.

Figure 2.1 illustrates the basic stages through which most projects proceed.[2] Any project involving new technology almost necessarily entails some *research and development* work, and R&D usually, but not always, precedes other stages of the project.[3] A project then goes to

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

[2] Although pioneer plants predominate, the data base includes a few standard plants as well.

[3] In some cases the need for development work is not perceived until after the project has progressed and some unforeseen technical problem has been identified.

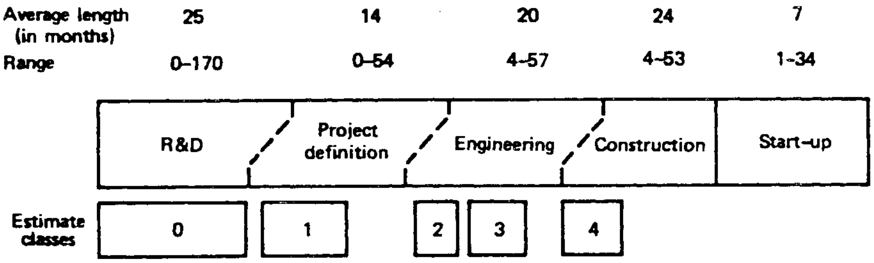

Fig. 2.1 — Project stages and duration for sampled plants

project definition and from there to *detailed engineering, construction* and, finally, plant *start-up*. Figure 2.1 also shows the average amount of time required for each stage for the plants in our data base (described in Sec. III) and the ranges of the time spent.

The tremendous variability in the length of the phases stems primarily from differences in project size and complexity. In addition, standard units do not have an R&D phase, and a few projects proceeded directly to engineering without an explicit project definition exercise.

Estimates of the capital costs of a process plant are made throughout the development cycle. These estimates shape allocation decisions, influence long-term spending plans, serve as a framework for accounting and control, and serve as a baseline against which to measure the performance of project management and contractors. Figure 2.1 shows the points at which different types of capital cost estimates are made. To avoid problems of nomenclature, we have simply designated the estimate types by numbers, starting with the earliest "Class-0" estimates made in R&D, and proceeding through highly detailed estimates made when definitive engineering is complete. (Section IV discusses these estimate classes in greater detail.) Each of these estimates derives from its own knowledge base and methodology, and assumes its own level of accuracy. In the following sections we discuss each of the stages in the evolution of a process plant and the function and accuracy of the estimates made during each stage.

Research and Development

If a plant entails a new process or new equipment, a research and development (R&D) group assumes initial development responsibility.

The function of R&D is to provide the basic theoretical understanding of the process necessary for establishing its feasibility or to work on some particularly troublesome aspect of the plant. If the process is new, R&D may include a process development unit—a small batch unit that tests some part of the process.

During R&D, one or more "conceptual" cost estimates will be made. Their basic function is screening. If the estimates are high, the project may remain in R&D while designers seek alternatives to the plant characteristics that drive the cost. Because the purpose of these estimates is to screen projects, and because both the scope and basic design of a process are fluid during R&D, initial estimates may vary widely. The target confidence interval is typically plus or minus 30 to 40 percent.

R&D, like all of the other project stages, is not necessarily performed in-house by the eventual plant owner. It may be performed by another operating company that will then license the technology, by a process development firm, or by an engineering firm. Discussions with plant owners reveal widespread skepticism of the reliability of any estimates prepared by the R&D performers. Two factors are cited. First, because R&D performers are trying to sell their process, they have powerful incentives to make costs appear attractive. This problem is perceived to be especially acute when the R&D performers are not in-house. Second, because most R&D performers have little experience with plant design and construction, realistic estimation may be simply beyond their powers. For these reasons, the proposed owner or his engineering contractor usually rework any cost estimates prepared by R&D performers before any serious screening is done.

Project Definition

The delineation of a commercial plant begins in the project definition stage. For this reason, the most formidable hurdle for a new process is the decision to move it from R&D into project definition. The decision involves committing funds to define the scope of the proposed plant, the basic plant layout, and the process flow conditions. Most major equipment needs are also defined at this point, at least in a preliminary way, and examination of a possible site or sites is begun.

The amount of work required to bring projects to equivalent levels of definition varies with how much is already known about the proposed site,[4] and the firm's past experience with the kind of unit involved. The

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[4] Process plants are often located next to existing facilities. If a firm has recently completed a facility on the same site, much of that information may be available for the

more a proposed facility departs from previously established technology, the more work will be required to arrive at a reasonable definition of the project, because prior experience will not be available to provide critical information such as plant layout, heat and materials balances,[5] equipment needs, and so forth.

Project definition will sometimes identify technical uncertainties that have not been resolved in R&D. In these cases, the process may be returned to R&D for additional work. In others, management may be requested to authorize construction of an integrated pilot plant, that is, a small-scale version of the eventual plant that incorporates all or a number of the key units that will be required for the commercial facility. Even a small integrated pilot facility is expensive and may adversely affect the overall economics of a project. Consequently, funds for a pilot are requested only if the required design information cannot be provided in some other way.[6]

An important product of the project definition stage is the preliminary or Phase I authorization estimate, which we call the Class 2 estimate. This estimate is based on the design of the plant as formulated by the project definition exercise. The cost estimator depends on the quality and thoroughness of the project definition to compose the preliminary estimate.

Good preliminary estimates are essential to sound management decisions about the project's future because they are the basis for the first complete review of the project's economics. If a "go" decision is made, then money is appropriated for a full engineering design of the plant. Since design costs may be 10 percent or more of the total capital costs of the facility, the decision to proceed to a full design is normally tantamount to a decision to construct the plant. For relatively standard plants, site preparation and other civil engineering work may begin immediately. For innovative plants or plants with otherwise uncertain economics, the decision to begin such work may be deferred to the next step.

Company practices with respect to project definition vary enormously. Some companies have extensive requirements for what consti-

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new facility. Several companies have told us, however, that they overestimated what they thought they knew about the existing project, with the result that they severely underestimated capital costs.

[5] The heat and materials balances are input-output equations modeling the flows of energy and process materials for each unit of a plant. The balances govern the sizing of all equipment in the plant.

[6] Companies differ, however, in their attitudes toward attempting large scale-ups and bypassing an integrated pilot. Some companies are explicitly averse to taking scale-up risks and are more likely to build a pilot in those cases in which a pioneer plant is being considered. Other companies are much more comfortable with their ability to jump from "the bench" to commercial scale, and will only build a pilot as a last resort.

tutes an acceptable project definition exercise and strictly adhere to those requirements. The requirements often include long checklists of items relating to the site, regulatory requirements, preparation of preliminary flow sheets, and so forth. At the opposite extreme are firms that have essentially no project definition stage at all. Some firms require a definition exercise for a large or pioneer facility, but require little or no definition work for standard facilities. As discussed in the analysis of cost growth in Sec. IV, project definition requirements have important consequences for the accuracy of cost estimates.

Engineering Design

Engineering design is the process of turning a set of sketchy drawings and process specifications into a "blueprint" from which an operating plant can be constructed. Procurement specifications and detailed phasing for construction are also worked out.

When engineering is 30 percent or more complete, a new cost estimate is usually made. This estimate, called the budget or Phase II authorization estimate, has three important functions. First, it constitutes another important checkpoint for a project's economics, especially in the case of a pioneer plant. If the estimated cost has increased substantially since the preliminary estimate, the project's feasibility may be closely reexamined. Second, this estimate is used as the basis for planning capital expenditures on the project. Third, the budget estimate is used to establish the cost accounts that will be used to control expenditures during procurement and construction. This estimate is often the last estimate formally presented to management for authorization.

After the budget estimate is made, procurement begins in earnest. Equipment specifications are put out for bid and subcontracts are let. Site preparation will begin if it was not authorized earlier.

When engineering design is nearly completed, a final "definitive" estimate is sometimes made. Since the data for this estimate apply to a fully designed plant with firm bids on equipment and subcontracts and construction under way, the target confidence interval is generally about 5 percent.

Construction

When construction begins varies from plant to plant, but it usually begins when the design is less than half completed. For pioneer plants, it may not begin until the definitive engineering design is nearly complete.

The construction period ranges from less than one year for small plants to more than four years for large complexes. Cost updates are made frequently during construction, but are intended for cost monitoring and control rather than to provide management with new checkpoints. The commonest causes of delay are late delivery of materials, unavailability of labor, poor labor productivity, inclement weather, and strikes. Only rarely is construction delayed by errors in plant design. Usually, design problems that were not identified in project definition or engineering will not be manifest until start-up.

Start-up

As soon as construction is completed, the start-up phase begins. Planning for it will have begun during engineering, and estimates of start-up costs should have been included in the estimates. One to six months are usually allocated for start-up. In our data base, average actual start-up time was seven months, but the great majority of plants had completed start-up within four months.

The primary function of start-up is to "debug" the plant. First the equipment is operated with air, water, or other safe substances and the inevitable minor repairs and replacements are made. The plant is then tested at operating temperatures and pressures, and finally with process materials. Delays in start-up are obviously very expensive. The entire plant has been built, start-up personnel are highly paid, shipments of raw materials may have arrived, and product orders may go unfulfilled.

Start-up problems have four primary causes:

- Equipment failures
- Inadequate equipment
- Operator error
- Improper design

Process failures caused by improper design are generally by far the most serious. They may entail substantial delays in start-up while design changes and additional construction take place; in some cases, the plant may never operate at design capacity. The profitability of process plants is very sensitive to poor performance. Of course, major process failures occur almost exclusively in pioneer plants.[7]

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[7] Very occasionally, a process failure occurs in a plant that is entirely standard save for a modest (and presumably nearly risk-free) scale-up.

CONCEPTUAL MODELS OF COST GROWTH AND PERFORMANCE

By "cost growth" we mean the almost universal tendency for estimates of capital costs to understate the ultimate costs of a plant. Our focus, however, is not on all factors that can cause estimates to err, but on factors internal to a project that affect the accuracy of estimates.

By performance shortfalls we mean the failure of a plant to produce a product of acceptable quality in the quantities assumed in the plant's design. The ratio of actual to expected production is, of course, measured over time. As with cost growth, we are not concerned with factors exogenous to the project that might lower plant production, such as lack of demand for the product or a shortage of feedstocks.

The Conceptual Model of Cost Growth

As shown in Table 2.1, we distinguish between factors that increase the costs of a project, either by changing its character or by changing the economic and institutional environment in which the project develops, and those factors that affect the accuracy of estimates independent of all else.

Table 2.1

FACTORS THAT MAY INCREASE PLANT COSTS AND AFFECT ESTIMATION ACCURACY

Factors that may increase plant costs:
- Scope changes
- Unanticipated inflation/escalation
- Unanticipated regulatory changes
- Strikes, bad weather, etc.
- Management practices

Factors that may affect estimation accuracy:
- Process characteristics and knowledge
- Degree of project definition
- Incentives for accurate estimation

It is very important to distinguish between factors that increase plant costs and factors that affect the accuracy of cost estimates. An example will illustrate the point. Assume that a piece of major equipment was available for $5 million when an estimate was made and the estimator assumed that 10 percent inflation would occur before the item was actually purchased, bringing the estimated cost to $5.5 million. Instead, however, the cost of the piece of equipment soared to $7 million. The $1.5 million difference was due to a factor completely external to the nature of the project. On the other hand, if it was found that the piece of equipment originally specified could not perform the function required and that a more expensive piece of equipment had to be substituted for it, that change in costs was *internal* to the nature of the project.

The following pages discuss factors affecting costs of plants that we sought to remove in our analysis of cost growth. We then discuss our basic hypotheses concerning the sources of cost growth.

Factors that Change Plant Costs

In addition to a design, a cost estimator must start with a set of assumptions that certain factors affecting the cost of a plant will remain constant or change in predicted ways. If reasonable assumptions are made but prove wrong, the estimate will be wrong through no fault of the estimator. The estimator's key assumptions are (1) that the scope of the plant will not change, (2) that inflation will be as forecasted, (3) that no unanticipated regulatory changes will occur, (4) that the project will not encounter unusually bad luck in the form of strikes, especially inclement weather and the like, and (5) that the project will not be mismanaged.

Scope Changes. By scope changes we mean changes in the proposed plant design capacity, changes in the product slate, or other *discretionary* changes. We do not include as scope changes modifications to plant design found to be necessary to make the plant operate. Scope changes may be made because the market for a plant's product expands or contracts, to cut total capital costs by reducing the size of the plant, or to reduce unit costs by increasing the size of the plant where economies of scale exist. Whatever the motivation for scope changes, the cost of building the plant will necessarily change.

Inflation/Escalation. Over the past decade, a major challenge for estimators has been to assume an inflation rate that proves accurate. For the most part, inflation in the process industries has been somewhat higher than in the economy, but has been quite erratic. For example, the 1973-74 period was one of hyperinflation for about 18 months, followed immediately by a period of very little change in prices. While inflation is a source of continuing vexation to estimators and corporate planners, it is a factor to be removed when attempting to examine estimation accuracy.

Regulatory Changes. When we started the study, we suspected that one major contributor to cost-estimating problems would be changes that took place in environmental, health, and safety regulations between the time an estimate was made and construction of the plant. The 1970s—the period during which nearly all of the plants in our data base were estimated and constructed—were a time of rapid and unprecedented change in regulatory standards that affected process plants. We expected that many changes would not be anticipated by estimators and would therefore result in low estimates. As discussed in later sections, we were almost completely wrong. Regulatory changes undoubtedly contributed to higher process plant costs in the 1970s, but most of them were correctly anticipated and therefore did not cause serious underestimation.

Bad Luck. Strikes, bad weather, late delivery of equipment, shortages of labor, and the like constitute a largely random "bad luck" element in controlling plant costs. As with all the other factors discussed above, such factors are not important to an analysis of estimating accuracy, however painful they might have been to those involved. As explained in subsequent sections, such factors were measured and systematically excluded from our analysis.

Management Practices. Poor project management, like the other factors above, is not something that an estimator can predict, but poor scheduling, inadequate cost control, weak supervision of contractors, and so forth can plunge a project into financial ruin. Unlike the situation with the other factors, however, there was no way in which to solicit or estimate a dollar cost of poor management with which to adjust actual costs or estimates in order to remove the effect. For that reason, we collected some characteristics of project management, discussed more fully in the next section, but none of the relationships was sufficiently strong to allow us to estimate the effects.

The Sources of Cost Growth and Performance Shortfalls

On the basis of the initial exploratory phase of this study, we postulated two basic hypotheses about the sources of cost growth and performance shortfalls:

- The more a plant's technology departed from previously established commercial systems, the larger would be the cost growth in estimates and the poorer would be the plant's performance.
- Cost growth, measured between any estimate and actual costs, would decline as the completeness of plant definition increased.

Although we also sought to test a number of 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.

Neither of the two hypotheses will be surprising to anyone who is at all familiar with process plants or the literature on cost-estimating problems. Our goal, however, was to reduce these abstractions to measurable factors that could be quantified and assessed as early as the R&D stage and thereby form the basis for a realistic assessment of a project's ultimate cost and performance. If successful in finding such measures, it was also our hope that we could suggest improvements in estimating methodology, and that our analysis would point to areas in which additional R&D would lead to lower costs and better system performance for energy and other process plants.

The remainder of this section discusses our two basic hypotheses and touches briefly on some of the other factors considered.

The Introduction of Unproven Technology

Our notion of "unproven technology" incorporates a number of possible ways that a plant might deviate from previously established commercial technology:

- New chemical conversion steps
- New equipment
- New feedstocks
- Large scale-ups of previously used units.

By hypothesizing (and later demonstrating) that unproven technology is related to cost growth and performance problems, we are *not* suggesting that innovation is "bad." Although the estimates for an innovative process plant may grow far more than those for a conventional counterpart, the innovative plant still may cost considerably less than the technology it replaces. Even if that innovative plant performs poorly, it may ultimately pay a handsome profit to the innovating company if the subsequent units (employing what has then become demonstrated technology) perform well.

The logic of a hypothesized relationship between unproven technology and cost growth and performance problems is straightforward. Doing something new inevitably gives rise to a set of uncertainties, some subset of which will be clearly identified early in development and may become the focus of the R&D team, design engineers, and cost engineers. Typically, the identified areas of uncertainty will receive extra design work and cost estimators will attach special contingencies to their cost estimates for those areas.

The problems arise because no matter how thorough the analysis, there are usually problems that go unidentified.[8] In retrospect, unforeseen problems often appear obvious: "We should have known we couldn't hold a liquid phase in that reactor." "Everybody knows that stuff turns into concrete." "So and so identified X in that feedstock in 1963." In reality, however, our ability to foresee problems when introducing new things into technically complex systems is always limited. Any time a highly innovative project proceeds without a hitch, an element of luck as well as skill is involved.

As a project proceeds from R&D through definition and into engineering, many previously unidentified problems surface and changes in the design are made. These will almost always lead to higher instead of lower costs: a new unit to clean up impurities, more costly materials to resist corrosion, more intermediate storage to allow for downtime, and so forth.

We believe that it is very important to distinguish such design modifications from "scope changes" as we defined it above, because they stem from fundamentally different sources. Scope changes result from discretionary decisions to change the characteristics of the project, such as design capacity or product slate. Scope changes as we define them occur in standard plants as well as pioneer plants. Pioneer plant design modifications typically result from attempts to resolve previously unidentified problems and are not really matters of discretion.[9]

The relationship between unproven technology and performance problems is merely an extension of the discussion above. Any problems that are not caught in engineering will surely become clear in start-up and early operation. For pioneer plants, start-up is more likely to be plagued by the various kinds of problems discussed earlier in the section, including operator errors because operating instructions lack the

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[8] Although there will also almost always be someone who will say, "I told you so."

[9] This obviously oversimplifies the situation. First, *scope changes* are undoubtedly more common for pioneer than standard units. For a highly innovative unit (as opposed to a plant incorporating some new technology into an otherwise standard facility) the "right" scale is difficult to establish early. Only when the heat and materials balances are stabilized, and equipment specifications established and believed to be feasible, can a scale be pinned down. Second, management may be more likely to get "cold feet" about a pioneer unit and urge a scale-down to reduce risk. Finally, very few process plants—even those that we call standard—are really identical to previous units. The designs evolve from prior plants and the problem of freezing a design (that is, deciding to allow no further design modifications) can be a problem with standard plants as well as pioneers. For the former, design modifications are a matter of making marginal improvements. For the latter, modifications may be essential to technical feasibility.

value of experience. Even after the start-up period has ended, pioneer plants can be expected to run a higher risk of having design problems that will limit production.

The Degree of Project Definition

The cost estimator uses whatever information is available about a project to generate an estimate of the capital costs. When detailed information is not available, the estimator will employ factors or rules of thumb generated from other projects, or make assumptions about the nature and cost of items not included in specific information supplied by process designers. We hypothesized that the less specific and detailed the information available to cost estimators, the greater would be the cost growth between estimate and actuality.

We suspect that several factors work to produce cost growth. First, the less detailed and comprehensive the information supplied to the estimator, the more likely will some cost items simply be omitted from estimates. These items will be omitted because estimators cannot predict everything a plant will require. The second factor is what we call the "Anytown, U.S.A. syndrome." The literature and our discussions with industry officials suggested that hypothetical—"Anytown"—sites routinely seem to have lower costs than any other town. This may occur because the hypothetical site is in fact an ideal site and ideal sites are rarely found, or it may spring from a long-term trend toward increased site costs. Site costs may be increasing because many of the best sites have already been occupied, as well as from increasingly stringent environmental regulations that reduce the pool of available sites. Finally, when project details are fuzzy, undue optimism may pervade cost estimates. If estimators or designers have an incentive to be unduly optimistic (and it is fair to assume they sometimes will), they can give free rein to their optimism only when the details of a project are not available. When an item and its specifications have been included in the information provided to the estimator, it must be reasonably priced or the estimator is not fulfilling his professional obligation. On the other hand, if the designer or estimator is free to choose among several assumptions about the specifications for an item, optimism may govern the choice.

We expected that the degree of definition in a number of dimensions would affect the quality of estimates. In particular, we expected that the amount of work defining the project at its real site would be important, as well as how far along the engineering design was when an estimate was prepared. We expected that the methods used to generate an estimate would be indicators of its quality, but would depend almost wholly on the stage of engineering.[10] We also hypothesized that the inclusiveness of an estimate as measured by a checklist of items specifically included would help predict the degree of definition.

For an estimate made at a particular point in a project's development—for example, at the end of project definition—two of the dimensions of definition mentioned above depend entirely on the stage of the project's development. These are the amount of engineering and the closely associated estimating methods. The degree of site-related detail and the inclusiveness of an estimate are discretionary to a significant extent. They depend on the thoroughness of the project definition exercise, how much the firm doing the project has been willing to invest in information, and the firm's requirements for information to be included in a particular estimate.

Other Cost Growth Hypotheses

Although we anticipated that the two general factors discussed above would be most important in explaining cost growth, we also wished to test other possibly influential factors.

Many of the additional hypotheses concerned the characteristics of the plant: plant size, complexity, type of chemicals produced, and types of feedstocks used. Other hypotheses related to the experience of the firm with a particular process, the experience of the key personnel on the project, and the extent of turnover in key project staff.

Another potential source of cost growth, cited in the weapons acquisition analyses, was the extent to which a project embodied incentives for accurate estimation and cost control. In at least some cases, we expected to find that people trying to sell a technology to a corporation, or people within the corporation who advocated a particular project, would have incentives to underestimate project costs. The extent to which such incentives culminate in underestimation, however, is very much a function of the institutional setting in which cost estimates are made and evaluated. We expected to find that in general there would be fewer problems of deliberate misestimation of costs among those firms that conducted estimation in-house compared with those that accepted estimates made by process developers. We expected that those firms checking estimates outside the line of project advocacy would show less cost growth in their estimates, and that firms with strong management control systems for plant design and construction would do somewhat better in estimating and controlling project costs. In general, however, we expected the scope for deliberately underestimating

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[10] See Merrow, Chapel, and Worthing, Sec. IV.

costs would be much narrower among private sector projects than in those cases where government involvement leads to a degree of monopolistic behavior as suggested in some of the works on major weapon systems acquisition.[11]

RELATIONSHIP TO PRIOR STUDIES

A number of the major factors in our conceptual models of cost growth and performance shortfalls for process plants are drawn from a substantial body of analyses of cost-estimation problems in major weapon systems procured by the U.S. Government. This work, starting in a number of respects with the landmark study by Marshall and Meckling,[12] focused our attention on technical advance as a major determinant of cost growth. As detailed in the first report from the Pioneer Plants Study,[13] technical advance has been measured in several ways in the weapons literature and repeatedly identified as a major source of inaccurate estimates.[14] The work most directly analogous to the Pioneer Plants Study is that done by Robert Summers.[15] Summers explains a great deal of the variation in cost estimates with basically three factors: first, a measure of technical advance required in a program; second, the length of the development program for a system; and finally, when an estimate was made as a fraction of program length. Summers and those who followed[16] developed regression models to predict the ratio of actual costs to estimated costs for weapon systems.

Although we draw heavily on that weapons literature for ideas and methods of analysis, this study differs from prior analyses in several ways. First, there is no complete analog of project definition for a weapon system, partly because issues of siting are largely irrelevant to weapon projects. A second difference is that we sought to develop statistical models that can be estimated with information available at the

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[11] J. P. Large, *Bias in Initial Cost Estimates: How Low Estimates Can Increase the Cost of Acquiring Weapon Systems*, The Rand Corporation, R-1467-PA&E, July 1974; and M. J. Peck and F. M. Scherer, *The Weapons Acquisition Process: An Economic Analysis*, Harvard University Press, Cambridge, Massachusetts, 1962.

[12] A. W. Marshall and W. H. Meckling, *Predictability of the Costs, Time, and Success of Development*, The Rand Corporation, P-1821, December 1959.

[13] Merrow, Chapel, and Worthing.

[14] Robert Perry et al., *Systems Acquisition Strategies*, The Rand Corporation, R-733-PR/ARPA, July 1971.

[15] Robert Summers, *Cost Estimates as Predictors of Actual Weapons Costs: A Study of Major Hardware Articles*, The Rand Corporation, RM-3061-PR, March 1965.

[16] For example, A. J. Harman and S. Henrichsen, *A Methodology for Cost Factor Comparison and Prediction*, The Rand Corporation, RM-6269-ARPA, August 1970.

time an estimate is made rather than after a project has been completed. A third difference, related to the second, is that we wanted to avoid using the length of a project as an explanatory variable for cost growth. The reason for this is twofold: First, length can only be measured after the fact; second, and more important, the length of a project is not itself a causal variable in cost growth or poor performance. Rather the length of a project is the result of other factors—such as technical changes that require lengthening the project schedule—that are the basic causes of increased costs.

III. THE PIONEER PLANTS STUDY DATA BASE

Our analysis of cost estimating and performance difficulties in technically advanced process plants relied on information provided by private sector firms. To permit quantitative evaluations of the hypotheses on the causes of cost growth and performance discussed in Sec. II, we required extensive data from a variety of companies. Because such data are proprietary to each corporation, no data base encompassing the breadth of information needed to analyze these hypotheses existed across more than a single firm. The Pioneer Plants Study data base, therefore, represents a unique assembly of information on the cost-estimating and performance histories for a sample of advanced process plants.

This section describes our data base. Each of the 44 chemical process plants sampled is characterized by over 400 separate items. Participating companies voluntarily provided proprietary data under written nondisclosure agreements with The Rand Corporation. Although we requested permission to publicly recognize each of the participating companies, only those firms extending express permission to do so are acknowledged at the beginning of the report. Our nondisclosure agreements with all the participating companies expressly prohibit any data presentation that may permit identification of individual plants. The report therefore includes no simple two-variable point plots or other potentially identifying presentation.

In the pages that follow we discuss the procedures for gathering the data and broadly characterize the study participants and the specific plants on which they provided information. We then describe some of the data available to address our basic models of cost growth and performance.

THE STUDY PARTICIPANTS

We solicited the participation of a wide range of companies representing a broad cross-section of firms in the process industries. A total of 34 companies in the chemical, oil, minerals, and design services industries provided sufficient systematic cost and performance data to support a comprehensive statistical analysis. These 34 firms accounted for well over half of the total chemical sales in the United States in 1978. Although not all companies we contacted were ultimately able to participate, the 34 that did vary widely in many respects. They were distributed as follows:

Oil	10
Engineering and design services	4
Chemicals	13
Minerals and metallurgical	5
Other	2

The companies vary considerably not only in terms of specific process industry, but also in size—from relatively small firms to industry giants. They also differ widely in their corporate attitudes toward risk-taking in new technologies: The sample includes self-described "followers" as well as leaders in innovation. In breadth of industries, product categories, technical processes and equipment employed, and involvement in energy development, the sample of firms (and their plants) appears to be generally representative of companies likely to become involved in the planning, construction, and operation of new energy process plants.

Not all companies contacted were able to participate in the study, most of them smaller firms that lacked sufficient resources to assemble the requested information. Firms otherwise declining to participate usually cited one of the following reasons: Their engineering staffs were overburdened and therefore lacked the necessary time; they could not supply even reasonably complete data for a single plant because of incomplete or inadequate data archives; the part of their business involved in the process industry was largely peripheral to their main concerns and they therefore had little interest in participating; or they considered the data requested too sensitive or proprietary even for restricted release. In several instances, data-confidentiality problems arose with architect-engineering firms whose contracts with the plants' owners or process developers, or both, prohibited release of any information to outside sources.

THE PLANTS IN THE DATA BASE

The Pioneer Plants data base contains information on 44 commercial-scale chemical process plants, selected to maximize the analogy with energy process plants.[1] Although the study was designed to

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[1] As discussed at the end of this section, data were received for 58 plants. In 14 cases, however, missing data precluded inclusion of a plant in either the cost or performance analysis. In addition, 4 plants were missing critical estimate data and could not be used in the cost analysis, while one plant was excluded from the performance analysis because

explore cost and performance estimation in energy process plants, especially synthetic fuels, too few of these plants have been designed and constructed to sustain systematic analysis. We therefore solicited information on broadly analogous chemical process plants. The results of the analysis should apply to continuous process plants in general. Most of the plants are new, having started production within the last six years at a total capital investment of $7.5 billion in 1980 dollars. All were built in the United States or Canada.

The plants included in the data base represent a wide range of generic processes. 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
- Minerals processing

Table 3.1 summarizes several major characteristics of the 44 plants in the data base, including total capital cost (in 1980 dollars), age, plant design capacity, plant complexity or block count, and feedstock. As the table shows, the plants varied considerably on each of these dimensions.

Data collection began in September 1978 and continued through April 1980. Each participating company supplied material at its own expense. Firms estimated that they spent an average of six months and $10,000 per plant to assemble the information requested.

SELECTION GUIDELINES

The choice of what plants to be included was ultimately left to the participating companies. Many of them gave us a list of plants from which we could choose one or more. We provided participating firms with seven criteria to guide their choices, however. They were asked to select:

- Plants that involve some degree or kind of technical change from prior plants, e.g., new process steps, new equipment, large scale-up, new plant configuration, etc.

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of missing information. As a result, the cost growth analysis is based on a sample of 40 plants, while the performance analysis is based on 43 plants.

Table 3.1

MAJOR CHARACTERISTICS OF PLANTS IN DATA BASE

Characteristic	Average	Standard Deviation
Total capital cost[a]	$174.9	311.0
Capitalized start-up cost[a]	10.8	29.9
Design capacity[b]	1353.6	2064.6
Complexity (block unit count)	5.4	2.6
Years since mechanical completion	6.6	3.7
Principal types of materials processed:		
Solids 33%		
Liquids 23%		
Gases 44%		

[a] In $ million 1980.

[b] Million lb/year.

- Medium-sized to large plants in terms of annual output—100 million pounds per year or more.
- Plants that involve liquid and/or solids processing rather than strictly gas or cryogenic processes.
- Plants constructed in the U.S. and Canada within the past 15 years.
- 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.

With the exception of the last two items, these guidelines were necessarily flexible and helped produce a sample from which one could reasonably extrapolate to synthetic fuels and other energy process plants. Taken as a whole, the sample includes plants that introduce more technical advance than average; are somewhat larger in terms of production capacity; and overrepresent solids and liquids handling at the expense of gas processing compared with process plants in general. A major intent of the guidelines was to ensure sufficient variation along key dimensions to support our analysis. For example, it was not our intent to completely exclude plants that were quite standard, to exclude plants of less than 100 million pounds per year output, or to exclude plants that involved primarily gas handling, and in fact we did not. We did wish to ensure that we had enough plants that were large, innovative, solids and/or liquids processing facilities to make a reasonable analogy with energy process plants, and also to include some standard plants to establish a baseline.

KEY DATA BASE CHARACTERISTICS

The data for each plant consist of some 400 variables describing virtually every aspect of the project, including its technical characteristics and the technical problems encountered during various development stages, detailed cost-estimation histories, key beginning dates and lengths of time planned and spent for each major project stage, environmental and regulatory issues affecting the project, actual project costs, start-up problems, and performance records.

These data may be grouped into four generic categories that correspond to the major issues raised in Sec. II:

- Cost Growth and Performance
- Physical Character of the Plant
- Measures of Technological Change
- Measures of Project Development

We discuss each of these categories below.

Cost Growth and Performance

As noted in Sec. II, the two phenomena we most wanted to investigate were cost-estimation error (which we call "cost growth" simply because the notion of growth accurately captures what typically happens) and plant performance.

Cost Growth. Measuring cost growth accurately was much more difficult than measuring performance. Specifying the extent of cost growth experienced for each estimate required that we obtain detailed information about actual project costs and the key cost estimates generated at different stages of the project. Since we were interested in tracing the cost estimation histories of the plants to understand how well different estimates matched actual expenditures, it was necessary to solicit extensive background information about each estimate. For many reasons tangential to our central concerns, cost estimates can deviate significantly from actual costs. We therefore sought information that would enable us to reconstruct each project's history, the point at which estimates were made, the dollar amounts of the estimates, the methods used to generate the estimates, and a host of items necessary to adjust both actual and estimated costs to constant dollar values.[2] It was also necessary to identify changes in project scope (chiefly, alterations in the product slate or changes in design capacity) so that these effects could be removed from estimates that were essentially targeted toward a plant whose overall level of effort was different from that actually constructed.

In addition to adjusting for the effects of inflation, assumed escalation, and scope changes,[3] we needed to be able to control for the effects of other factors that lie completely outside a company's ability to control. Such factors included changes in regulations or permitting requirements, worker and product safety rules, unusually inclement weather, and shortages in materials and labor. For each of these factors we solicited the following information:

- Date at which the project was affected
- Severity of the effect
- Effects on project schedule
- Effects on plant performance
- Effects on final plant costs

Performance. We asked the companies to provide data on actual plant performance so that production, as a percentage of design capacity, could be traced for each month in the 30-month period following plant start-up. As a check on how quickly the facility began to generate revenues from product sales, we asked for the date on which the product quality specifications were met. Firms also indicated whether product quality specifications were changed at any point, why they were changed, and how much the changes cost the project.

Finally, to control for those periods when market demands or bottlenecks in feedstock supply were the real causes of low plant productivity, we also collected separate data on the plant's actual availability during the first 30 months after start-up.

Physical Character of the Plant

As noted earlier, we conjectured that cost growth or performance might be influenced by the physical character of the plant itself—this issue being considered separately from the particular measures of how

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[2] The procedure for adjusting the cost estimates to a constant dollar basis is discussed in App. A.

[3] When we use the term "scope changes" we are not referring to changes that may be required to make a process work properly, but to decisions made by the owner to change the capacity or product slate, and other changes not related to the acquisition of technical information about the process.

the plant deviated technically from previous commercial-scale plants. Therefore, we gathered data that included (1) the plant's designed production capacity, (2) the complexity of the process (i.e., the number of continuously linked process units required to carry out all unit conversions and operations), (3) the major feedstocks, (4) the major products, and (5) a generic description of what key processes were employed to transform feedstocks into saleable products. Although most participating firms were initially reluctant to forward hard copies of the process flowsheets, in many instances we were invited to working sessions where senior process engineers and project managers used such flowsheets to explain the details of the process as completely as possible.

Measures of Technological Change

A strong presumption on our part was that cost growth and performance problems would be associated with plants whose technology departed sharply from that of prior facilities. We needed measures of technical change with two characteristics: items that are easily measured early in the project development, and items that are general to process plants rather than characteristic of only one or a few processes. Such items included:

- The number of process steps that were new at commercial scale
- The scale-up of the plant from prior units
- The percent of the estimated capital investment in new steps
- Whether the plant represented the first time the technology had been used commercially in North America
- The extent to which the heat and materials balance equations were known on the basis of data from prior plants as opposed to being calculated on the basis of theory or simply unknown at various points in the project.

We also solicited and received data that captured the technical difficulties encountered during each stage of the project's development: failure of key equipment, materials difficulties, and basic design problems.

We asked companies to rate on a scale of 0 to 5 the extent to which they encountered difficulties in the following areas during development:[4]

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[4] The exact wording of the question was: "These are some of the fundamental reasons why there may have been significant technical problems that had to be solved during the development. Please indicate the extent that the following items were a source of design and development problems. Please explain briefly."

- Feedstock characterization
- Impurity build-ups in process and recycle streams
- Process temperatures
- Process pressures
- Corrosion
- Abrasion
- Solids, liquids, and gas handling
- Environmental compliance
- Safety

We supplemented these rankings by asking companies to estimate the amount of technological change represented by the process, the difficulty of the overall project, and the difficulty of various aspects of the project.

We also requested data on any development facilities associated with the plant in order to see if any consistent relationship could be found between cost growth, performance, and the type or size of pilot plants and other precommercial facilities.[5]

Measures of Project Development

In addition to certain obvious project characteristics such as location, plant capacity, and primary feedstock and products, we received details on the extent to which projects had been defined when each cost estimate was made. A total of 14 items were rated in terms of the degree of definition, including economic characteristics of the location, soils hydrology, environmental requirements, and others. Companies completed a separate checklist of items included or excluded in each cost estimate. This list provided a way of assessing the scope, or inclusiveness, of each estimate as well as the degree of definition tapped by the list described above.

Companies also rated the stage of process development when an estimate was prepared, using the following categories:

- *Exploratory/predevelopment*: Most process information is obtained from small-scale laboratory experiments and literature.
- *Development*: Where a coordinated program is under way.
- *Precommercialization*: Work is characterized by efforts to minimize the risk for commercial applications. Pilot work is generally of the demonstration type and there are sufficient

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[5] We found a great deal of variation in company approach to building development facilities, but no relationship to either cost estimation or performance outcomes. Our analysis was hampered, however, by missing-data problems.

data to start design on a commercial unit or a large demonstration plant.
- *Completed development*: Major process uncertainties have been resolved and a design specification has been completed.

Firms provided the percent of total engineering complete and also degree of engineering definition when each estimate was made, using the following categories:

- Screening study: least definition
- Study design: limited basis of definition and owner input
- Study design: moderate or extensive basis of definition and owner input
- Design specification: most definition

Finally, we asked a separate set of questions about the manner in which the project was organized and managed. These questions addressed the project manager's authority on the project, turnover in product management, experience of key personnel, and related issues.

MISSING DATA

Although the analysis presented in this report is based on a total of 44 process plants, the entire data base included at least some information for 58 projects. The 14 plants not represented in the analysis were projects for which key data were missing. The sheer magnitude of the effort required by firms to complete the Pioneer Plants worksheet may have been inhibiting to some companies, but in most cases, we were able to obtain needed information through follow-up requests. Where data critical to our analysis remained missing, it was due to the inability of the participating firm to provide it. The most common reason for such missing-data problems was that the participating firm did not have effective access to the information. This problem was usually limited to those instances in which an architect-engineering company acted as a study participant. In these cases, the firm was involved in only a portion of the total project, and lacked data on actual costs or plant performance. In other cases, firms were deterred by prohibitive costs of locating detailed project development information, such as specific estimate characteristics.

SUMMARY

The data base that supports the analysis in the next two sections is unique in several respects. It includes a reasonable cross-section of the process industries' experience with cost estimation and performance for new plants. It is large enough in terms of the number of plants included to sustain a statistical analysis of cost estimation and performance problems, yet detailed enough to allow the adjustments necessary to present a realistic picture of the problems. The data base is also unique in the high degree of cooperation it represents from a large number of firms.

IV. COST ESTIMATION FOR PIONEER PLANTS

INTRODUCTION

This section presents the results of our statistical analysis of capital cost growth for a sample of chemical process plants. The problem addressed is termed "cost growth" because the final capital costs incurred in designing and constructing these plants almost always exceeded the amounts estimated. Many of the problems associated with cost growth are not confined to pioneer plants; the results have important implications for cost-estimating methods for both technically advanced and standard plants. The goals of this section are:

- To describe the difficulties often encountered in estimating capital costs, especially for plants using pioneer technologies;
- To explain more clearly why actual costs almost always exceed estimated costs for pioneer plants;
- To identify and measure the major causes of cost growth and statistically analyze their effects; and
- To offer those charged with evaluating process plant capital cost estimates, as well as engineers and cost estimators themselves, a statistical means of assessing the reliability of cost estimates before substantial project funds are committed.

Reasonably accurate projections of actual costs are an obvious precondition of efficient capital planning. Project as well as corporate managers necessarily rely on forecasts of the total capital investment a proposed plant will ultimately require so that they can effectively plan for their firm's projected future (no small part of which involves judiciously allocating the capital resources available to meet that plan). Routine financial analyses of the expected market impact of a proposed plant's product slate and desired production rate also depend in large part on the expected capital cost. Obviously, such calculations are most usefully performed with a realistic understanding of the actual capital expenditures that will be amortized into the unit cost. At least as important, these evaluations require capital cost estimates that are as reliable as possible at relatively early planning stages for each project —but particularly before large allocations have been made.

The experiences of the plants in our data base suggest that in a large number of cases, managers are unpleasantly surprised once the extent of underestimation becomes clear. The unreliability and uncertainty surrounding the accuracy of the cost estimates for these plants, in retrospect, vastly exceeded any normal range of expected uncertainty associated with capital cost projections. These estimates, generated through standard estimating methods,[1] proved so highly unreliable and uncertain as to have effectively distorted—or at best confounded—efficient capital planning, because managers did not possess realistic forecasts of the total capital that the projects ultimately required. In many cases, the severity of the problem was only recognized after a large portion of the expected capital was already committed.

Our results identify a set of factors that may be used to supplement standard estimating methods in order to evaluate an estimate's reliability and also to reduce uncertainty about its ultimate match with project costs to more narrow levels useful to capital planners. The results of our analysis of capital cost estimation difficulties for first-of-a-kind technologies are designed to evaluate probabilistically the expected error of these estimates. In this sense, our research results are not designed either to estimate capital costs directly or to replace standard estimating methods. They are offered as an empirically based, supplemental framework for evaluating the reliability of capital cost estimates for pioneer process plants.

In this section, we review the perspective of cost estimates and estimation accuracy most commonly represented in the cost-estimating literature, emphasizing the role that view plays in capital planning. We contrast the expectations typically engendered by this view with the estimating experience of the plants in our data base, survey the most often cited causes of unreliable estimation, and describe our approach to these issues in our analysis. We then present a conceptual model to explain misestimation based upon an understanding of its major sources as suggested in both the literature on capital cost estimation and earlier Rand research on similar estimation problems in weapons acquisition. We follow this by describing alternative measures examined, the way in which the specific model parameters were chosen and

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[1] The phrase "standard estimating methods" is used in its broadest sense, and is meant to encompass all commonly used methodologies. See Merrow, Chapel, and Worthing, pp. 61-85. While the earlier report noted difficulties with various estimating techniques employed by estimators at different points in a project's development, it should be emphasized that the method by which the estimates in our data base were produced is not directly addressed in the analysis presented here. As will become clear in the discussion of the role that project definition plays in misestimation, it is not that the method used to generate an estimate bears no relationship to its reliability, but rather that the method used is largely dependent on the degree of project definition and engineering information available to the estimator at the time. Throughout this report, the phrase "standard estimating methods" is used in contrasting conventional estimating techniques with the supplemental statistical evaluation model developed in the Pioneer Plants Study.

constructed, and the statistical analysis we undertook in our search for a specified model that would encompass the primary sources of misestimation in a manner useful to industry and government estimators, managers, and policymakers. We conclude by discussing how both industry and government could use the model to shape more realistic expectations about estimation accuracy for pioneer plants.

THE CONVENTIONAL VIEW OF ESTIMATION ACCURACY

Two perspectives govern how "accurate estimation" is defined. To management, it usually implies something close to common usage: A given estimate is accurate if it is close to actual final costs. This perspective focuses on a single cost estimate. The cost estimator takes a broader perspective, typically viewing estimation accuracy over a number of estimates and projects. Any single estimate forms part of a probabilistic distribution that, ideally, clusters around a highly accurate average. A "good" cost estimator is one whose estimates are "reasonably" close to the actual costs *most of the time.* That is, the good estimator's distribution is modally peaked around actual costs, with a reasonably small average deviation. The definition of "reasonably close" depends on the type of estimate, which, in turn, depends on the amount of information available to the cost estimator at the time the estimate was prepared. In most cases, what is reasonably close for a given estimate class takes the form of a specified confidence range within which a "good" estimate will fall. This range is meant to represent the likely upper and lower bounds within which the actual costs may reasonably be expected to fall. The size of the interval depends on the type of estimate and when it is made. For early estimates, the typical confidence range is larger than it is for later, more definitive estimates made for the same project. Because the estimator always lacks complete information, estimates always incorporate some uncertainty about final project costs. This uncertainty is greatest in early project stages, and decreases as the project becomes more thoroughly defined.

The Use of Confidence Intervals to Reflect Estimate Uncertainty

Figure 4.1 illustrates the relationship between the typically assumed range of estimate accuracy and the amount of information available through a project's development.[2] Also identified are approximate points at which estimates are often prepared.[3] As the estimator acquires more definitive information, the confidence ranges steadily narrow. (The number of estimates and their accompanying intervals on which Fig. 4.1 is based are not meant to typify the practice of all firms, but they are sufficiently representative for illustration.)

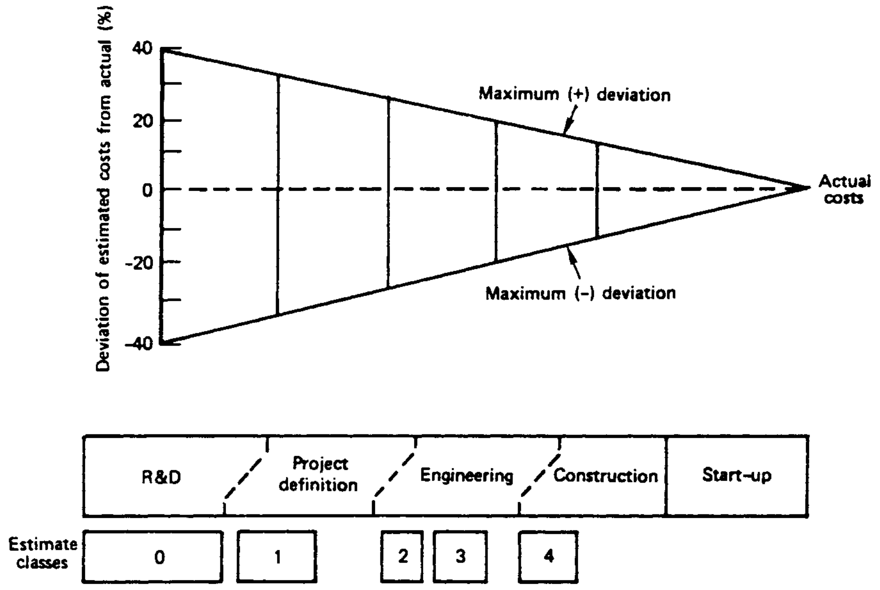

Fig. 4.1 — The conventional view of how information and project phase affect estimation accuracy

Very early estimates—often referred to as "conceptual" or "order of magnitude" estimates—are the most uncertain. The approximate plus or minus 40 percent confidence range typically associated with these

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[2] Here, as with our classification of estimates according to their general purpose and project phase, the percentages presented as the conventional estimating expectations represent no more than the approximate ranges commonly used in industry. Even so, they are used only to illustrate the assumptions that estimating error is limited, declines during the project, and tends on the whole to be unbiased. While the exact ranges used are by no means the same for all firms, the intervals presented broadly characterize the general expectations of most estimate designers and evaluators.

[3] We have grouped the estimates primarily according to the point in the project at which each was prepared. They are defined in Sec. II. While the labels, purposes, timing, and number of estimates prepared differ widely by company, the classification scheme in Fig. 4.1 provides a heuristic means of comparing estimates made at approximately similar points in a project's development. The use of the Class-0 through Class-4 scheme is only meant to roughly aggregate similar types of estimates, and not represent exactly the practice of all firms.

estimates reflects the lack of information about the precise site and process configurations to be employed in the plant. As Fig. 4.1 illustrates, such estimates are typically made during R&D to give a rough indication of the potential commercial viability of a proposed project. Subsequent estimates are made through the project's development as continuing checks on final cost expectations. The later estimates are necessarily assumed to be increasingly accurate predictors of final costs, and the confidence intervals normally decline to a point where a final, or "definitive," estimate is expected to be very close (plus or minus 5 percent) to actual costs.

Both the allowable and the expected ranges decline through a project's development for two reasons. First, more detailed information about specific process and site problems becomes available to the cost estimator, especially as engineering progresses. The estimator then has a better idea of what the plant will actually cost, thereby reducing his uncertainty and the size of the contingencies needed. Management's perspective also contributes to the progressive decline in the allowable confidence ranges. Because increasingly large portions of the expected total capital are being expended as the project moves through engineering and then into construction, management typically sees the ultimate commercial viability of the project as hinging on a specific dollar expectation of its ultimate capital cost. Corporate planners therefore often insist on progressively narrowing the allowable range of uncertainty surrounding later estimates. Projects failing to meet these expectations may be radically scaled down or abandoned altogether, resulting in significant capital losses. As a consequence, management sometimes uses late estimates, which assume very limited uncertainty (plus or minus 5 percent) more for cost control than for estimating purposes.

Interpreting Confidence Intervals

Despite their general use in project planning and capital allocation, the precise meaning and use of these confidence ranges is far from clear. Interpreting the confidence intervals for an estimate or class of estimates presents two fundamental problems. The first involves the proportion of estimates expected to fall within the given range. Some authors seem to imply that *all* estimates should be expected to fall within the confidence interval.[4] Others adopt a more probabilistic perspective and assume that the intervals represent two standard

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[4] M. Rosenthal and E. O. Green, "Discussion of Estimating Methods," *AACE Transactions,* Section I-2, pp. 343-348.

deviations, encompassing about 95 percent of the estimates.[5] Still others suggest another figure, such as 80[6] or 90 percent.[7] Some firms may use intervals developed from actual experience; however, in general the figures chosen appear to be normative rather than empirically derived rules of thumb, and therefore complicate statistical inferences.

The second major problem in interpreting the confidence range associated with a class of estimates stems from the implied assumption that the collection of estimates is *symmetrically distributed* around the actual costs. In the ideal case, of course, the average estimate equals the actual costs. If it does not, and the average estimate instead tends to fall above or below the actual cost, the estimating technique being used is systematically biased. To illustrate, consider three hypothetical distributions of estimates presented in Fig. 4.2.

In the first example, the distribution of the estimates is symmetrical and centers on the actual costs. The average estimate is very close to actual costs, and the method used to develop these estimates may be considered reliable. In the second example, the distribution is symmetrical but does not center on the actual costs: The average estimate is systematically *lower* than actual costs. The estimates reflected in this distribution are biased—they do not, on average, estimate actual costs very completely. The method used to construct these estimates is not adequately accounting for something that is systematically affecting actual costs. The reverse is true for the third distribution: On average, the estimates are higher than actual costs.

In cases of systematic bias, where the distributions cluster tightly around a central but inaccurate average, a solution is available once the extent of the bias is recognized: The estimator can apply a corrective factor to the estimates that will shift the average closer to actual costs. It is not advisable to adjust the estimating method for that purpose when a large deviation exists. That solution is not sufficiently reliable. The degree to which uncertainty is a serious problem depends on how tightly clustered the collection of estimates is, regardless of whether the average estimate approximates actual costs.

A set of estimates that are highly uncertain or embody unrecognized bias, or both, carry serious implications, particularly when they are early estimates. To a large extent, management decisions to commit substantial amounts of capital to a project rely on early cost estimates. Capital resources cannot be allocated efficiently if the estimates are too

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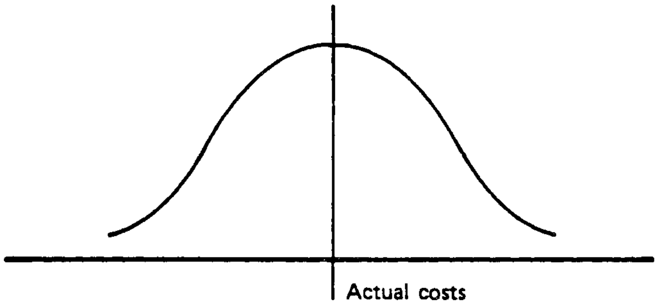
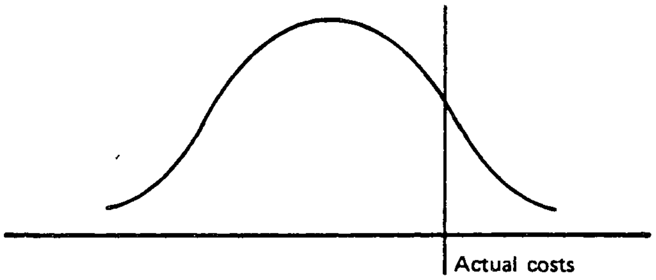
[5] J. W. Hackney, *Control and Management of Capital Projects,* John Wiley & Sons, Inc., New York, 1965, App. B.

[6] Ibid.

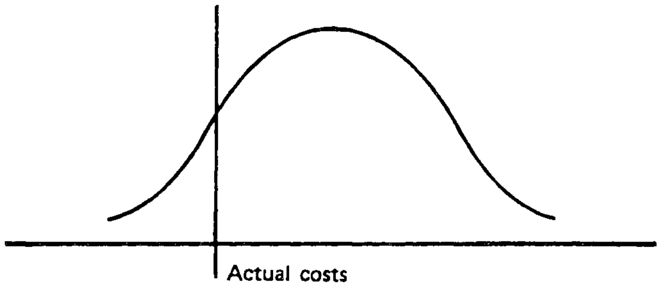
[7] Forrest D. Clark, "Cost Control for Process Plants from the Owner's View," *Chemical Engineering,* July 7, 1975, pp. 76-77.



(a) Average estimate equals actual costs



(b) Average estimate less than actual costs



(c) Average estimate greater than actual costs

Fig. 4.2 — Hypothetical frequency distributions of estimates versus actual costs

far off. When they are too low, sizeable expenditures may be made before management gains an accurate sense of the total capital required. If so, projects may have to be terminated at a considerable loss, or they may be continued with cost overruns that divert capital from other purposes. Management sees accurate early estimates as vital because at every step in the project increasingly large shares of the total expected capital are being expended.

ACTUAL EXPERIENCE WITH PIONEER PLANT ESTIMATION

The experience of the plants in our data base reveals a pattern and magnitude of misestimation that stand in sharp contrast to the usual expectation that actual costs will fall symmetrically within established and relatively limited ranges of the estimated costs. Figure 4.3 outlines the cost estimation histories for the sample of process plants that sustain the analysis in this section. The figure summarizes an index of estimation accuracy that is grouped by the five classes of estimates defined in Sec. II. Each class is characterized by an average value, represented by the solid point, and by a measure of the extent of variation around that average, represented by the plus and minus range of a single standard deviation in the solid lines.

The basic dependent variable used in our analysis is measured as the constant-dollar ratio of forecasted costs to the capital cost actually incurred (that is, each estimate prepared for a given project is divided by the project's total final costs). This ratio would have a value of one only for perfectly estimated plants (estimate = actual costs). Too low an estimate (estimate < actual costs) would produce a ratio of less than one, signifying cost overruns. Too high an estimate (estimate > actual costs) would yield a ratio larger than one.[8]

The figure contrasts the estimation experience of these plants with the typically assumed ranges illustrated earlier in Fig. 4.1. The funnel at the top of the figure approximates the typical assumption that esti-

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[8] Some previous research on cost estimation (including preliminary drafts of this report) analyzed the reciprocal of this ratio, that is, actual capital costs divided by the estimated costs. Our use here of the ratio of estimated to actual costs to measure the extent of misestimation instead stems primarily from an important statistical complication (one not necessarily confined to this data base). The frequency distribution of the actual to estimated costs ratio for the plants in our data base is highly skewed by a few extremely poor estimates. In part because the ratio of estimated to actual costs possesses a somewhat naturally limited range from some point above zero to one not too much greater than one, statistical analysis of this measure proved much less susceptible to the problem of a few cases of extreme underestimation exerting disproportionate influence on the statistical results.

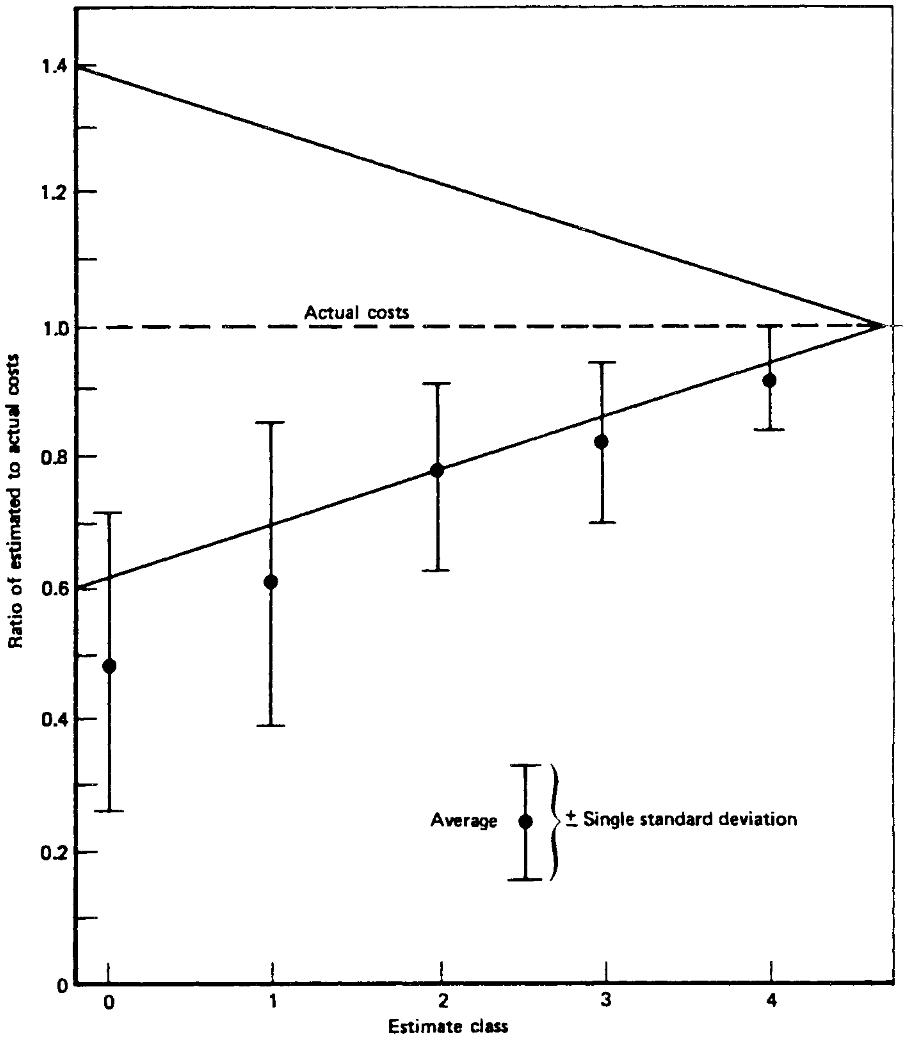

Fig. 4.3 — Experience of the pioneer plants sample with estimation accuracy

mates will tend, on average, to equal actual project costs, with uncertainty usually declining monotonically over time from about plus or minus 40 percent to about 5 percent.

It is immediately obvious from Fig. 4.3 that the early estimates were much too low, but steadily improved with the passage of time, and the standard deviations narrowed as well. The earliest classes of estimates made for these plants averaged *less than one-half* of actual costs. And many of the early estimates—even those generated during early engineering—reflected little more than *one-third* of what the plants actually cost to design and construct, or a cost growth ratio of 0.33.

Columns (1) and (2) of Table 4.1 tabulate the expected average accuracy and the confidence ranges typically associated with the five classes of estimates. Columns (3) and (4) contrast these with the average cost-growth ratios and the associated range of a single standard deviation actually experienced by the plants in our data base. The implication of these findings for corporate and government managers is obvious: To the extent their planning was guided by conventional expectations that the estimates presented to them were reasonably accurate within some limited plus or minus range, they were severely disappointed and their capital planning was disrupted. These estimates were on average very poor predictors of actual costs. Moreover, the range of misestimation was so large that it would have been difficult to apply a simple factoring ratio to correct for the underestimation.

Table 4.1

RELATIONSHIP OF ESTIMATED TO ACTUAL COSTS:
CONVENTIONAL EXPECTATION VS. PIONEER PLANTS
STUDY SAMPLE

	Conventional Expectation		Pioneer Plants Study Sample[b]	
	(1)	(2)	(3)	(4)
Class of Estimate	Average[a]	Range of Accuracy[a]	Average[a]	Plus or Minus One Standard Deviation[a]
0	100%	60-140%	49%	27-72%
1	100	70-130	62	40-85
2	100	80-120	78	63-92
3	100	90-110	83	71-95
4	100	95-105	93	85-101

[a] Estimated costs as percent of actual costs.

[b] Excludes cost of external factors.

We now turn to a review of the most often cited causes of misestimation. Based upon this review, we combined into a conceptual model the major factors hypothesized as systematically contributing to cost growth. A primary emphasis rests on those items subject to early assessment and control in a project's development. The dimensions of this model are explored, measured, and subjected to statistical examination. We then offer a respecified model to encompass additional factors that, while not common in the literature, nonetheless significantly fortify the model's capacity to explain the cost-growth problem. Understanding the primary causes of estimation error for these plants not only can help shape more reasonable, early expectations of the ultimate cost of future pioneer plants, but can also isolate those areas of the problem susceptible to early control.

FACTORS AFFECTING ESTIMATE RELIABILITY

Cost estimates are merely predictions and therefore can be wrong. In forecasting the capital investment that the construction of a process plant will require—as in most such forecasts—the possibility of being wrong typically translates into probabilistic ranges of expected or allowable error. As we have seen, even these ranges proved to be unrealistic for the majority of estimates in our sample. Below, we briefly discuss the factors most often cited in the literature and in our discussions with industry as the major causes of unreliable estimates for process plant capital expenditures.[9] They fall into three groups:

- Project uncertainty and estimation methodology
- Process uncertainty
- "External" effects on cost (e.g., inflation, bad weather, regulatory changes, strikes)

Some of these factors are likely to remain outside the realm of human control. As yet, for example, no one can accurately predict inflation rates, labor strikes, or unusually inclement weather very far in advance, and we dealt with some of these difficulties differently from others. Since our analysis deliberately focused on only some of these factors, we discuss our approach below.

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[9] This section draws heavily on the more extended discussion of these issues in Merrow, Chapel, and Worthing, where the reader will find greater detail, particularly on the roles of project management and estimation methodology for pioneer plants.

Project Uncertainty and Estimation Methodology

As noted earlier, the more information available to the estimator about the proposed plant on an actual site, and the higher the quality of that information, the more reliable his estimate. To reduce uncertainty about the proposed plant at its ultimate location requires improved knowledge of the actual project site. This knowledge usually results from engineering efforts at the site. While rarely complete when most cost estimates are prepared, the flow of this information improves an estimate's likely accuracy, and at the same time enhances confidence that the final costs will at least fall within an acceptable percentage range of the projected costs. "Anytown, U.S.A." estimates are typically generated early in a project prior to site selection—let alone before much detail is known about the ultimate plant environs. As the estimator acquires more detailed information as project definition progresses, the confidence ranges applied to the estimates narrow. (This is largely the case for the estimates in our sample as well, as Fig. 4.3 illustrated.)

The accumulation of more and better information also makes it possible to use more sophisticated estimation methods. As engineering progresses, cost capacity or component ratios can be supplemented with—or supplanted by—equipment and installation ratios until, eventually, firm quotations from vendors and subcontractors become available. Difficulties inherent in each of these methods are widely recognized, particularly if historical cost ratios are applied to pioneer plants.[10] Overriding the ability to use more detailed methods, however, is the quality of information available.

The choice of estimating methodology is in effect dependent on the level of informational precision available during the time spanning project definition and engineering efforts. Spurious sophistication at that time can be self-defeating. In fact, a very carefully devised, time-consuming, and therefore costly, estimate based on highly uncertain plant characteristics not only will be no more reliable than a rough estimate performed quickly, but also may be injudiciously accepted as a hard estimate.[11] For that reason, knowing which method was used in generating an estimate provides little or no *additional* information about why the estimate may be unreliable, beyond what can be inferred from even a rough indicator of the degree of definitive engineering and project definition accomplished at the time of the estimate. That indicator can be much more enlightening than the choice of estimating

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[10] See Merrow, Chapel, and Worthing on the errors and difficulties associated with the various ratio-estimating techniques.

[11] See Edward W. Merrow, *Constraints on the Commercialization of Oil Shale,* The Rand Corporation, R-2293-DOE, September 1978.

methodology. The degree of engineering and project definition accomplished can vary considerably, and therefore may point to the critical informational inputs that significantly influence estimate reliability. The rather limited assortment of estimating techniques does not offer such potential analytic richness.

Process Uncertainty

Cost estimators base their estimates on information available about the process and the particular plant. They depend upon the designers and engineers for information that is as complete and accurate as possible *given the stage of development.* Fundamental design changes occurring during a project can invalidate earlier cost estimates, of course. Process uncertainty can also contribute to poor estimation if the planned product scope is changed, or if part or all of the technological process has never been used before in commercial-scale production. In such cases, the estimator is on much shakier ground than he is with more standard technologies.

Scope Changes. One of the most commonly cited causes of cost growth is a gap between planned and actual scope of the plant. A clear definition of the plant's scope provides the first critical information necessary for accurate cost estimation, and changes in scope can be a leading cause of misestimation. Because "scope changes" can be variously defined, however, people often seize on the term and use it retrospectively as an amorphous catch-all to explain away cost growth. We use the term here to encompass only what the plant will produce and at what rate. We define scope changes, in other words, to include only discretionary changes in the plant's *design capacity* or *product slate.* During the course of a project, plant scope may be changed for a variety of reasons, such as changes in expected market conditions; if it is changed by altering the plant's design capacity or product slate, cost estimates must be adjusted accordingly. Defined in this manner, scope changes are largely exogenous, or external, to the accuracy of an estimate.

On the other hand, cost growth frequently occurs as more precise design information is obtained during a project, particularly for pioneer processes. Strictly speaking, we do not define these as scope changes. They are rarely discretionary, but result from previously unrecognized design requirements. As engineering design progresses, more detailed process requirements become plain and often require additional investment in equipment specifications or process configurations not anticipated earlier. These changes may involve a new clean-up step or tighter pressure or temperature tolerances requiring more expensive vessel alloys, for example. Such changes are often referred to as "design creep," and are major factors in cost growth.

The Effect of Pioneering on Estimate Reliability. There is virtual consensus in the literature that cost estimation becomes more difficult and less reliable as one moves away from duplicate plants toward entirely new processes.[12] Confidence intervals are somewhat relaxed and the estimates frequently include a larger contingency allowance.[13] The primary reason that pioneer plants are more subject to cost growth than standard plants is obvious: *Other things being equal,* less is known about first-of-a-kind processes. Consequently, design changes are often more frequent in pioneer plants.

Relationship of Project and Process Uncertainty. Estimating errors with pioneer technologies may also manifest themselves in higher uncertainty surrounding the degree of project definition, compared with more standard plants at roughly parallel project phases. We have conceptually distinguished *project uncertainty*—which affects *all* estimates for *all* plants—from *process uncertainty*—which by definition confronts only unproven technologies. For pioneer plants, however, these two dimensions cannot be fully separated. A large share of project definition depends upon an understanding of the application of the pioneer process to the specific plant site. Where process uncertainties remain while project definition and engineering progress, one might reasonably expect special estimating difficulties. Defining and engineering a plant using an unproven technological process on a real site is understandably more problematic than when the process is fully understood from experience. (Hence, for example, the effect of pollution requirements on the ultimate plant cost may not be fully recognized until much later in the project because the extent and characteristics of potential discharges may not be sufficiently known earlier. Such information may only become available once the process has been applied commercially.)

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[12] See, for example, Harry F. Peters, "Field Construction," in Ralph Landau (ed.), *The Chemical Plant,* Reinhold Publishing Co., New York, 1966; L. F. Williams, "Capital Cost Estimating From the Viewpoint of the Process Plant Contractor," *AACE Bulletin,* Part I, December 1972, Part II, February 1973; and O. T. Zimmerman, "Capital Investment Cost Estimation," in F. C. Jelen (ed.), *Cost and Optimization Engineering,* McGraw-Hill, New York, 1970, pp. 311-334.

[13] Including somewhat larger contingency allowances for pioneer process plants, especially in early estimates, appears to be common industry practice. Our data do not contain the detailed estimate breakdowns necessary to permit us to address this issue, however, and we have made no attempt to adjust for variation in the size of contingencies included in the estimates.

External Effects on Cost

A number of unanticipated factors and events stemming from forces outside the project may change the cost of a process plant after a cost estimate has been made. When measuring the relationship between estimated and actual costs, one would wish to adjust the figures to remove some or all of these factors, at least for certain purposes.

Inflation. Inflation can distort cost estimates in two ways. First, an estimate that includes dollar escalation for the remaining schedule planned for a project's capital expenditures might fail to project future inflation rates accurately. In this case, everything else being equal, estimated costs will not match actual costs. The discrepancy can be especially large for estimates made perhaps several years before project completion, with inflation running so much higher than expected that the final figures look like cost overruns. In reality, the estimates may have been accurate if all costs are compared in constant dollars.

A second difficulty arising from inflation involves retrospective evaluations of estimate accuracy. Later cost-control efforts depend partly on correctly differentiating the results of unanticipated, and uncontrollable, escalation from inaccurate estimation due to other causes, including inadequate cost control. This requires comparing components of the estimates with actual cost breakdowns in constant dollars.

Accurately isolating and accounting for inflation is also problematic. The problems of accurately forecasting inflation rates, sometimes three to five years ahead, and then adjusting all estimated and actual expenditures to constant dollars are particularly sensitive to the mid-1973 through late-1974 surge in process plant construction costs as well as to the means used to account for the inflation. The choice of adjustment device can make a significant difference. Not only do many inflation indexes understate real escalation (especially during periods of labor and equipment shortages) by relying on unrealistic list prices, but the commonly used indexes vary considerably in describing both long- and short-term inflation rates.[14] And finally, of course, inflation forecasts are not much more than "guesstimates" extrapolated from recent trends.[15]

Regulatory Standards. In the last decade, government-mandated

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[14] See C. A. Miller, "Selection of a Cost Index," in American Association of Cost Engineers, *Cost Engineer's Notebook,* June 1978, Section E-1.

[15] See "Feature Report: How to Assess Inflation of Plant Costs," *Chemical Engineering,* July 7, 1975, pp. 70-85, which presents three different perspectives: Forrest D. Clark, "Cost Control for Process Plants from the Owner's View," pp. 70-77; Albert C. Savay, "Effects of Inflation and Escalation on Plant Costs," pp. 78-80; Don R. Bonano, "Cost Escalation: Its Impact on Purchased Equipment," pp. 81-83.

environmental, health, and safety regulations have contributed significantly to the rise in capital costs faced by the process industry. While meeting the regulations has often been expensive, these costs are usually incorporated into capital estimates without great difficulty. When clear standards are established before an estimate is developed, the costs of the equipment needed to meet them do not cause serious estimation error.[16] The opposite can occur if new or revised standards are imposed after an estimate is prepared, but then the estimator can hardly be faulted for not including their impact on project costs. Their effect is external to the project. Misestimating the costs of meeting regulations already in effect, on the other hand, represents a design or estimating failure.

Other External Effects on Costs. Particularly if construction is well under way, bad weather, labor strikes, major delays in expected equipment deliveries, and the like, can inflict serious cost increases beyond the estimator's capability to anticipate, and should also be classified as external influences on project costs.

METHOD OF ADDRESSING MAJOR CAUSES OF MISESTIMATION

In coming to grips with the principal sources of the underestimation that is characteristic of the process plant capital forecasts seen in Fig. 4.3, we sought to discriminate the primary, controllable causal agents from any secondary or external factors. Below, we outline the methods by which we did so. We explain the dependent variable measuring cost-estimation accuracy, or the estimate ratio, and how we isolated and removed estimating errors attributable to scope changes and external factors. The development, measurements, and statistical evaluation and respecification of models hypothesized to explain cost misestimation then follow.

Measuring Estimation Accuracy: The Ratio of Estimated to Actual Costs

Assessing an estimate's accuracy fundamentally involves measuring how close it came to actual costs. This assessment may take several forms. For example, one might simply measure the discrepancy between actual and estimated costs in either dollars or percent. Measur-

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[16] Allen V. Kneese and Charles L. Schultze, *Pollution, Prices, and Public Policy,* The Brookings Institution, Washington, D.C., 1975.

ing the estimation error as the proportion of final costs predicted by the estimate (i.e., cost-growth ratio = estimated cost/actual costs), however, permits analysis of the degree of error, a precision unavailable with a crude good-bad dichotomy, and also permits direct comparison of estimation accuracy across any number of projects, irrespective of their total cost.

It can be very misleading to base such comparisons on absolute dollar differences, especially comparisons between large and small plants. Because of sheer scale, a large plant is likely to look disproportionately good or bad in relation to its smaller counterpart. Let us say that the estimates for the two plants were $80 million and $240 million, and their actual costs were $100 million and $300 million. Both estimates were low by 20 percent, but the $60 million discrepancy for the large plant is three times the $20 million discrepancy for the smaller one. The use of ratios avoids such distortions due to scale. Instead, misestimation is measured proportionately, and the two examples are treated (and weighted) as errors of equivalent magnitude: Both estimates represent 80 percent of the ultimate capital investment.

Estimated and Actual Capital Costs

The data base for this analysis contains some 106 useable cost estimates for 40 of the process plants in our sample. The average is almost three estimates per plant, although some have as many as five and others as few as one. In order to examine the estimates in comparable terms, and to focus upon controllable factors, we made several adjustments to standardize all cost totals. Those paralleling the external factors discussed above appear in Table 4.2.

First, we attempted to maximize the comparability of accounting categories included in the estimates and final costs for each plant. Thus, project research and development costs were not included as part of actual project costs unless all the estimates for the project also included them. (In any event, most firms do not directly charge R&D costs to specific commercial projects.) The capitalized portion of start-up costs has been included in final costs in a similar manner. Additional cost breakdowns were not sufficiently detailed, however, to allow systematic comparisons between other categories.

Second, 9 cost estimates reflected a plant scope different from the other estimates for the same plant and from the scope actually constructed. To permit comparisons between these estimates and the final costs incurred, independent of scope variation between estimates, we adjusted the estimated costs to reflect final plant scope by methods widely used in the industry. These techniques and their supporting documentation are outlined in App. B for interested readers.

Table 4.2
ADJUSTMENTS FOR EXTERNAL FACTORS INFLUENCING COST GROWTH

Factor	Percentage of Plants Affected (N)	Percentage of Estimates Affected (N)	Method by Which Cost-Effect Removed
Scope changes	12.5 (5)	8.5 (9)	Estimated cost adjusted to reflect final plant scope (see Appendix B)
Inaccurate projections of inflation	90 (36)	85 (90)[a]	Assumed dollar escalation included in estimate removed and replaced by actual inflation rate
Unanticipated regulatory standards	25 (10)	25.5 (27)	Dollar cost of meeting standards removed from actual costs only for those estimates prepared *prior to* imposition of regulation
Strikes, bad weather, materials and labor shortages, other unforeseeable events	27.5 (11)	22.6 (24)	Dollar cost subtracted from actual costs for those estimates prepared prior to date of occurrence

[a] The remaining 16 estimates were prepared as "build today—operate today" dollars, without inflation allowances. These were adjusted to mid-1980 dollars directly.

Third, we adjusted both actual and estimated costs to constant (mid-1980) dollar values using the *Chemical Engineering* Plant Cost Index.

Fourth, we removed errors associated with inaccurate forecasts of inflation by subtracting or "backing out" any assumed future dollar escalation over the remaining investment life of the project, prior to the constant dollar adjustment. (Appendix A contains a full explanation of the constant dollar adjustments.)

Finally, we excluded from the actual costs the reported costs of "external" effects, factors genuinely beyond the ability of design and cost teams to predict (e.g., strikes, bad weather, and regulatory mandates imposed after the date of the estimate in question).

AN INITIAL LOOK AT THE SOURCES OF COST GROWTH

Cost Growth vs. External Factors in Underestimation

Over the last decade, the many external factors discussed earlier have caused process plant capital costs to rise. They amount to "bad luck," and cost estimators cannot be faulted for not anticipating them. It is tempting, however, to shift the blame onto external factors for any case of misestimation, as estimators occasionally have done. Since our analysis focused on controllable aspects of misestimation, we strove to maintain the distinction between external and controllable factors.

Our data simply do not support the commonly voiced opinion that misestimation derives primarily from unforeseen (a) inflation, (b) regulatory standards, (c) scope changes, or (d) other disturbances peculiar to individual projects, such as shortages, strikes, or bad weather. Figure 4.4 partitions the average contribution of each factor to that portion of capital costs not covered by the average estimate. That is, the chart represents about 27 percent of actual capital costs since the average estimate underestimates capital costs by that amount. Cost growth —not external factors—is clearly the major culprit, accounting for nearly three-fourths of the total average underestimation. All external factors combined are guilty for only the remaining one-fourth.

The extent of misestimation remains severe even after excluding all external effects on plant costs. The 106 estimates analyzed range

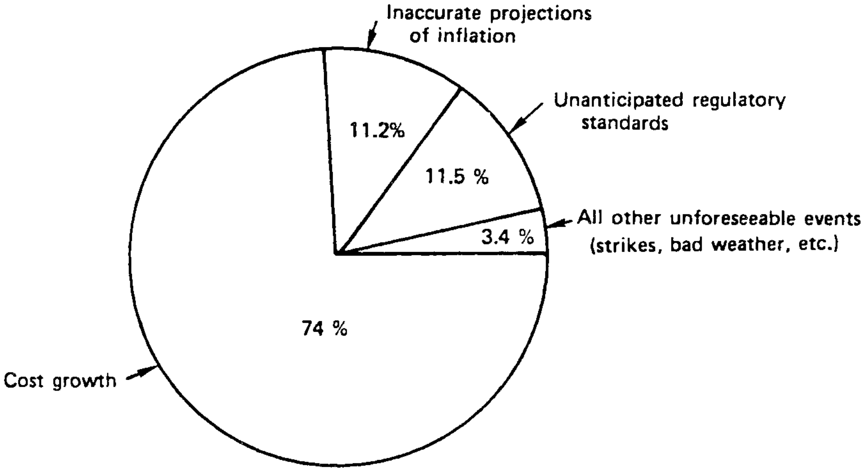

Fig. 4.4 — Importance of cost growth vs external factors in underestimation of costs

enormously in accuracy, from less than 20 percent of actual plant costs to as much as 10 percent above. Table 4.3 contains summary statistical descriptions of the cost-growth values.

Table 4.3

COST-GROWTH RATIOS BY CLASS OF ESTIMATE FOR PIONEER PLANTS STUDY SAMPLE

Class of Estimate	Average[a]	Standard Deviation	Number of Estimates
0	.49	.23	7
1	.62	.23	18
2	.78	.15	30
3	.83	.12	27
4	.93	.08	24

[a] Ratio of estimated to actual costs (excluding external factors).

As discussed in Sec. II, our conceptual model argues that cost growth stems directly from low levels of information both about technical processes and about the project itself on an actual site. Below, we discuss the general nature of this model and the relationship of these two informational dimensions to misestimation.

The fundamental problem of estimation is information: the more information available and the higher its quality, the better the estimate. Engineering estimation methods, no matter how carefully devised, cannot fully compensate for scantiness of information. Particularly when little project definition has been accomplished, and commercially unproven technology is to be employed, the estimator has no relevant prior experience with the same site and process configurations to guide his estimates.

Cost growth stems primarily from the fact that at early stages of engineering, especially for pioneer plants, many cost elements cannot be estimated because they simply do not yet exist. Obviously, this is not the fault of the estimator, but rather the basic inability of usual estimating methodologies to incorporate factors that may systematically lead to higher costs but are not revealed through normal engineering-based estimation techniques.

Our model of cost growth therefore posits that cost growth above a conventionally derived estimate will be primarily a function of the degree of process understanding and level of project information.

Process Information and Unproven Technology

It is widely recognized that commercially unproven technology may be the source of problems in design, construction, and start-up that often culminate in higher than expected final plant costs. Estimators may attempt to cover these costs by setting aside larger contingencies; however, standard estimating methods have usually proved unable to predict these added costs for pioneer plants with much precision. These methods provide no adequate, systematic means for estimating plants that embody technologies, process steps, integrations, equipment, and the like, not previously demonstrated in a commercial plant. It is important to recognize, however, that a technology's being unproven is not a direct cause of underestimation. Instead, the culprit is the unforeseen design, engineering, construction, or start-up problems that unproven technologies can run into and that often require expensive redesign or repair.

"Unproven technology" can best be conceived of on a continuum, ranging from completely standard technologies being commercially replicated to those at the opposite extreme that are pushing the limits of the technical state of the art. For example, the advance over existing technology may be a new chemical process step, an entirely new process, new hardware, old hardware with a new feedstock, or the scale-up of a process already demonstrated in a pilot or other research facility. Moreover, depending on the plant's design and intended product slate, the degree of technological advance also depends on the relative portion of the total plant capacity or cost which that new process represents.

The data base description presented earlier outlined the variety of ways to measure the degree of process uncertainty that we collected. Although we had earlier hypothesized that the best measure of this factor for cost estimation would be the proportion of the expected capital accounted for by technology unproven at commercial scale, we also examined several others. These included the number of block units, or process steps, unproven in commercial use, the percentage of such new steps among the plant's total steps, whether the plant entailed commercially unproven equipment, and whether the technology had been commercially used before by that company, or in North America by any firm.

Table 4.4 presents the relationship of cost growth to each of a series of technical innovation measures. Of all the innovation measures examined, PCTNEW in fact has the highest correlation with cost growth. Subsequent analysis confirmed the importance of the percentage of the total estimated cost consisting of commercially new processes (PCTNEW) in predicting an estimate's accuracy. The value for any particular cost estimate is calculated by aggregating the costs associat-

Table 4.4

THE RELATIONSHIP BETWEEN COST GROWTH AND MEASURES OF NEW TECHNOLOGY

(106 Estimates)

Variable Name	Correlation	Statistical Significance[a]
Percent of capital cost in technology unproven in commercial use (PCTNEW)	-.53	.0001
Number of steps (counted on block basis) incorporating new technology (NEWSTEPS)	-.44	.0001
Number of new steps divided by total number of steps in plant (FRACNEW)	-.35	.0003
Number of integrations of *proven* steps that have not been integrated in commercial use before (NEWINT)	-.12	n.s.
The percentage of the heat and mass balance equations based on actual data from prior plants rather than calculated from theory (BALEQ)	+.28	.0041
Whether or not the plant entailed equipment that had not been used before commercially (yes or no)	-.18	.059
Whether this was the first time that a technology had been used commercially in the U.S. or Canada (yes or no)	-.30	.0019
Whether this was the first experience of the *company* with the technology used in the plant (yes or no)	-.17	.0815

[a] Indicates the probability that the association reported is not different from zero.

ed with commercially undemonstrated technology and dividing by the total estimated capital cost. This value may change during a project's history as better understanding is gained of the capital cost involved in the new process. Some or all of the innovative steps may even be dropped entirely because of design problems. Thus, the value of PCTNEW may differ across the various cost estimates made for the same plant. While useful in ranking the plants along a broad continuum of technological advancement, PCTNEW does not provide precise information about the specific design problems most often encountered in pioneer plants.

Technical Design Problems. As part of the data collection effort, we gathered information about the level of technical difficulty encountered during the R&D and early process development stages. This information was assembled for each of the following generic problem categories on a scale of 0 (no problem) to 5 (major problem):

- Feedstock characteristics
- Catalyst deactivation and impurity buildup
- Temperature tolerances
- Pressures
- Corrosive materials
- Abrasive materials
- Solids/liquids/gas handling

Table 4.5 contains the correlations of these measures with cost growth. The measures of impurity and corrosion problems are distinguished from the others by the size of their correlations with cost growth (and with each other). Our analysis revealed that, more than any other single problem category, first-of-a-kind plants exhibit particularly high levels of design difficulties with impurity buildup and corrosiveness. Impurities are particularly a problem for processes that involve catalysis or extensive recycle in which the buildup of impurities can cause corrosion. Moreover, impurity buildup problems are usually linked with problems that occur in meeting temperature and pressure

Table 4.5

RELATIONSHIP BETWEEN COST GROWTH AND PROBLEMS EXPERIENCED IN PLANT DEVELOPMENT PROCESS

(106 Estimates)

Variable	Correlation	Statistical Significance
Feedstock characteization	-.09	n.s.
Impurity buildup	-.41	.0001
Process temperature	-.26	.0083
Process pressures	-.37	.0001
Corrosion	-.36	.0001
Abrasion	.04	n.s.
Solids handling	.06	n.s.
Liquids handling	-.29	.003
Gas handling	-.39	.0001
Waste handling	-.06	n.s.

tolerances. The variable used to represent the level of early design problems encountered in pioneer plants is a six-point scale that measures the extent to which impurity buildup was a significant source of design and development problems. A value of 0 on IMPURITY indicates no such problems occurred, while a value of 5 means that impurities were a major source of difficulties during early design. (It should be noted, however, that the corrosion index (separately or combined with impurity) would work nearly as well as impurity in predicting the estimated ratio).

Level of Project Information

The level of project information can be viewed as a function of both the amount and quality of plant—as opposed to process—information available to the estimator at the time an estimate is prepared. Both the amount and quality of project information are in part determined by the amount of engineering definition and process development accomplished prior to the estimate. A project has not been very well defined, for instance, if a specific site has not yet been selected, or, even if it has, if its characteristics are not well known by the time the estimate is made, or if little site- and project-specific engineering has been completed. The higher the level and quality of project-specific information included in an estimate, the more accurate the estimate is likely to be.

In developing a measure of the level of project definition, we therefore focused on both the quality of site-specific information used in each estimate and the stage of engineering at the time each estimate was prepared.

The level of engineering completed by the time of each estimate was assessed on a four-point scale. This ranged from completed design specification to little or no engineering completed:

(1) Design specification (engineering completed)
(2) Study design (moderate or extensive basis)
(3) Study design (limited basis)
(4) Screening study (least definition)

In addition to this general index of engineering level, information was gathered for each estimate on the degree of definition corresponding to a number of informational categories about the specific plant site. For each estimate, participating firms were asked to indicate whether information for each of these categories was included in the estimate, and if so, the quality of that information. The categories were rated on a series of four scales for each estimate. In decreasing order, the quality of information was rated as having been based on:

(1) Definitive or completed work
(2) Preliminary or limited work
(3) Assumed or implicit analysis
(4) Not used in the cost estimate at all

In general, the degree to which each of these categories was defined and used in the estimate is highly correlated, as evidenced in Table 4.6; the inter-item average correlation is nearly 0.7. The four categories of on-site and off-site unit configurations, soils and hydrology data, environmental requirements, and health and safety requirements proved to be important predictors of cost growth. These four items provide a reasonable breadth of site-specific information and were together closely related to estimation accuracy. (Altering the number or combination of categories included in a composite measure in fact made very little difference.)

Table 4.6

CORRELATIONS AMONG PROJECT DEFINITION COMPONENTS AND COST GROWTH

Items	Cost Growth Ratio	Level of Engineering	On-site and Off-site Unit Configuration	Soils and Hydrology Data	Health and Safety Requirements
Level of engineering	-.65				
Quality of information included in estimate on:					
On-site and off-site unit configurations	-.49	.64			
Soils and hydrology data	-.51	.71	.65		
Health and safety requirements	-.60	.75	.64	.70	
Environmental requirements	-.68	.70	.69	.63	.85

NOTE: All correlations are significant at .0001.

The variable PROJECT DEFINITION was constructed by computing the average value of the four site-information variables and adding the level-of-engineering variable to it. It thus ranges from a low of 2 (maximum definition) to a high of 8 (no definition). A project estimate for which no site has yet been selected, and which has not yet progressed to engineering, would have a value of 8, for example, while an estimate made during engineering and for which moderate site work had been completed would have a value of around 5 or 6.

Statistically Estimating the Model

The measures of project information, PROJECT DEFINITION, and process information, PCTNEW and IMPURITIES, were used in a preliminary test of our model of cost misestimation. This test regressed the estimate ratio on the set of three independent factors, in the following model form:

$$\begin{aligned}\text{Cost Growth} = a &- b_1\,\text{PCTNEW} - b_2\,\text{IMPURITIES} \\ &- b_3\,\text{PROJECT DEFINITION}\end{aligned}$$

where "a" represents the equation intercept and each "b" an estimated regression coefficient. The results are shown in Table 4.7. Because each variable exerts an independent and statistically significant effect on the estimate ratio, any notion that misestimation cannot be explained by these factors must be rejected. Over 70 percent of the total variance in the misestimation measure is accounted for by these three factors.

Table 4.7

SUMMARY MULTIPLE REGRESSION STATISTICS FOR INITIAL MODEL OF COST GROWTH

(106 Estimates/40 Plants)

Variable in Model	Parameter Estimate	t-ratio[a]
INTERCEPT	1.18231	44.7
PCTNEW	-0.00336	8.1
IMPURITIES	-0.02066	3.7
PROJECT DEFINITION	-0.06705	11.8

Coefficient of determination: $R^2 = 0.73$.

Standard error of estimate = ±0.102.

[a] All parameter estimates significant at less than .0003.

A FULLY SPECIFIED MODEL OF COST GROWTH

Subsequent examination of the unexplained portion of the estimate ratio variance, however, revealed that the model could be more fully specified by including three other factors. Although we examined a large number of alternative specifications with different sets of variables, including total plant cost, plant capacity, project length, plant age, and feedstock characteristics, for example (as well as alternative measures of the dimensions already included), none proved more significant than even the original version.

We therefore turn directly to a description of what our analysis showed to be the best model specification by describing the three new variables, an explanation of their importance, and the final statistical analysis. At that point, the results are explained, and some of the important implications of the entire model are discussed.

The three additional variables included in our complete model of capital cost estimation error represent measures of plant complexity, estimate detail, and the interaction of process development with project definition.

Plant Complexity

The variable labeled COMPLEXITY is simply a 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. This is hardly surprising; it merely suggests that where there is more to estimate, more can be overlooked.

Estimate Detail or Inclusiveness

Another project information variable proved useful in predicting the extent of misestimation. This variable, INCLUSIVENESS, represents the percentage of three items included in the scope of an estimate:

- Land purchase/leases/property rentals
- Initial plant inventory/warehouse parts/catalysts
- Pre-operating personnel costs

Each item was coded 1 if it was included in the estimate, 0 if it was not. Estimates that included all three were more accurate than those that did not.

It is possible that this variable may be operating to compensate for variation in the way firms handle project accounts. Not all firms include property costs as part of their estimates, even though they may ultimately be charged to the project, for instance. Our data base does not possess the detail necessary to examine this problem further. The items included in this variable as the most useful in evaluating the cost-estimate ratio represent only three out of a checklist that contained over twenty such items, however, and none of the others proved statistically relevant.

We therefore suspect that this variable probably measures the detail of the information included in the estimate, rather than representing these categories alone. In this sense, it is likely that the three items do not uniquely influence the extent of misestimation, but merely proxy a level of estimate detail not fully accounted for by our index of project definition.

Interaction of Process Information and Project Definition

As suggested in the earlier discussions of these dimensions, the levels of process information and project definition seem to act jointly as well as independently in explaining cost growth. Cost growth is greatest for plants when they are in the earliest stages of project definition—precisely those points at which the cost estimator has the benefit of only minimal engineering and site-specific information. Although this is the stage at which the largest cost growth occurs for all plants, it is particularly severe for plants that depart from commercially proven technologies.

Cost estimators may find project definition information less useful for pioneer plants until more detailed process understanding is gained. In other words, the project definition index affects estimate accuracy differently for pioneer and for standard plants.

Our analysis of this hypothesis confirmed the importance of this interaction between project definition and process information. We found an independent, statistically significant effect for the level of project definition for unproven technologies, in addition to its influence on the accuracy of all estimates.

This interactive dimension was measured by calculating the parameter estimate for the PROJECT DEFINITION variable in a manner dependent on the stage of process development reached by the time of the estimate. For each estimate, the Process Development Stage was assessed on a four-point scale:

1. *Exploratory/predevelopment*: Most process information is obtained from small-scale laboratory experiments and literature.

2. *Development*: A coordinated R&D program is under way.
3. *Precommercialization*: Work is characterized by efforts to minimize the risk for commercial applications. Pilot work is generally of the demonstration type and there are sufficient data to start design on a commercial unit or a large demonstration plant.
4. *Completed development*: Major process uncertainties have been resolved and a design specification has been completed.

A dummy variable was created to represent the Process Development Stage by recoding the categories (1) and (2) to equal 1, and the categories (3) and (4) to equal 0, and multiplying the PROJECT DEFINITION variable by this term. In other words, if the process development was still in the exploratory/predevelopment or development stages, the dummy variable equaled 1; otherwise, it was set at 0. In addition to an unconstrained PROJECT DEFINITION variable, a second variable was included in the estimated equation representing the product of the dummy variable and PROJECT DEFINITION. Thus, the parameter estimates for the PROJECT DEFINITION variables were obtained for all estimates and for only those estimates made for processes still in development.[17]

Table 4.8 defines and provides summary statistics for the entire set of independent variables used in the cost growth model.

Statistically Estimating the Cost Growth Model

The relative influence of each of the predictive factors was statistically estimated by simultaneously regressing the cost-growth ratio on the set of independent variables. The estimated model took the following form:

$$\begin{aligned}\text{Cost Growth} = a &- b_1\ \text{PCTNEW} - b_2\ \text{IMPURITIES} \\ &- b_3\ \text{COMPLEXITY} \\ &+ b_4\ \text{INCLUSIVENESS} - b_5\ \text{PROJECT DEFINITION} \\ &- b_6\ \text{PROJECT DEFINITION*Process Development in R\&D Stage},\end{aligned}$$

where "a" represents the equation intercept and "b_i" the estimated regression coefficients. Table 4.9 displays the results of the regression analysis.

These results statistically demonstrate the effects of process uncer-

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[17] Alternative specifications of this interaction revealed no significant differences between the estimated slopes for categories (1) and (2), or between categories (3) and (4), thus encouraging the more parsimonious specification presented here.

Table 4.8
VARIABLES IN COST GROWTH MODEL

Variable Name	Definition	Mean	Standard Deviation	Permissible Range of Values
PCTNEW	Percent of estimate incorporating technology unproven in commercial use	28.7	25.0	0 to 100
IMPURITIES	Assessment by industry process engineers of difficulties with process impurities encountered during development	2.3	1.9	0 to 5
COMPLEXITY	Block count of all process steps in plant	5.7	2.6	1+
INCLUSIVENESS	Derived from checklist measuring completeness of estimate (percent of items included)	35.8	31.8	0 to 100
PROJECT DEFINITION	Levels of site-specific information and engineering included in estimate	3.8	1.8	2 to 8
COST GROWTH	Ratio of estimated to actual costs, excluding external cost factors	0.78	0.194	> 0

tainty, measured by both PCTNEW and IMPURITIES, plant complexity, estimate inclusiveness, and project definition on the cost-growth ratio. Interpreted literally, each 10 percent of the estimated investment involved in process steps new at commercial scale, for example, reduces the ratio of estimated to actual costs (in effect reducing the expected accuracy of the estimate) by nearly three percentage points. Each process step in the plant also lowers the cost-growth ratio by about one and a half percentage points. Other coefficients are similarly interpreted.

Interpreting the Effect of PROJECT DEFINITION

The level of project definition operates to reduce the ratio by over 4 percentage points for each level of the definition index, or up to a maximum of about 30 percentage points for estimates that are prepared prior to any engineering and include no site-specific data.

If the technical process used in the plant is still in R&D stages, however, the effect of project definition on the ratio is even greater: Nearly 2½ *additional* percentage points must be subtracted from the

Table 4.9
SUMMARY MULTIPLE REGRESSION STATISTICS FOR FULL MODEL OF COST GROWTH
(106 Estimates/40 Plants)

Variables in Model	Parameter Estimate	t-ratio[a]
INTERCEPT	1.12196	35.1
PCTNEW	-0.00297	8.5
IMPURITIES	-0.02125	4.7
COMPLEXITY	-0.01137	3.6
INCLUSIVENESS	0.00111	4.2
PROJECT DEFINITION:		
If process proven at precommercial or commercial scale	-0.04011	6.2
If process in R&D stages	-0.06361	5.0

Cofficient of determination: $R^2 = 0.83$.

Standard error of estimate = ±0.083.

[a] All parameter estimates significant at less than .0005.

expected ratio of estimated to actual costs for each level of the index, up to a maximum of almost 20 percentage points, if the process involved in project definition has not been demonstrated at precommercial or commercial scale before. In practice, the two parameter estimates for the influence of the project definition index should be added together for estimates prepared while the process remains in R&D (as they are in the "Parameter Estimate" column in Table 4.9). Interpreted in a single step, this means that each level of the index reduces the expected cost growth ratio by over 4 percentage points for commercial (or nearly commercial) processes, but by almost 6½ percentage points for processes still in R&D.

For processes in R&D, in other words, the effect of project definition on cost growth is half again what it is once (or if) the process is established by large-scale demonstration or commercial experience. Figure 4.5 illustrates this differential role of project definition in explaining cost growth. The horizontal axis represents the level of PROJECT DEFINITION index, and ranges from 2 (maximum definition) to 8 (minimum definition). The vertical axis depicts the expected ratio of

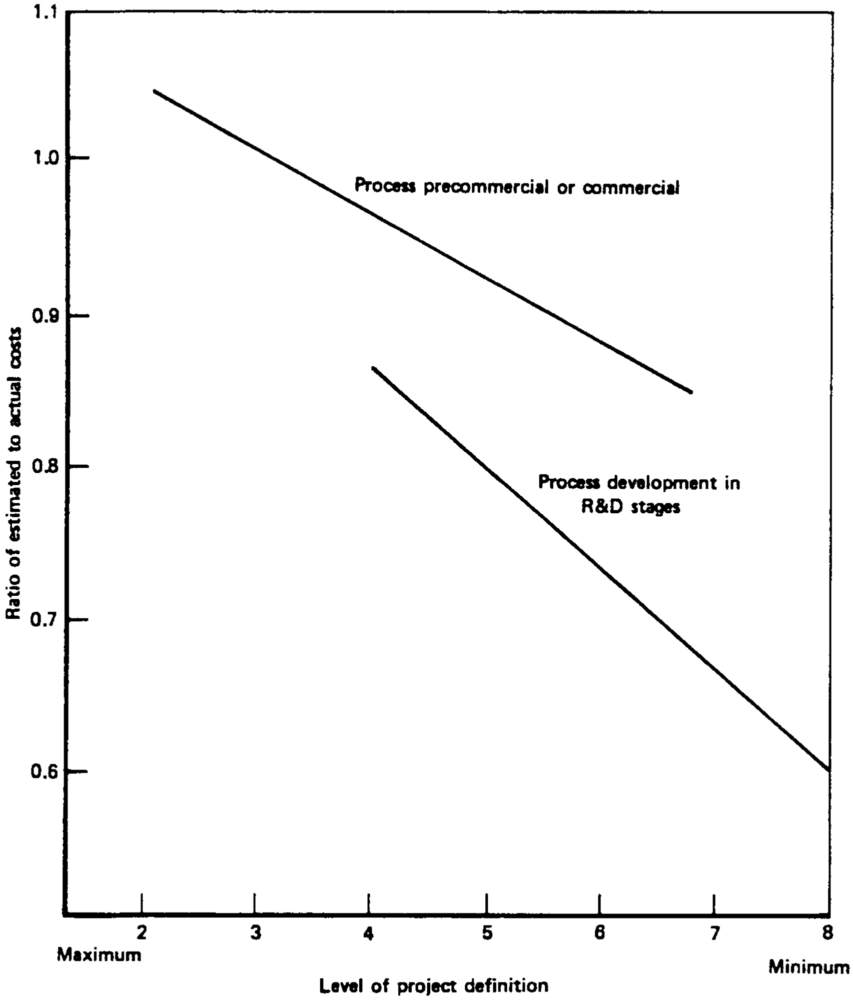

Fig. 4.5 — Relationship of project definition to cost growth dependent on level of process development

estimated to actual costs. The slope of the top line shows the approximate effect of project definition on cost growth for plants using precommercial or commercial processes, while the slope of the bottom line portrays that effect for all other plants—that is, those designed to use a process that is still in R&D when the estimate is prepared.[18] (The truncated project definition range for those processes still in R&D illustrates that no estimates in our data base reached maximum project definition until after R&D was completed, and suggests how closely tied process development and project definition are in practice.)

Three broad conclusions emerge clearly from the regression analysis: First, despite the wide variation in the amount of cost-growth across the 106 estimates, most of the estimation error can be convincingly explained. The coefficient of determination (R-square) of .83 indicates that the estimated equation explains over four-fifths of the variance in the cost-growth ratio. Moreover, the model is highly accurate. As Table 4.10 shows, nearly one-half of the estimates are predicted within plus or minus 5 percentage points of their actual cost growth; nearly all are predicted within plus or minus 15 percentage points. Each variable in the model exerts a statistically significant effect on cost growth.[19] Cost growth is directly associated with low levels of process and project definition. The explanation for their influence is straightforward: The use of commercially unproven technology can lead to higher cost growth by requiring additional units to cope with process impurities or

Table 4.10
ACCURACY OF MODEL IN PREDICTING COST GROWTH

Percentage Point Deviation of Actual From Predicted Cost Growth	Percentage of Sample	(N)	Cumulative Percentage of Sample	(N)
0-5	47%	(50)	47%	(50)
6-10	36%	(38)	83%	(88)
11-15	11%	(12)	94%	(100)
16-17	6%	(6)	100%	(106)

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[18] The intercepts for each "line" arbitrarily assume that the other variables are equal to zero, and therefore should not be interpreted literally. The figure is used only to illustrate the PROJECT DEFINITION slope differences.

[19] Appendix C describes some of the statistical diagnostics we used to evaluate the cost growth and performance models. Included are those for multicollinearity, residual variance behavior, and influential observation detection.

more costly than expected construction materials, by introducing process integration problems, or by requiring higher capital expenses to meet minimal start-up requirements. And while complete definition is not necessary to obtain reasonably accurate estimates, poor project definition results in higher cost growth, both separately and in combination with the use of unproven technology.

The regression analysis also led to a second and at least as important conclusion. All the variables in the model represent factors that are measurable with some precision very early in a project's development. The probable accuracy of a given estimate may be assessed very early, primarily on the basis of the level of process understanding, plant complexity, and estimate inclusiveness. This initial assessment may provide a baseline expectation of probable cost growth that can be refined as project definition increases.

And third, it should be emphasized that the cost-growth effects of unanticipated inflation, regulatory changes, labor strikes, bad weather, and other external factors have already been accounted for and removed. Although these factors may increase final project costs well above the amounts estimated, they are not the sole, or even the primary, causes of cost growth (and even if they were, they are largely uncontrollable). The statistical analysis strongly suggests that cost growth results not from factors peculiar to each project, but from systematic and controllable sources. Estimation accuracy depends directly on the degrees of process understanding and project definition.

CONTROLLING THE UNCERTAINTY OF PIONEER PLANT COST ESTIMATION

The results of our analysis are subject to two interpretations, one explanatory, the other predictive. In the first instance, the analysis highlights major problem areas that constrain the ability to accurately estimate actual plant costs. The cost-growth model clearly points to a set of easily understood factors that are statistically associated with misestimation. Their statistical association plausibly links cost growth to specific plant and process characteristics and to the levels of information about process understanding and project definition. Not surprisingly, the accuracy of an estimate depends on the amount and quality of information that went into it. By providing a systematic explanation of the factors driving cost growth, particularly for pioneer plants, the model may be used to supplement conventional engineering estimates. It allows the cost estimator to fold into his accounting system a set of factors normally not included in conventional estimates.

In addition to their explanatory utility, the results also have a more predictive interpretation. They provide a statistically estimated model of cost growth which, with appropriate inferential caution, may be applied to an estimate developed for a project similar to those represented in our data base. While the application of the estimated equation parameters to a candidate project estimate will carry a necessarily greater degree of uncertainty (i.e., larger standard error, or confidence region) than that surrounding the sampled plants, the equation could be literally applied as an approximate test of the project's expected cost growth.

Although the results of the statistical analysis of the cost growth model described in this section may be used as a predictive tool, caution is advised. It would be misleading to infer that the parameter estimates produced through our analysis of these 40 plants are in fact the exact parameter values that would apply to any or all other plants. The extent to which these factors account for cost growth by the amounts implied by their coefficients for other projects largely depends on how closely the characteristics of a candidate project mirror the average values in our data base. Statistical inference must always be made carefully. Since the representativeness of our sample vis-a-vis any other project or set of projects is not exactly known, the equation must be used with extreme care, bearing in mind the sampling frame and data base characteristics detailed throughout this report. Firms wishing to apply these results to their own estimates should do so in the context of their own experience by estimating a similar equation developed and tested with data from their past projects.

An additional caution may be in order. Some firms have already begun incorporating results of this research into their estimating methods. Those charged with evaluating estimates should therefore be alert to the possibility that an estimate presented to them may already include extra contingency allowances derived from an application of this analysis. If evaluators are unaware of that, they may penalize such estimates for being too high. This would be especially true if our analysis were then used to evaluate the estimate's potential cost growth—in effect doubling the expected cost growth. To avoid this problem, we strongly recommend that evaluators know the precise basis on which all contingency allowances are based.[20]

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[20] This is an instance where significant actors may intrude on the research situation itself, thus changing the very phenomenon under study. This is often termed the "Hawthorne effect" in the experimental design literature. See M. W. Riley, *Sociological Research*, Harcourt, Brace & World, New York, 1963, for further discussion.

SUMMARY

In this section, we have presented a model that posits plausible causal relationships between the levels of process and project information and cost growth. These dimensions were measured and their relative influence on estimation error was examined statistically. The major conclusions of the analysis are:

- The assumptions that planners make about the accuracy and uncertainty of their capital cost estimates are frequently unrealistic.
- Estimates made for projects that use commercially unproven technologies not only are characteristically biased low, but also are so uncertain that they cannot be relied upon at all.
- Despite their notoriety, the major villains in cost growth are not uncontrollable or external influences such as inflation or "scope changes." Most of this bias and uncertainty result from low levels of process and project understanding, particularly for new technologies.
- Application of our model can control this bias and reduce the uncertainty to levels typically assumed.
- The dimensions of the model are measurable from very early points in a project's development.
- With appropriate caution, the statistical equation can be used to supplement conventional engineering estimates and provide planners with reasonably accurate and early evaluations of a project's expected cost growth.

V. PROCESS PLANT PERFORMANCE

Although accurate capital cost estimation would greatly improve government and industry planning, plant performance relative to expectations is equally important. Estimators have to make assumptions about plant performance to calculate product costs and overall plant economics. Plant performance is also a critical consideration when firms do market planning and when the government hopes that synthetic fuels or other energy process facilities will relieve the nation's energy difficulties.

Usual performance assumptions range from 85 to 95 percent of a plant's design (or "nameplate") capacity. For example, if the design capacity of a plant were one billion pounds of product per year, the expected output would be 850 to 950 million pounds, depending on the performance assumption employed. The shortfall is intended to account for maintenance and related activities.[1]

In the discussion below, we consider a plant to be performing well if its average production after a six-month start-up period is 85 percent of design capacity or better. We regard a figure of 50 percent or less as poor performance.

The effect of poor performance on product costs is difficult to exaggerate; because process plants are capital intensive—especially energy process plants—production costs increase rapidly with any decline in plant performance. For example, if a plant operates at only 50 percent of its design capacity, the effective capital cost per unit of output is nearly doubled, and in some cases the operating and maintenance (O&M) costs may more than double.[2]

Figure 5.1 illustrates the importance of plant performance to unit costs. The solid curve shows the relationship between performance and product costs for a hypothetical 500,000 barrel per day oil shale facility whose capital cost is assumed to be $1.6 billion. Under the financial assumptions listed in the figure, such a plant would yield a 15 percent

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[1] Unfortunately, design capacity is an imperfect measure of expectations. It will occasionally be exceeded, especially for very standard units. In some cases equipment is deliberately oversized either to ensure that production goals can be achieved, or to allow for increased production from the facility later after "debottlenecking." In general, however, the design capacity provides a reasonable basis against which to judge how well the plant is performing.

[2] The relationship between performance and O&M costs per unit output will vary from plant to plant depending on the extent to which operating cost can be avoided when the plant is not producing at its expected rate. In general, maintenance costs will be much higher when a plant is not operating well, for obvious reasons.

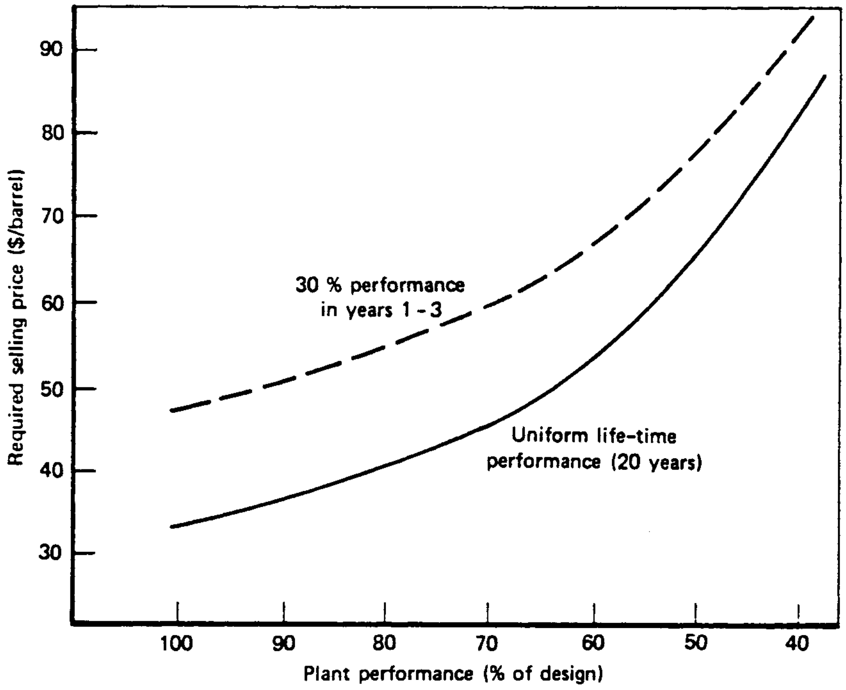

Fig. 5.1 — Importance of performance for economic viability

ASSUMPTIONS: Upgraded shale-oil product from 50,000 barrel per day surface retorting facility. Total capital cost, $1.6 billion (1980$); no inflation; 10 percent investment tax credit; 50 percent federal income tax; no state or local taxes; no insurance; 100 percent equity; 6-year construction; 20-year useful plant life; feedstock consumption 24 million tons per year; 15 percent return on equity; depreciable life, 16 years; no lease costs; $46 million per year operating and maintenance costs.

rate of return with upgraded shale oil selling at less than $40 per barrel if its production averaged 85 percent of design capacity, but would require a selling price of over $60 to produce the same return if the plant averaged only 50 percent of its design rate over its 20-year life.

Achieving design capacity as quickly as possible after start-up is important to preserve the economics of a plant. Poor performance in the early years is damaging because of the time-value of money. In an extreme case, no production in the first year after construction is completed is essentially equivalent to adding a year at the end of construction, with revenues forgone in *today's* dollars.

The dashed curve in Fig. 5.1 illustrates the importance of achieving high levels of performance early in a plant's life. The curve shows the required selling prices for shale oil if performance in the first three years after the completion of construction were only 30 percent of design. Note that in this case, even if the plant worked very well—e.g., 90 percent of design capacity—in years 4 through 20, the required selling price would have to be over $50 per barrel to recover the losses sustained in the first three years.

Given the importance of performance to overall plant economics, we used the Pioneer Plants data base to address two questions:

- How well did the plants in our data base perform?
- What factors are associated with plant performance?

As with our analysis of cost growth, our goal was to isolate factors related to performance that could be measured easily and early in a project's development, at least as soon as the beginning of the project definition exercise, and hopefully as early as the R&D stage.

PERFORMANCE OF PLANTS IN DATA BASE

Of the 44 plants incorporated into the final data base, performance data are available for 43. For these plants, monthly production as a percent of design capacity is provided for at least the first twelve months after start-up.[3] Because our interest is primarily in plant performance after normal start-up corrections and repairs are made, we used the average plant production expressed as a percent of design capacity in the second six months after start-up as our measure of plant performance. The normal start-up period for process plants ranges from as little as one month to as much as six months for large and complex units.[4] For the plants in our data base, the planned start-up period averaged about three and one-half months.

As shown in Fig. 5.2, average performance of plants in the data base improved as a function of the amount of time after initial start-up. In the first three months of operation, the plants averaged only about 40

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[3] Performance data were requested for the first 30 months of plant operation. In many cases, however, the plants lacked sufficient operating history to provide the information beyond a 12-month period, or firms were unable to provide complete data for other reasons. While this limits the analysis to some extent, the limitation is not serious. Although plant production may improve marginally after a year of operation through the adoption of better operating practices, major improvement in performance is very unlikely without major reworking of the facility. In other words, if a plant does not work well after 12 months, the problems are serious and require substantial amounts of additional capital investment to resolve.

[4] An occasional exception occurs when a plant is constructed in modules so that one portion of the plant is in start-up while another is still in construction. In these cases, the start-up period might be better defined in terms of modules rather than the entire plant.

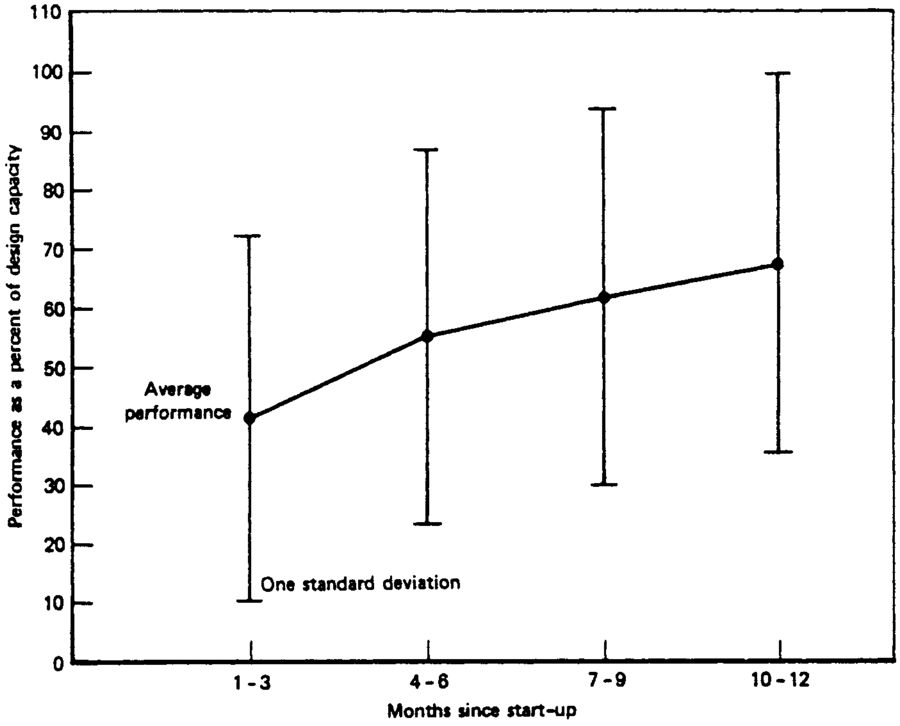

Fig. 5.2 — Performance improvement trends for plants in sample

percent of their design capacity, improved rapidly to about 63 percent in the 7-to-9 month period, and achieved only marginal improvement in the 10-to-12 month period. Figure 5.2 also shows the standard deviation from the average performance for plants in the data base. The standard deviation is large, about plus or minus 30 percent of design capacity. Furthermore, this considerable spread does not narrow as time passes. This spread is also shown in Table 5.1, which provides a breakdown of the plants in our data base by performance in the 7 to 12 months after start-up. Over half the plants in the sample produced better than 75 percent of design capacity. But note that 23 percent of the plants produced at less than 50. Many of those units were later permanently "derated"; the firms changed their expectations of what the plants would ever be able to produce, and most of them reported having lost money on the plants. Of the 43 plants in the analysis, 22 had failed to reach the usual minimum goal of 85 percent of design capacity in the second six months after start-up.

Table 5.1
DISTRIBUTION OF
PROCESS PLANT PERFORMANCE

Average Plant Performance (Percent of Design Capacity)	Percent of Sample in Range
0-25	7
26-50	16
51-75	21
75+	56

CONCEPTUAL MODEL OF PLANT PERFORMANCE

Process plants are complex technical systems involving a large number of interdependencies between hundreds of major and minor equipment items to effect a number of physical and chemical changes on process materials. Often, the failure of a single equipment item can cause part or all of a plant to shut down. Equipment may fail because it was improperly manufactured, because it was improperly designed or sized for its purpose, because of operator error, or because of inadequate or faulty maintenance.

Minor equipment failures can usually be corrected within minutes or hours, and the plant or process train returned to service without much loss of production. Repeated failures of minor equipment items, failure of major reactors, or failure of the process to yield the desired product quality or quantity will usually result in major losses of production, losses that cannot be made up quickly or easily. In the extreme case, a plant may be plagued with so many failures that the owner gives up and abandons the plant. At that point all that can be salvaged is scrap value and a multimillion-dollar tax write-off.

In our examination of plant performance we are not concerned with minor difficulties that are common in the initial start-up of plants, or even minor problems that may recur and cause small losses of production from time to time. Rather, we sought to capture the differences between plants that operate well and those that suffer major performance difficulties.

As discussed in Sec. II, we began with a strong presupposition that the foremost difficulties with plant performance would stem from the introduction of technology that was not proven in commercial use. Our early discussions with industry, the anecdotal literature, and analyses of performance problems in other areas such as weapon systems, all pointed to new technology as the key predictor of performance.

We also wished to explore the possibility that plants with certain characteristics would exhibit performance problems independently or in conjunction with unproven technology. Characteristics typical of synthetic fuels and other energy process plants (e.g., large size, a high degree of complexity, and handling of solids), especially interested us because of the possible implications for energy planning.

CORRELATES OF PLANT PERFORMANCE

In the following pages we discuss the relationship between performance and two kinds of variables: those that seek to measure the extent to which a plant incorporates unproven technology, and factors that characterize plants and projects. This section reports simple two-variable correlations, but such simple correlations can be misleading and should therefore be viewed tentatively. Our intent is to show patterns of relationships between performance and variables in the data base, to provide a sense of the range of potential explanators of performance examined, and to prepare the reader for the multivariate regression analysis that follows.

The Role of Unproven Technology in Plant Performance

Because of our belief in the importance of technical innovation, the data collected from participating firms included several measures of the extent to which a plant departed from established technology. Table 5.2 lists eight measures of innovation and their statistical relationship to the actual performance of plants in the data base.[5]

The first three variables are direct measures of the extent to which a plant incorporates technology that has not been used before commercially. "New technology" includes both major equipment items that are new in commercial use and new chemical or physical processes. The PCTNEW variable is similar to the variable discussed in the cost growth analysis, except that the actual as opposed to estimated percent of the investment in new technology is used. This variable, unlike that

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[5] The correlation coefficient measures the extent to which the measures of innovation vary (positively or negatively) with plant performance. For a data base of 43 plants, one begins to suspect that a correlation actually exists in the data when the coefficient is over .25 (plus or minus). But at that point there is still a considerable chance (about one in 10) that the relationship is randomly generated. In our analysis we have used one chance in 20, a significance level of .05 or less, as the minimally acceptable level. With 43 plants that is equivalent to a correlation coefficient of about .30.

Table 5.2
THE RELATIONSHIP BETWEEN PLANT PERFORMANCE AND MEASURES OF NEW TECHNOLOGY

(43 Plants)

Variable Name	Correlation	Statistical Significance[a]
Percent of capital cost in technology unproven in commercial use (PCTNEW)	-.33	.03
Number of steps (counted on block basis) incorporating new technology (NEWSTEPS)	-.67	.0001
Number of new steps divided by total number of steps in plant (FRACNEW)	-.51	.0004
Number of integrations of *proven* steps that have not been integrated in commercial use before (NEWINT)	-.29	.10
The percentage of the heat and mass balance equations based on actual data from prior plants rather than calculated from theory (BALEQ)	+.76	.0001
Whether or not the plant entailed equipment that had not been used before commercially (yes or no)	-.45	.003
Whether this was the first time that a technology had been used commercially in the U.S. or Canada (yes or no)	-.53	.0004
Whether this was the first experience of the *company* with the technology used in the plant (yes or no)	-.34	.03

[a] Indicates the probability that the association reported is not different from zero.

in the cost growth analysis, can only be known when the project is completed. The next variable, NEWSTEPS, is a simple count of the number of "blocks" in the plant that contain new technology.

A "block" is a functional unit or step in which a chemical or physical transformation of the process materials is performed. A block step often contains several major equipment items. An accurate count of the number of new steps can usually be made as soon as a basic diagram of the process is available, often in the R&D stage. The next variable is the fraction of all block steps that are new steps. This measure adjusts the number of new steps for the complexity of the plant. Note that while FRACNEW is still highly correlated with performance, the relationship is not as strong as it is for NEWSTEPS. Of the three variables seeking to measure directly the extent to which a plant involved new chemical or physical processes, NEWSTEPS has by far the strongest relationship to plant performance.

The next variable (NEWINT) measures another aspect of doing something new: integrating "off-the-shelf" process steps in ways that had not been tried before. The variable is a simple count of the number of new links of commercially proven steps. Although the correlation between NEWINT and performance is negative, it is only marginal and does not meet our 5 percent cutoff for statistical significance.

The next variable in Table 5.2 is the percent of the heat and materials (mass) balances for a plant that were based on actual data from prior commercial units or calculated from theory. The heat and mass balance equations model all of the energy and material flows in and out of every step in a plant. They are essential for determining the proper sizes for equipment. When the equations are not available from prior experience, they can be calculated on the basis of theoretical knowledge of the chemistry of the process steps. If the theoretical foundations are not very good, however, the calculated equations will not be matched in practice. The relationship between plant performance and the knowledge of the heat and mass balance equations is very strong among the plants sampled. More will be said about the importance of this variable in the multivariate analysis that follows.

The final three measures in Table 5.2 are simple "dummy" variables.[6] If the plant requires first-of-a-kind equipment it shows poorer performance. If the plant represents the company's first experience with the technology, the plant will tend to display poorer performance, and first-time use of a technology in the U.S. or Canada is also associated with poorer plant performance.

Table 5.3 shows the relationship between plant performance and the scales of development difficulties in various areas (discussed in Secs. III and IV above). Once again, all of the relationships are in the expected direction but their strength varies considerably. The pattern is clear: Plants that performed poorly were much more likely to have presented a number of difficulties in development. This is entirely as expected. It is interesting to note, however, that the "impurity buildup" scale that was so important to cost growth is not strongly related to performance in a simple correlational sense. Of particular interest (because it will enter the model of plant performance discussed below)

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[6] A dummy variable takes a value of 1 or 0; it therefore divides cases into two classes.

Table 5.3

RELATIONSHIP BETWEEN PLANT PERFORMANCE AND PROBLEMS EXPERIENCED IN PLANT DEVELOPMENT PROCESS

(43 Plants)

Variable	Correlation	Statistical Significance
Feedstock characterization	-.28	.10
Impurity buildup	-.28	.10
Process temperatures	-.34	.03
Process pressures	-.28	.10
Corrosion	-.37	.02
Abrasion	-.48	.002
Solids handling	-.55	.0001
Liquids handling	-.52	.0005
Gas handling	-.35	.03
Waste handling	-.44	.004

is the relationship between performance and difficulties that cropped up in design with waste handling.

The discussion above establishes clearly the relationship between process plant performance and the use of unproven technology as measured in a number of ways. Under the next heading we explore the relationship between performance and other characteristics of plants and projects.

The Role of Plant Characteristics in Performance

The principal goal of this study was to examine industry's experience with pioneer process plants so as to better understand the extent to which cost growth and performance shortfalls might arise for first-of-a-kind energy process plants. In general, pioneer energy process plants such as synthetic fuels plants will be larger (in capacity and total capital cost), will be more complex, and will take longer to design and construct than average process plants. In addition, the overwhelming majority of these plants process solid feedstocks.

Table 5.4 shows the relationship between these and other characteristics and performance. Several important points emerge. We can find no relationship between performance and plant size—measured in

Table 5.4

RELATIONSHIP BETWEEN PERFORMANCE AND SELECTED PLANT CHARACTERISTICS

Variable	Correlation	Statistical Significance
Plant capacity	+.09	n.s.
Total capital cost	+.07	n.s.
Complexity	-.26	.10
Project length	-.28	.10
Type of material processed		
Gases	+.15	n.s.
Liquids	+.26	.10
Solids	-.52	.0004
Year project was completed	+.02	n.s.

terms of capacity or total capital costs (in 1980 dollars)—nor does any such relationship appear in any of the subsequent analyses.[7]

Plant complexity, as measured by the total number of block units in the plants, appears to be weakly related to performance, but as discussed below, when other factors are controlled, no relationship between complexity and performance remains.

Several of the analyses of weapon system acquisition discussed in Sec. II, and the prior report from this study, have found strong relationships between the length of a project and cost growth and performance shortfalls. As shown in Table 5.4, the relationship between performance and project length (measured from the beginning of project definition to the end of construction) takes the expected negative sign, but is weak and is not significant using our normal standard of accepting no more than a 5 percent chance that a relationship is not different from zero.[8]

The next set of plant characteristics presented in Table 5.4 is the relationship between the primary type of materials processed by a plant and performance. When categorized according to gases, liquids, and

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[7] This, of course, does not prove the absence of such a relationship in process plants not in the sample, nor does it prove that such a relationship may not exist for synthetic fuels plants. It does, however, fail to lend credence to such a hypothesis.

[8] Because project length is knowable only after the fact and can only be a proxy for other factors that might actually cause cost growth or poor performance, we hoped that the variable would not be significant after other factors were considered. As discussed below, it is not.

solids processing, only the last is strongly associated with plant performance. As discussed further in this section, the strongly negative relationship between solids processing and performance continues to hold in the multivariate analysis. Plants were categorized as solids processing facilities if they used solids as the primary feedstock or if they produced primarily a solid product. Solid by-products, such as elemental sulfur from a refinery, would not qualify the plant as a solids facility.

The final project characteristics shown in Table 5.4 is the relationship between performance and the calendar year in which a plant was completed. We included this variable to explore the possibility that a trend toward better or worse performance could be found. No such trend can be found in either the simple correlation shown or any other part of our analysis.

THE STATISTICAL MODEL OF PLANT PERFORMANCE

From the possible explanators of plant performance described above, we used multiple regression to select the set that, taken together, best accounted for the variation in performance among the 43 plants in the sample. As discussed in App. C, multiple regression and accompanying diagnostic techniques enable one to test whether a variable is contributing to the explanation of variation in the dependent variable independently of other factors.

Among the variables discussed above, four contribute significantly to explaining the variation in performance:

- The number of steps new in commercial use (NEWSTEPS)
- The percentage of the heat and mass balance equations based on actual data from prior plants (BALEQS)
- The level of design difficulty encountered with waste handling (WASTE)
- Whether the plant processed solids (SOLID)

These four variables constitute the best set of variables. They are statistically the most robust; none of the other variables discussed above can add significantly to our ability to explain performance; no other variables or variable does as well as these four.

The mean values for these variables in the data base, along with their standard deviations, permissible range of value, and methods of measurement are contained in Table 5.5.

Table 5.5

VARIABLES IN THE MODEL OF PLANT PERFORMANCE

Variable Name	Definition	Mean	Standard Deviation	Permissible Range of Value
NEWSTEPS	Number of process units that incorporate technology unproven in commercial use	1.72	1.6	0 to total number of process steps (counted on block basis)
BALANCE EQUATIONS	Percent of heat and mass balance equations based on actual data from prior plants	54	37	0 to 100
WASTE	Assessment by industry process engineers of difficulties with waste handling encountered during develpment	2.0	1.6	0 to 5
SOLIDS	Designates that a plant processes primarily solid feedstocks of products	.35	.48	1 if solids plant, otherwise 0
Performance	Actual average production in months 7 to 12 after start-up as a percent of plant design capacity production	72	30	0 to 100+

The estimated model takes the following form:[9]

$$\text{Plant Performance} = a - b_1 \text{ NEWSTEPS} + b_2 \text{ BALEQS} - b_3 \text{ SOLID} - b_4 \text{ WASTE},$$

where "a" represents the intercept (constant) value for the equation and the "b_i"s represent the parameter estimates (coefficients) for each independent variable. The model indicates that plant performance declines with more new steps, increases with the percentage of the heat and

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[9] Several functional forms of the model were tested, including logarithmic and other nonlinear models. This testing was done for the sake of completeness; based on plots of the variables, we had no reason to expect any nonlinear form to be superior and it was not. As in Sec. IV, it is the bias of the authors to start with linear models because they lend themselves to straightforward interpretation unless we have reason to suspect another form. In this case, as with the cost growth model, the linear model is also the "best model."

mass balance equations based on actual data, declines as the severity of development problems with waste handling increases, and is poorer if the plant processes primarily solids instead of liquids or gases.

The fully specified regression model is presented in Table 5.6. Several features of the model are noteworthy. Each of the independent variables is very strong statistically.[10] The probabilities are trivial that the independent variables are not really related to the performance of plants sampled in the direction stated. The four variables account for about 90 percent of the observed variation in plant performance with a standard error of about 10 percent. Table 5.7 summarizes the accuracy of the equation in predicting the performance of plants in the sample. About three-quarters of the plants in the sample are predicted with an error of less than 11 percent of actual performance. Fully 98 percent of the plants are predicted to within 20 percent. Perhaps the most interesting aspect of the model, however, is that the four independent (predictor) variables are relatively easy to measure and can be assessed as soon as a basic block diagram of the plant is available.

Table 5.6

SUMMARY OF MULTIPLE REGRESSION STATISTICS FOR THE MODEL OF PLANT PERFORMANCE

Variable in Model	Parameter Estimate	Standard Error of Parameter Estimate	t-ratio[a]
INTERCEPT	85.77	5.75	14.9
NEWSTEPS	-9.69	1.05	-9.3
BALANCE EQUATIONS	0.33	0.05	6.0
WASTE	-4.12	1.06	-3.9
SOLIDS	-17.91	3.85	-4.7

Coefficient of determination: $R^2 = 0.90$.

Standard error of estimate = ±9.3 percent.

[a] All parameter estimates significant at less than .0004.

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[10] As measured by the "t-ratio."

Table 5.7

ACCURACY OF MODEL IN PREDICTING PLANT PERFORMANCE

Percentage Point Deviation of Actual from Predicted Performance	Percentage of Sample	(N)	Cumulative Percentage of Sample	(N)
0-5	42%	(18)	42%	(18)
6-10	33%	(14)	74%	(32)
11-15	14%	(6)	89%	(38)
15-20	9%	(4)	98%	(42)
20-25	2%	(1)	100%	(43)

UNDERSTANDING THE MODEL

In this section we discuss our interpretation of what the model of performance means: why the variables work as they do, possible ambiguities in interpretation, and the importance of the variables to an explanation of performance.

New Steps

Of the several direct measures of innovation listed in Table 5.2, the number of process steps in a plant that are new in commercial use, is one of the strongest predictors of performance shortfalls. The fact that the number of new steps is a better indicator of performance problems than the percent of the capital investment in new steps (PCTNEW) should not surprise us: It merely suggests that whether a step is cheap or expensive has little bearing on how well the step works.

NEWSTEPS is also a much stronger predictor of performance than the fraction of all steps in the plant that are new. We believe that the continuously linked nature of process plants explains this pattern. If the failure of any major unit (step) leads to plant or train shutdown, then the probability of failure is determined by the *number* rather than the *percentage* of units with significant probabilities of failure; those probabilities in turn are a function of the extent to which steps involve new technology.

The importance of the number of *new* steps to plant performance is underscored by the fact that adding complexity (the total number of continuously linked steps, measured on a block basis) adds no explanatory power to the equation. This indicates to us that the probability of failure in commercially proven units is very small.[11] The average performance of the nine plants that had no new steps was 94 percent of design capacity compared with 66 percent for plants with one or more.

We were somewhat surprised that the number of new integrations of process steps—that is, the first time that commercially proven steps had been linked in commercial use—did not add to the explanation of performance shortfalls. Our rationale was that new integrations would give rise to at least occasional problems that would not be apparent until start-up. As with complexity, however, new integrations add nothing to the model.

Knowledge of the Heat and Mass Balance Equations

Perhaps our biggest surprise was the strength of the independent contribution of the balance equations variable to the explanation of performance. That such a relationship emerged did not surprise us at all; the heat and materials balances are the basic equations governing flows in the plant and are necessary to size all equipment and determine needs for energy in and out the system at different points. Any error in the balances, which we presumed would be much more likely when data from prior plants were not used, could seriously affect plant performance. What surprised us was that the balance equations variable is *not* tapping the same dimension of innovation in the plant as the number of new steps. The simple correlation of the two variables is not even statistically significant using our criterion.

The independent contribution of the balance equations variable to performance is underscored by the fact that while NEWSTEPS alone can account for about 45 percent of the variation in performance, the addition of the percentage of the balance equations known on the basis of data from prior units increases the explained variation to over 80 percent. This result is shown in Table 5.8.

We suspect that the balance equations are influential because they may be measuring something we were unable to address explicitly: where in the plant stream the new units were located. Heat and mass balance equations are least likely to be known not only for a new step, but for steps downstream from the point at which the new unit is located. To give an example, if a plant involves 10 steps and the new

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[11] The correlation between complexity and the residual variance of the performance model is −.18, which is not significantly different from zero.

Table 5.8
PERFORMANCE AS PREDICTED BY NEWSTEPS AND BALANCE EQUATIONS
(43 Plants)

Variable in Model	Parameter Estimate	Standard Error of Parameter Estimate	t-ratio[a]
INTERCEPT	60.74	4.95	12.3
NEWSTEPS	9.24	1.38	-6.7
BALANCE EQUATIONS	0.51	0.06	8.6

Coefficient of determination: $R^2 = 0.80$.
Standard error of estimate: ±13.7.

[a] All parameter estimates significant at .0001.

step is the 10th, then almost all of the heat and mass balance equations can be known from prior experience. If, however, the first unit is new, then it may be very difficult to calculate materials flows for the remainder of the plant. Assumptions have to be made about the materials and energy flows from the first step—assumptions that may or may not prove to be correct.

Problems with Waste Handling Development

Of the four independent variables in the performance equation, the interpretation of WASTE is the least straightforward. As discussed in previous sections, the WASTE variable was one of 10 scales seeking to measure problems that were encountered in development for plants. On a scale of 0 to 5, company engineers familiar with a plant were asked to rate the severity of problems encountered in development with waste handling. The scale is therefore subjective, but when we have applied the scales to projects currently in development, disagreements among process engineers have rarely exceeded one point on the scale. A difference of one point on the scale would change our prediction for a plant in the data base only by about 4 percent of design capacity.

It is not clear whether waste handling difficulties should be classified under the general rubric of problems associated with innovation or whether they should be considered a characteristic of a process or project. Of all the measures of innovation discussed in Table 5.2, the waste handling scale is correlated with only two: first-time use of a technology in the U.S. or Canada, and the balance equations variable. Both correlations are reasonable. Because both the U.S. and Canada have strong environmental regulations, the transfer of a technology from abroad is likely to give rise to a need to develop new waste handling techniques. Therefore, the positive correlation between first use in the U.S. or Canada and increased waste handling problems is sensible. The negative correlation between waste and the balance equations variable problem stems simply from the fact that waste streams are part of the materials balances, and to the extent that development is required in waste streams, the appropriate balances are unknown almost by definition.

Our finding that difficulties in development for waste handling affect plant performance is significant for two reasons. It suggests that regulatory requirements may affect process plant performance in addition to the often-cited effects on capital costs. Second, synthetic fuels plants almost universally entail some special waste handling difficulties.

Performance of Solids Processing Plants

From the viewpoint of synthetic fuels development, our most disturbing result is the poor performance of solids processing plants. As shown in Table 5.9, the average performance of the 15 solids plants in the data base is only 49 percent of design capacity production. Only two of the 15 operated at 85 percent or more of design capacity in months 7 to 12. By contrast, the average performance of the 28 gas and liquids plants in the data base is 84 percent. Part of the explanation for the difference is that the solids units in our sample were slightly more innovative on average, as measured by the number of new steps. In addition, we were not surprised to find that the solids plants had slightly more difficulty in development with waste handling.

The major difference between solids plants and the others is in the percent of the balance equations known on the basis of data from prior units. Only about a quarter of the equations were known for solids versus nearly 70 percent for the other plants. If our sample reasonably reflects the universe of solids plants, then we can conclude that heat and mass balance equations are much less likely to be known for solids plants than for others. Additional research will be required to understand why. It may be that changes in solids plants are more likely to be made on the "front end" of the process than they are in other plants. It may be that less experience is available for solids units from which to specify the balance equations empirically. Or it may be (as we

Table 5.9
COMPARISON OF SOLIDS VS.LIQUIDS AND GAS PROCESSING PLANT PERFORMANCE

Variable	Average for: All Plants (N=43)	Solids Plants (N=15)	Liquids/Gases (N=28)
Performance (%)	72	49	84
NEWSTEPS	1.72	1.86	1.64
BALANCE EQUATIONS	54	26	69
WASTE	2.0	2.4	1.8

strongly suspect) that process instrumentation and control and our theoretical knowledge of the behavior of solids is much more primitive than it is for liquids and gases, and we therefore have great difficulty translating prior experience to new situations for solids processing.

INTERPRETING THE RESULTS

The basic conceptual model of plant performance with which we started this analysis is strongly supported by the statistical results. For the plants in the sample, performance problems are largely predictable on the basis of a few simple measures of technical unknowns and the type of materials processed.

Because the plants in the sample represent a wide variety of continuous process plants, we conclude that the factors that we have found to be associated with performance difficulties are probably generic to process facilities rather than unique to any particular type of plant.[12]

The statistical results can be interpreted and used in two ways, the first "explanatory" and the other "predictive." The explanatory interpretation treats the statistical results as supporting the basic model, thereby isolating the generic factors associated with performance difficulties and suggesting a set of measures that can be used by government and industry planners. Using the model and the specific measures as a guide, DOE and companies might then develop a data base from their own experience as a way of calibrating the model to their own specific situation. In this case one is accepting the *direction* of the

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[12] The type of plant defined in terms of the type of chemical produced was unrelated to performance among the plants in the data base.

effects of specific variables, e.g., that performance declines as the number of new steps increases, but not necessarily the *parameter estimate* on the independent variables, e.g., that performance will decline about 9.7 percent for each new step added.

The statistical analysis can also be used as a predictive tool, but only by courting certain dangers. First, there is variance unexplained by the statistical model. That residual may be the innocuous result of "noise" in the data, or it may result from the absence of some factor or factors that would significantly change the results when applied to a particular plant or to the plants of a particular company. A second danger in using the parameter estimates as predictors is the extent of sampling error. Use of the statistical model as a predictive tool requires that the sample be truly representative of the population of plants. It is never possible to know with certainty that this is the case, if only because the population of plants changes continually with time. (The structure of our sample and potential problems with it are discussed in Sec. III.) Furthermore, the farther a particular plant deviates from the mean of our sample in terms of the characteristics measured by the statistical model, the larger the uncertainty range that must be applied to the plant's predicted performance.

Despite the dangers involved, one may be better advised to explore the use of the statistical models of cost growth and performance as predictive tools than to revert to conventionally derived estimates of cost and assumptions about performance. Even if the precise parameter estimates are considerably wide of the "true" mark, the models may enable one to differentiate between a high-risk project and a low-risk project.

SUMMARY

In this section we have shown that poor plant performance is a largely predictable phenomenon. It occurs when new technology is being introduced for the first time in a commercial plant, when waste handling difficulties are involved, and fairly consistently when the plant engages in solids processing. By implication, we have also shown that plants free from these characteristics tend to perform very well.

The results of this analysis should help both industry and government to set realistic expectations for plant performance and to examine the effect of those revised expectations on a plant's economic viability. Many firms in industry are well aware that their first-of-a-kind plants do not perform as well on average as their more standard facilities. The possibility raised by this analysis is a means by which performance losses for some plants can be reasonably quantified early in project development, thereby raising the possibility of modifying or rejecting projects in which the level of risk engendered by poor performance exceeds the economic benefits of proceeding with the project.

VI. IMPLICATIONS OF THE ANALYSIS

The foregoing analysis has enabled us to isolate statistically the factors that are strongly related to cost growth and performance shortfalls in process plants. Among the plants in our sample, the introduction of new technology, the degree to which a real project has been defined, and several characteristics of proposed plants account for most of the deviation of cost estimates from actual costs and of actual performance from design performance. Contrary to conventional wisdom, unanticipated inflation, unanticipated regulatory changes, and "bad luck" are on average fairly minor factors in explaining discrepancies between cost estimates and actual costs. Our analysis therefore leads us to discount the arguments of those who routinely blame inflation and regulation for inaccurate estimates of process plant costs; admittedly, these have added substantially to the costs of plants over the past decade, but we find that cost estimators in the process industries have generally been quite good at anticipating their effects.

In this section, we discuss the implications of our analysis for planning and estimating projects, for comparing technologies, and for commercializing new technologies. We also mention some promising avenues for R&D that our analysis suggests.

PROJECT PLANNING AND ESTIMATING

The introduction of new technology and poor project definition are the key indicators of inaccurate estimates and other project difficulties. Improvements in project planning will have to come in these two areas.

Coping with New Technology

Except when regulations mandate new technology, firms in the private sector introduce new processes in order to make money, either through reducing the costs of producing an old product or by introducing a new one. Added profits can accrue in two ways from introducing new technology: from the pioneer plant itself, or from follow-on plants incorporating the new technology that are built by the company introducing the process or by license to other firms. Although our data base cannot address the question directly, it is reasonable to assume that innovation routinely pays. But it is very clear from our analysis that introducing new technology does not always return a profit, and that it creates some special problems in project planning and execution.

Our analysis suggests several strategies for reducing risks and coping with the difficulties inherent in introducing new technology.

First, the amount of new technology to introduce in a single plant is often a matter of discretion. Among the plants in the data base, new technology was frequently introduced in a number of steps simultaneously when each new step could have been introduced alone. In other words, the company decided to build a "best possible technology" plant, independently incorporating a variety of innovative aspects. Our analysis suggests that such a strategy may make economic sense only under certain special circumstances: (1) the return on investment looks so high on the basis of early estimates that substantial cost growth and poor performance will still allow a profit, or (2) the pioneer plant is really being used as a commercial-scale pilot or demonstration facility with which to test new technologies; these technologies will be incorporated into subsequent modified units from which substantial profits are expected. Even these two reasons need to be tempered with a caveat: If the plant performs very poorly, profits are impossible and little or nothing may be learned to incorporate into future plants. The analysis in Sec. V can be used to anticipate what the performance of a plant will be. The characteristics of plants that performed at less than 40 percent of design capacity in the second six months after start-up are straightforward: They incorporated four or more new steps, and the great majority of the heat and mass balance equations could not be fixed on the basis of data from prior units.

In some cases it is simply not feasible to limit the amount of new technology and commercialize a new process at the same time. This situation occurs where the innovative aspects of the plant are interdependent and call for several new steps and a high percentage of total estimated plant cost in technology not previously used at commercial scale. Such cases exist in our data base as well as in some advanced energy process technologies. The economics of such plants are inherently risky, and the decision to proceed should probably be based on an analysis of the technology's long-term prospects rather than on returns from the first plant.

Markedly better performance can be expected in follow-on plants because much of the technology in those plants is no longer new in commercial use, knowledge of the heat and mass balance equations should be markedly better, and waste handling aspects will have been tackled and hopefully resolved in the process of building the first plant. Because of the extreme sensitivity of product costs to performance, product costs will usually decline in the later plants even if capital costs fail to decline or even increase somewhat as the performance difficulties of the first plant are capitalized into improvements in the second and later units.[1]

It is important to note, however, that improved performance in follow-on units will not occur automatically; it is contingent on:

- The second plant actually following the start-up and early operation of the pioneer,
- The information generated in the pioneer plant actually being transferred to the design and operation of the follow-on units, and
- Avoiding major unnecessary "improvements" in the follow-on plants that introduce new technical uncertainties.

Coping with Project Definition

It is virtually a platitude to suggest that time spent in planning and preparation pays off, but it requires repeating because those tasks are sometimes not done. The exercise of defining a project in terms of an actual site, taking local regulatory requirements into account, performing soil and hydrological analyses, and working out off-site requirements such as roads and other transportation facilities in a preliminary way, clearly pays off in considerably more accurate estimates. Firms that appear to estimate better than others have established criteria for what constitutes an acceptable level of definition before an estimate is presented to management for the first authorization of funds.

We are unable to explain why project definition exercises are conducted so differently among process industries, but we suspect that two factors are important. First, some firms lack the sizeable engineering units that would normally be charged with project definition. In these cases, architect-engineering firms typically provide all services for the planning, design, and construction of a plant, and the owner will lack the expertise to ensure that the project definition is well prepared and that the plant will truly fit his needs. Second, owners are sometimes in a hurry to get a plant built or are simply trying to economize by

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[1] Our data base cannot address the question of whether capital costs tend to decline in real terms as the number of plants built of a particular type increases. For a number of reasons we would caution against assuming large "learning curve" decreases in capital costs for synthetic fuels plants. See Sec. III of Edward W. Merrow, *Constraints on the Commercialization of Oil Shale*, The Rand Corporation, R-2293-DOE, September 1978. The performance analysis does suggest a particular type of learning that should result in lower costs for later units. The decreases discussed here, however, may not continue beyond the second or third plant and are decreases from a level higher than assumed with standard performance assumption inputs to financial analyses.

skimping on up-front planning and analysis. Our understanding of the plants in the data base suggests very strongly that attempts to save time and money on initial planning and definition almost never pay. Several of the plants with the longest overruns in schedule were those that were accelerated in the early stages.

Implications for Cost Estimating Methods and Practice

We can detect no trend of improvement in cost estimating over the 12 years or so covered by plants in our data base, nor can we discern any change in expectations about plant performance. The persistence of underestimation of costs and over-optimistic assumptions about performance raises questions about why industry has not been able to adjust its expectations over the years. We can supply no single and definitive answer, but several possible reasons can be adduced.

First, the great majority of plants built by any company will be relatively standard units for which conventional estimating methods are reasonably well suited. Although early estimates for even standard units are typically too low, they are often reasonable approximations of actual costs and improve rapidly as the projects progress. Therefore, the average experience of a company will usually be considerably better than the average for our data base, which consists primarily of pioneer plants.

A second and more powerful reason that many companies do not learn is that they do not invest in "remembering." Some companies do not preserve data in any centralized or systematic fashion; some of those who keep extensive data do not keep the kind of data that would enable them to examine their corporate performances in ways similar to this analysis; some of those who collect the appropriate data do not invest the necessary resources for analyzing them.[2]

Third, there appears to be a tendency to view unhappy experiences with estimation or performance as the product of highly idiosyncratic circumstances. Sometimes if a project goes "sour," an investigation will be conducted, the *immediate* causes of the problems will be identified, and those involved confidently conclude that "it won't happen again." Such confidence is justified only for highly specific causes of problems. At a slightly higher level of abstraction, something entirely analogous probably *will* happen again.

Finally, so many external factors have affected plant costs over the

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[2] A discussion of the process industries' collection and use of data is found in S. J. Bodilly, R. E. Horvath, and M. Lieber, *The Formation of Pioneer Plant Projects in Chemical Processing Firms,* The Rand Corporation, N-1720-DOE, August 1981.

past decade that it is easy to ascribe problems to the wrong source. Inflation has soared to levels never before experienced by the process industries, dramatic hikes in energy prices have driven up costs, and the regulatory environment has been constantly changing. Such factors not only confound an analysis of what has caused problems, but also provide a ready excuse when things do not go well.

These reasons that companies have not changed their expectations about the cost growth and performance of pioneer plants apply much more forcefully to the Department of Energy. DOE lacks the experience that is prerequisite to analyzing the problem, lacks a data base that would permit analysis of projects it has undertaken, and operates in a political environment in which it is very tempting to attribute problems to inflation and regulation.

In this report we have primarily examined cost estimation as a technical problem, but some organizational aspects of estimation also deserve mention. First, cost estimators are quick to point out that they are prisoners of the information they receive from designers. Management in turn notes that it has little option but to depend on the cost estimators. But in some cases, management may be its own worst enemy. In a number of cases in the data base, management rejected estimates as "too high" and returned them to the estimators for reduction. They usually did so by reducing the contingency applied to the estimate and substituting optimistic for conservative assumptions. The resulting "reduced" estimates were routinely more severely underestimated than the estimates they replaced (which were themselves usually too low). Cases in which estimates were reduced on orders from management (and cost estimators were quick to point them out to us) were simply dropped from the cost growth analysis.

COMPARING TECHNOLOGIES

In light of our findings that cost-underestimation is systematically related to lower levels of project definition and larger amounts of unproven technology, and that poor plant performance is associated with new technology, we can safely conclude that cost and performance estimates will tend to unduly favor projects that are more technically advanced and relatively undefined over systems that are commercially available or closer to commercial application. In other words, straightforward comparisons of capital costs and performance between systems at different stages of development or with different amounts of unproven technology cannot (or at least should not) be made.

We find that some firms in the process industries clearly recognize this problem and attempt to cope with it in various ways. Some firms try to account for the bias by requiring that new projects involving unproven technology meet very stiff rate-of-return tests. After-tax rate-of-return requirements between 25 and 40 percent are common among chemical and oil companies for plants involving unproven technology. Such high rates of return compensate for the effects of cost growth and poor plant performance. In other cases, top management simply adjusts its expectations of costs for new plants upward in an informal way. In a few other cases, firms have introduced simple factors to adjust for the stage of a project's development. Such techniques help to remove the bias toward underestimation of costs and overestimation of performance, but fail to cope with the wide variation ("spread") that we find for both cost and performance. Most firms and the Department of Energy lack the experience and data necessary to attempt any adjustment, no matter how crude.

Using the results of the cost growth and performance analyses as predictive models can aid in overcoming the comparison problem. Alternative systems with differing levels of new technology and cost estimates of different stages of definition can be placed on a roughly comparable basis by examining the estimates in terms of the expected cost growth and by comparing product costs using different predicted levels of plant performance. The one contributor to product costs not addressed in this analysis is operating and maintenance costs, which would have to be estimated by a different approach. An application of this methodology to several synthetic fuels technologies will be the subject of a forthcoming report.[3]

Using the results of this analysis as a predictive tool courts a variety of dangers discussed in previous sections and in the appendixes. An additional consideration, especially for government planners examining estimates made by private sector firms, is the possibility that as the results of this analysis become widely available, they will lead companies to change the way in which they estimate costs or project plant performance. This potential "Hawthorne effect" does not constitute an insuperable problem, at least in the short run. It does, however, require that those evaluating an estimate in terms of this study's findings know whether the firm producing the estimate made any special adjustments to its estimates. As noted above, a few companies do adjust their conventionally derived estimates with a factor to account for the bias inherent in early estimates and in estimates for advanced tech-

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[3] *Cost and Performance of Advanced Energy Systems: Application of the Pioneer Plants Study*, The Rand Corporation, R-2571 (forthcoming).

nologies. If the results of this study are to be used, such adjustments must be removed or otherwise accounted for in any analysis.

TECHNOLOGY COMMERCIALIZATION

A very clear result of our analysis is that there are real and substantial costs associated with being the first to introduce a technology. These "first-of-a-kind" costs are most obvious in the poor performance associated with introducing new process steps, with designing plants for which no good data exist upon which to calculate the heat and materials balances, and with plants that require development for handling wastes.

These first-of-a-kind costs may deter firms from introducing technologies that could provide public benefits, such as a reduction in oil imports. The deterrent effect will be especially strong where firms do not believe that they will be able to recapture their extraordinary costs from pioneering by obtaining a clear advantage over their competitors. When first-of-a-kind costs deter introduction of a technology that appears feasible and promises substantial social benefits, there is a strong rationale for government assistance with the pioneer plant's costs.[4]

As discussed above, however, it is important to recall that having paid the first-of-a-kind costs does not automatically confer advantages. Accelerating the deployment of plants, and thus designing and constructing follow-on plants before the pioneer is up and operating, probably sacrifices many of the opportunities for learning. Although completing the design of a pioneer facility greatly reduces the risk of cost growth, the crucial performance risks are not reduced until the plant is up and operating well.

Another aspect of commercialization strategy in which the cost growth and performance models have important implications is in the design of demonstration projects. In both equations it is *commercial use* that distinguishes known from unknown technology. Having constructed pilot or other facilities to prove the technology at smaller scale does not alter this conclusion. Therefore, if demonstration projects are to significantly reduce cost growth and increase performance in the first commercial plant, they should at least be at a scale that allows the use of the same-size equipment that will be used in the commercial units. So-called "semi-works" plants probably do not provide a basis for cost estimation and performance for the commercial units.

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[4] There are other considerations that must enter any determination that government intervention is appropriate. For example, who will appropriate the knowledge gained in the subsidized pioneer plant and will it subsequently be used to lower the costs of product from subsequent plants?

PROMISING AVENUES FOR R&D

The fact that certain types of technical problems or plant characteristics are strongly associated with cost growth or performance shortfalls in pioneer plants suggests that research and development on those problems might pay substantial dividends.

In the cost-growth equation, problems associated with the buildup of impurities in intermediate process streams was identified as a major source of difficulties. Highly correlated with impurity problems were abrasion and corrosion of plant equipment and deactivation of process catalysts. These findings suggest the following as important areas for research funding by the government and private sector:

- Continued basic research into the nature of organic chemical reactions. Better understanding of the details of chemical reactions and of the conditions that produce only very small quantities of chemical impurities promises high potential payoff.
- Another avenue of attack on the impurities problem is through materials research, because the effect of impurities is often manifest in corrosion of process equipment downstream. Research into corrosion-resistant and abrasion-resistant materials should also include analysis of the methods required to bond such materials to equipment and pipe internals.
- Yet another manifestation of impurities is catalyst deactivation. Extending catalyst life can yield substantial cost savings, and very short catalyst life can render an otherwise attractive process uneconomic. Basic research into ways of preventing deactivation appears to hold considerable promise.

The performance equation offers one area in which an R&D emphasis seems obvious: the relationship between solids handling and poor plant performance. On average, the performance of plants that handle solids falls about 18 percent of design capacity lower than that of plants that handle no solids. The precise reasons for this substantial difference cannot be deduced from our analysis; the subject clearly calls for additional investigation.

Some possible areas for R&D on solids handling problems are the relationship between varying feedstock characteristics and plant design; materials and design research on prevention of abrasion; and the general area of solids flow, instrumentation, and control.

IMPLICATIONS FOR NATIONAL ENERGY POLICY

The purpose of this study was to develop a new planning tool for public and private managers who are concerned with the costs of advanced energy process plants and new chemical plants generally. The results of the analysis confirm something that many managers have long known: The cost and performance uncertainties for synthetic fuels and other advanced energy process plants are considerable. These uncertainties are compounded by the very large investment required for commercial synfuels plants and by institutional factors such as regulatory requirements. Under the circumstances, the reluctance of the private sector to push ahead with projects, even projects that look profitable on the basis of estimated costs, is understandable.

Through the Department of Energy and the Synthetic Fuels Corporation, the government is about to subsidize a number of pioneer energy process plants in order to reduce the risks of these projects to the point that the private sector will proceed. On the basis of our analysis, it is clear that the risks associated with cost growth and performance vary greatly from project to project and technology to technology. Well-defined projects using processes that entail a modest amount of unproven technology should not be treated in the same manner as projects in the early stages of planning for processes that push the state of the art. The results of this study should help planners at least to differentiate between high- and low-risk projects.

The results should also help those who plan our future energy supplies to develop realistic expectations about how much energy process plant technologies can contribute to the nation's energy supplies. Because the costs of these technologies will almost assuredly be higher than expected and the actual output lower, the near-term prospects for major increases in liquid hydrocarbon supplies from energy process plants are not good. But the longer-run benefits of having designed, constructed, and operated a well-chosen set of pioneer synthetic fuels plants could prove to be a national blessing in the 1990s.

Appendix A

COST ADJUSTMENT PROCEDURE

To evaluate the various actual and estimated costs in comparable dollars, we adjusted all cost figures to constant 1980 dollars. This standardization procedure essentially involved estimating the time at which each part of the total costs of a plant was incurred—or was projected to be incurred—and applying the appropriate inflation index to bring the amount forward to a 1980 equivalent amount. This required two pieces of information: first, how much money was spent at any point in time (or projected to be spent), and second, the 1980 value of the dollar at each of those points. This information was provided by the empirically-fit S-shaped expenditure curve developed by John Hackney using cost expenditures for chemical process plants,[1] and by the *Chemical Engineering* (CE) cost inflation index, respectively. Since actual outlays and estimated costs were adjusted slightly differently, both procedures are detailed separately below.

ACTUAL COSTS

For actual costs reported in "as spent" dollars, we first calculated the length of the project as the number of three-month intervals between the start of engineering and the end of mechanical completion. We then estimated the amount spent in each quarterly interval, using the S-curve and the appropriate CE inflation index factor for that calendar quarter to adjust each amount to 1980 dollars. The sum of each adjusted portion across the entire length of the project yielded an adjusted cost total. Start-up costs were separately adjusted and carried forward to 1980 dollars without the expenditure curve, since they generally involved small amounts of time and expenditure.

Where actual costs were reported as already in "constant dollars," the inflation factor for the appropriate base year was applied to bring the total forward to a 1980 adjusted amount, without the curve.

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[1] John W. Hackney, data provided in course on "Cost Engineering Economics" given in 1980.

ESTIMATES

Individual estimates were reported in a variety of forms, and sometimes included amounts already expended as well as amounts projected to be spent, necessitating a somewhat more complex adjustment procedure.

Most cost estimates provided included some built-in escalation for projected inflation. Since a major component of the analysis sought to isolate factors contributing to cost growth, independent of any errors in predicting inflation (a problem particularly acute for the 1973-74 period), any escalation included in an estimate was removed prior to standardizing the estimate in 1980 dollars. In cases where the inflation factor used to escalate the estimated cost was not specifically provided, we assumed estimators used an average of the previous year (lagged by six months)—or at least something approximating it. That figure was then used to "back out" the escalation for inflation from the unspent portion of the estimate. In essence, this removed any effect on cost growth attributable to underpredicting (or, less frequently, overpredicting) the future rate of inflation. Where an estimate did not include an escalation factor, but was reported in "build today—operate today" dollars, the entire estimate was adjusted to 1980 dollars using the appropriate CE actual inflation index.

In all other cases, escalation was removed in one of two ways. Where it was included only through the mid-point of construction, the inflated amount was removed by compounding the assumed inflation rate over the period between the date of the estimate and the projected mid-point of construction. For all other estimates, escalation was included through the end of mechanical completion, and the inflated amount was removed by compounding the assumed inflation rate applied to the expenditure curve for the period between the estimate date and the projected end of construction.

In both instances, where the date of the estimate followed the start of engineering, some portion already spent was assumed to have been included in the estimate total in "as spent" dollars, and had to be removed before deescalating the inflated, unspent amount. This amount spent was calculated by fitting the expenditure curve to the period between the start of engineering and projected end of construction. The proportion assumed to have been spent prior to the estimate date was subtracted from the estimate total and inflated appropriately to date-of-estimate equivalent dollars. This amount was added to the deescalated portion not spent and adjusted forward into 1980 dollars.

Additional detail about the adjustment procedure is available from the authors.

Appendix B

ADJUSTING COST ESTIMATES FOR CHANGES IN PLANT SCOPE

In nine of the capital cost estimates, plant scope differed from other estimates for the same plant and from the scope actually constructed. Scope changes are discretionary alterations in design capacity or product slate. We do not include, in that definition, scope changes that are design modifications or changes in plant design found necessary to make a plant operable. Scope changes defined in that manner are external influences on misestimation and require that estimated costs be adjusted to reflect the plant's actual scope.

When adjustments in cost estimates were required for plants in the data base, the costs were always changed *from* the value representing an originally specified plant scope *to* a value reflecting the actual design production capacity. The decision rule for adjusting each estimate, as well as the actual mathematical expression used, followed from the nature of the plant's overall design. The following ratio adjustment formula was employed to account for scope changes:

$$\begin{array}{l}\text{SCOPE-}\\ \text{ADJUSTED} \\ \text{ESTIMATE} \\ \quad(\$)\end{array} = [\text{FINAL SCOPE/ORIGINAL SCOPE}]^{k}[\text{ORIGINAL ESTIMATES}(\$)],$$

where the FINAL SCOPE represents the design production capacity actually built and the ORIGINAL SCOPE represents the scope for which the original unadjusted estimate applies.

The value of the exponent (k) was chosen to reflect the actual manner in which the scope change occurred between a particular estimate and the final production capacity. The "rule of six-tenths" was employed for the scope-adjustment calculation when the changes in production capacity came about through a scale-up (or scale-down) of a *single train plant.* This rule of thumb follows from empirical derivations performed for the chemical and other industries. The value of 0.6 for the exponent k represents a mean value for a distribution that ranges from 0.33 to 1.39, depending upon the type of plant and upon the fact that factors other than size clearly affect total project costs.[1] In those cases where the attained scope changes came about through the addition of parallel trains to increase production output, the validity of the "rule of six-tenths" is clearly less appropriate—partly because of the direct loss of the scale economies presumed for plants operating under a single train.[2] In this latter instance, the value of k in the expression above becomes 0.90, reflecting the significantly lower scale economies of multiple-train process plants.

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[1] See, for example, L. F. Williams, "Capital Cost Estimating From the Viewpoint of Process Plant Contractor," *AACE Bulletin,* Part I, December 1972, and O. T. Zimmerman, "Capital Investment Cost Estimation," in F. C. Jelen (ed.), *Cost and Optimization Engineering,* McGraw-Hill, New York, 1970.

[2] For discussion of limitations and difficulties in applying the "rule of six-tenths" and other ratio methods, see Ralph Landau, *The Chemical Plant,* Reinhold, New York, 1966; L. F. Williams, "Capital Cost Estimating From the Viewpoint of Process Plant Contractor," *AACE Bulletin,* Part II, February 1973; Zimmerman, op. cit., p. 311; and D. E. Chaulkey, "Is Bigger Really Better," paper presented at the 1975 meeting of ICI.

Appendix C

STATISTICAL DIAGNOSTICS

We expect that most readers of this report will find the statistical characterization of the regression models presented in Secs. IV and V sufficiently comprehensive. This appendix is provided to help more technical audiences evaluate the statistical integrity (or robustness) of the models. We briefly describe here the results of our tests in three illustrative areas: (1) violations of ordinary least squares (OLS) assumptions; (2) collinearity among the independent variables; and (3) the contribution of each observation to the parameter estimates.

REGRESSION ASSUMPTIONS

No violations of the underlying assumptions required by OLS regression (such as homoscedastic error variance) were detected in either the cost-growth or performance models. In addition, no variables not included in the models are significantly correlated with the independent variables used in the models, except as noted in the text; nor are any variables significantly correlated with the error terms from the models.

MULTICOLLINEARITY

The independent variables (and their parameter estimates) are not sufficiently correlated with each other to pose significant multicollinearity problems. For each model, the condition index values and the variance component breakdowns for the independent variables are presented in Table C.1.[1]

INFLUENTIAL OBSERVATION DETECTION

It is widely recognized that summary regression statistics (such as R^2 or MSE) are not the most appropriate criteria to employ in selecting

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[1] See David A. Besley, E. Kuh, and R. E. Welsch, *Regression Diagnostics: Identifying Influential Data and Sources of Collinearity*, John Wiley & Sons, New York, 1980.

Table C.1
MULTICOLLINEARITY DIAGNOSTICS

A. COST-GROWTH MODEL

		Variance Proportion						
							Project Definition	
Eigen Value	Condition Index[a]	Intercept	PCTNEW	IMPURITIES	COMPLEXITY	INCLUDE	All Ests.	If PDS ≤2
5.00	1	.00	.01	.01	.01	.01	.00	.00
.826	2.56	.00	.00	.00	.01	.09	.00	.33
.385	3.61	.00	.23	.37	.02	.24	.01	.06
.346	3.81	.01	.49	.11	.04	.23	.02	.03
.282	4.21	.01	.19	.43	.08	.39	.00	.05
.116	6.56	.06	.00	.06	.72	.00	.24	.12
.040	11.18	.92	.08	.00	.13	.03	.72	.40

B. PERFORMANCE MODEL

		Variance Proportion				
Eigen Value	Condition Index[a]	Intercept	NEWSTEPS	BALEQS	WASTE	SOLID
3.37	1	.01	.02	.01	.02	.02
.76	2.11	.00	.00	.09	.00	.38
.46	2.71	.00	.43	.09	.06	.20
.36	3.07	.00	.34	.01	.61	.03
.05	8.14	.99	.21	.79	.30	.36

[a] Values ≳ 30 indicate a problem when two or more variance proportions ≳ 0.5 in same row.

the "best" subset of available independent variables to include in a fully specified model. Such criteria can present a distorted picture, especially if relied on exclusively. Determining the contribution of each data point to the estimated parameter vector is particularly important when relying on relatively small numbers of observations. Examination of residual plots, studentized residuals, and the variances of the predicted and residual values can help isolate peculiar cases worthy of a closer look, if not deletion.[2]

Cook's distance statistic is one recognized measure that combines information from several of these dimensions.[3] It is defined as:

$$D_i = t_i^2 V(\hat{y}_i)/pV(e_i),$$

where t_i = studentized residual for case i,
p = number of parameters estimated,
$V(\hat{y}_i)$ = variance of predicted value for case i,
$V(e_i)$ = variance of residual value for case i.

The form of this diagnostic ensures that it will be sensitive to changes in the fitted model if the ith observation is deleted. In conjunction with the appropriate F-distribution, it reveals the position of each case within the confidence ellipsoids for the vector of parameter estimates.

Only in one instance did the Cook's distance statistic ($D = .299$) suggest the presence of an influential observation; even in this instance (in the performance model), its statistical significance was marginal. In contrast, the highest Cook's statistic in the cost-growth model was .099, well within reasonable range of the confidence ellipsoid. Additional diagnostic measures were also employed but none pointed clearly to significantly influential observations.

On the other hand, early iterations of the cost-growth model building process revealed several potentially peculiar cases, based in part upon the magnitude of their residuals or other diagnostic statistics; these cases were subjected to closer scrutiny. In a few instances, cost estimates had to be removed subsequently from the cost-growth analysis because of previously unrecognized, and uncorrectable, data-quality problems. A total of 18 estimates were thus excluded, typically for one or more of the following reasons:

- Actual capital cost data were incomplete;

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[2] Ibid.; and see S. Chatterjee and B. Price, *Regression Analysis by Example*, John Wiley & Sons, New York, 1977.

[3] See R. Dennis Cook, "Detection of Influential Observation in Linear Regression," *Technometrics*, Vol. 19, No. 1, February 1977.

- Constant-dollar adjustment data were incomplete or inconsistent;
- Management had ordered the estimate "reduced," without benefit of additional process understanding or project definition, and without changing plant scope;
- A&E "bid estimates" were provided that applied only to one portion of the projected plant.

(The first two categories account for nearly all of the exclusions.)

In each case, the deletions were made only after a thorough review of all available correspondence, trip reports, and worksheet marginalia failed to uncover information sufficient to correct the deficiencies. Observations were removed from the analysis not because they were "outliers" in any sense, but because uncorrectable distortions in the quality of their data rendered them unsuitable for the analysis. Although some of the diagnostic techniques highlighted some of these cases (as well as others), they were not dropped simply because they exceeded some statistical threshold as influential or outlying.

RAND/R-2569-DOE