# A Review of Cost Estimation in New Technologies

## Implications for Energy Process Plants

Edward W. Merrow, Stephen W. Chapel, and
Christopher Worthing

Rand

The work upon which this publication is based was performed pursuant to Contract No. DE-AC01-PE70078 with the U.S. Department of Energy.

**Library of Congress Cataloging in Publication Data**

Merrow, Edward W
A review of cost estimation in new technologies.

([Report] - Rand Corporation ; R-2481-DOE)
Bibliography: p.
1. Costs, Industrial. 2. Energy consumption--Costs.
3. Engineering--Estimates and costs. I. Chapel,
Stephen W., 1942- joint author. II. Worthing,
Christopher, joint author. III. United
States. Dept. of Energy. IV. Title. V. Series:
Rand Corporation. Rand report ; R-2481-DOE.
AS36.R3 R-2481 [HD47] 081s [658.1'552] 79-16558
ISBN 0-8330-0144-2

Published by The Rand Corporation

R-2481-DOE

# A Review of Cost Estimation in New Technologies

## Implications for Energy Process Plants

Edward W. Merrow, Stephen W. Chapel, and
Christopher Worthing

July 1979

Prepared for the U.S. Department of Energy

Rand
SANTA MONICA, CA. 90406

# PREFACE

Rapidly increasing estimates of capital costs and expressions of concern about ultimate plant performance have delayed the introduction of a commercial synthetic fuels industry in the United States. This report is the first product of Rand's Pioneer Plants Study, which seeks a better understanding of the reasons behind inaccurate cost estimation of first-of-a-kind energy process plants; of the extent to which the same factors can be expected in future process plant technologies; and of the strategies that might be adopted by the U.S. Department of Energy and by industry to cope with cost and performance uncertainty. The review of cost estimating experience in the areas included here helped in developing the basic framework for a detailed empirical examination of the causes of cost estimation error and performance problems in pioneer process plants.

Forthcoming Rand reports on the Pioneer Plants Study include:

- *Pioneer Plants Study: Executive Summary* (R-2568-DOE)
- *Pioneer Plants Study: Analysis of Cost and Performance* (R-2569-DOE)
- *Pioneer Plants Study: Scaling Technological Advance in Process Plants* (R-2570-DOE)
- *Pioneer Plants Study: Application to Synthetic Fuels Plant Cost and Performance* (R-2571-DOE)

This study was conducted as part of Rand's program of policy research and analysis for the Department of Energy. Funds for the study were provided under Contract DE-AC01 79PE70078 by the Offices of the Assistant Secretary for Policy and Evaluation, the Assistant Secretary for Nuclear Energy, and the Assistant Secretary for Resource Applications.

# SUMMARY

Estimates of capital costs of pioneer energy process plants have been poor predictors of actual capital costs. Pre-design and early design estimates (even in constant dollars) have routinely understated definitive design estimates or ultimate costs by more than 100 percent for oil shale, coal gasification and liquefaction, tar sands, solid waste, and nuclear fuel reprocessing plants. This phenomenon of "cost growth" creates significant planning and management problems for both industry and the Department of Energy. For industry, cost growth has led to canceled plans, wasted costly design efforts, and in some cases significant losses when premature capital commitments have been made. For government energy officials, cost growth has made R&D allocation decisions difficult, has increased the uncertainty in supply planning, and has hampered commercialization planning efforts.

This report reviews literature on cost estimation in several areas involving major capital expenditure programs: energy process plants, major weapons systems acquisition, public works and large construction projects, and cost estimating techniques and problems for chemical process plants. Specifically, the study of which this review is a part addresses the following questions:

- What has been industry's estimating and performance experience with first-of-a-kind plants?
- What factors have been associated with different levels of cost growth and performance shortfall?
- What are the implications of industry's experience for the ways in which the Department of Energy plans and manages the development and commercialization of new energy process plant technologies?

One of the goals of this review was to aid in the development of a conceptual framework for the study. That framework will be incorporated into subsequent reports.

Weapons systems acquisition studies suggest the basic feasibility of the approach to cost estimation problems taken by this study: Statistical analysis of historical experience can shed light on factors associated with cost and performance estimation error. Analyses of cost growth in weapons systems have generally found that scope changes, the amount of technological advance sought, and the length of the development program are consistently related to the degree of estimation error.

Equally important, the weapons systems analyses demonstrate that meaningful scales of technical characteristics of systems can be developed. Despite important technical, economic, and institutional differences between weapons development and pioneer process plants, the weapons systems studies constitute an important methodological heritage upon which we draw.

Cost growth is not unique to energy process plants or weapons systems; water projects, other public works, and some large private construction efforts have cost considerably more than originally estimated. Over time, considerable improvement has been made in reducing the low bias in water project estimates, but the problem of variance ("spread") in the estimates has been more intractable. Scope changes, project management performance, changes in the economic and institutional environment, and project uncertainties are the most frequently cited causes of cost growth in public works and other large construction projects.

There is a substantial literature discussing the techniques and problems of cost estimation for industrial process plants. Factors associated with cost estimation error in process plants can be grouped into four areas: (1) plant and process uncertainty, (2) estimation methodology, (3) project organization, and (4) exogenous effects on cost. Scope and design changes and introducing new technology are the most frequently mentioned sources of estimation problems under the first category. The inherent limitations of ratio estimating methods are especially acute for pioneer plants. Of increasing concern in recent years has been the effect of changing environmental, health, and safety regulations on estimation accuracy and plant performance. Despite the fact that many possible causes of capital cost estimation error have been cited in the literature, the evidence remains almost entirely anecdotal. For the process industry as a whole, it is not known how frequently significant misestimation occurs, how much estimates improve as a plant moves through project definition and design, how much poorer estimation is for pioneer plants than more standard plants, the relative importance of the factors that have been cited as sources of error, or how well pioneer process plants have performed. Without such information, it is difficult for DOE to assess the uncertainty in estimates for pioneer energy process plant costs and performance or for firms to benefit from a broader range of experiences than their own.

The most obvious conclusion of this review is that cost estimation for new technologies is a difficult and uncertain task. Furthermore, the level of uncertainty for energy process plants is *not* simply a function of the development stage of the technology. The stages of design and engineering for the first commercial plant appears to play an important role in estimating accuracy.

Three approaches for DOE in dealing with uncertainty in cost estimates derive from this review and our discussions with industry firms:

- *Downplay the importance of cost estimates in decisionmaking for R,D&D when uncertainty is very high.* Depend more heavily upon other factors such as theoretical energy conversion efficiencies, the resource base employed, etc., until better quality information can be obtained.
- *Attempt to limit the scope for optimism in cost estimates.* This might be done by establishing cost estimation quality criteria and obtaining independent evaluations of estimates. The usefulness of this approach is very limited when technical uncertainty is high.
- *Make adjustments to help debias early estimates and, if possible, place some realistic confidence intervals around the estimates even if such intervals are fairly wide.* Making this option viable requires empirical investigation of the relative importance of the factors that contribute to cost estimation error for new process plant technologies. The requisite data collection and analysis is the task of the study of which this report is the first publicly available product.

# ACKNOWLEDGMENTS

The authors owe a considerable debt to a number of Rand colleagues who carefully read and critiqued this report in various stages. Special thanks are due W. Baer, T. Glennan, Jr., and G. Fisher. We also wish to acknowledge the invaluable aid of other members of the study team: R. Horvath, J. R. Nelson, and K. Phillips. Technical review of the report was performed by D. Novick and J. Schank. The manuscript was edited by W. Harriss, and L. Haigazian typed and prepared the report for publication.

We also wish to thank the scores of people at engineering, oil, and chemical companies who have spent valuable time answering our many questions. Without their assistance the study would not be possible.

# CONTENTS

# FIGURES

# TABLES

# I. INTRODUCTION

This report discusses the initial phase of a study that examines the problems of estimating capital costs and performance of pioneer ("first-of-a-kind") energy process plants.[1] Figure 1.1 illustrates the capital cost estimation problems for 10 energy process plants. Capital cost estimate sequences are presented starting with the initial estimate prepared just prior to beginning definitive plant design, and are carried as far forward in the design and construction process as data availability allows. Cost growth—increases as subsequent estimates are made—is shown to be pervasive for these plants, even after the effects of dollar inflation are removed.[2] Also significant is the wide variation in the degree of cost growth that has occurred between estimate types. Interestimate increases for these plants are summarized in Table 1.1. As is evident from the table, average increases for succeeding estimates were very substantial. The average increase measured on a time basis was over 30 percent per year compounded in constant dollars.[3]

Early estimates and even estimates made well into the definitive design have proven to be poor predictors of pioneer energy process plant cost or performance. Construction plans for 5 of the 10 plants have been canceled, seriously delayed, or suspended indefinitely. Of the four plants that were actually constructed, one failed completely to operate, one cannot be operated for want of regulatory approval, one has not achieved either sustained operation or more than 50 percent of design capacity three years after the end of construction, and one is now experiencing some difficulty in start-up. The design of the remaining plant was still on schedule as of this writing, but one of the partners recently withdrew its 50 percent share, citing increased capital cost estimates.

---

[1] An energy process plant is any plant producing fuel by means of chemical processing. Included under this rubric would be oil shale, coal gasification and liquefaction, and solid waste-to-fuel plants, some biomass technologies, and plants to separate fissile materials from nuclear reactor spent fuel. A plant is considered a pioneer if it introduces at commercial scale a new product or new process, or if a large scale-up from prior commercial sizes is involved. Plants can obviously vary in the extent to which they pioneer new technologies.

[2] "Cost growth" as used in this report is formally defined as the ratio of actual total capital costs to the initial estimate costs. The definitions of the estimate tvpes are given and discussed in detail in Sec. IV. Capitol costs have generally risen faster than dollar inflation for process plants over the past 10 years. If the cost estimates for the 10 energy plants are adjusted using the Du Pont Index, however, the results are not significantly different. See Appendix, pp. 98ff.

[3] See the appendix to this report for details on the plants surveyed, selection criteria, and additional analysis of the increases.

The phenomenon of cost growth creates significant planning and management problems for both industry and the Department of Energy. For industry, cost growth has led to canceled plans, wasted costly design effort, and, in some cases, significant losses of capital investment. For government energy officials, cost growth has made R&D allocation decisions difficult, has increased the uncertainty in supply planning, has hampered commercialization planning efforts, and has caused some amount of embarrassment in relations with Congress.

The present study was initiated with these problems in mind. By examining the chemical and oil industries' experience with pioneer process plants, the study seeks to develop a better basic understanding of the uncertainty surrounding capital cost estimates and performance forecasts for future energy process plants. Specifically, the study addresses the following questions:

- What is industry's estimating and performance experience with first-of-a-kind plants?
- What factors, including characteristics of the plant, the management development strategy, and the economic institutional context in which a plant is developed and built, have been associated with different levels of cost growth and performance shortfalls?
- What are implications of industry's experience for the ways in which the Department of Energy plans and manages the development and commercialization of new energy process plant technologies, and what are the implications for the Department of Energy's role relative to the private sector?

As a first step in the study, this report reviews what is known about estimation accuracy and performance results in several areas that might provide insights into cost and performance estimation problems in energy process plants. The area in which the most extensive and systematic empirical analyses have been undertaken is for major weapons systems acquired by the Department of Defense. Section II reviews that literature including the considerable methodological work that has been done. Despite significant differences, the techniques proven successful in the analyses of weapons systems are a useful methodological heritage for the examination of pioneer process plants.

Section III reviews analyses of cost estimation error in major public works (especially water projects) and large private construction projects. Some data and analyses are available, particularly in the water projects area. Although the public works projects are dissimilar from process plants, both often involve very large-scale construction efforts. The literature was initially searched to see if any consistent relationship between large size and cost growth had been found.

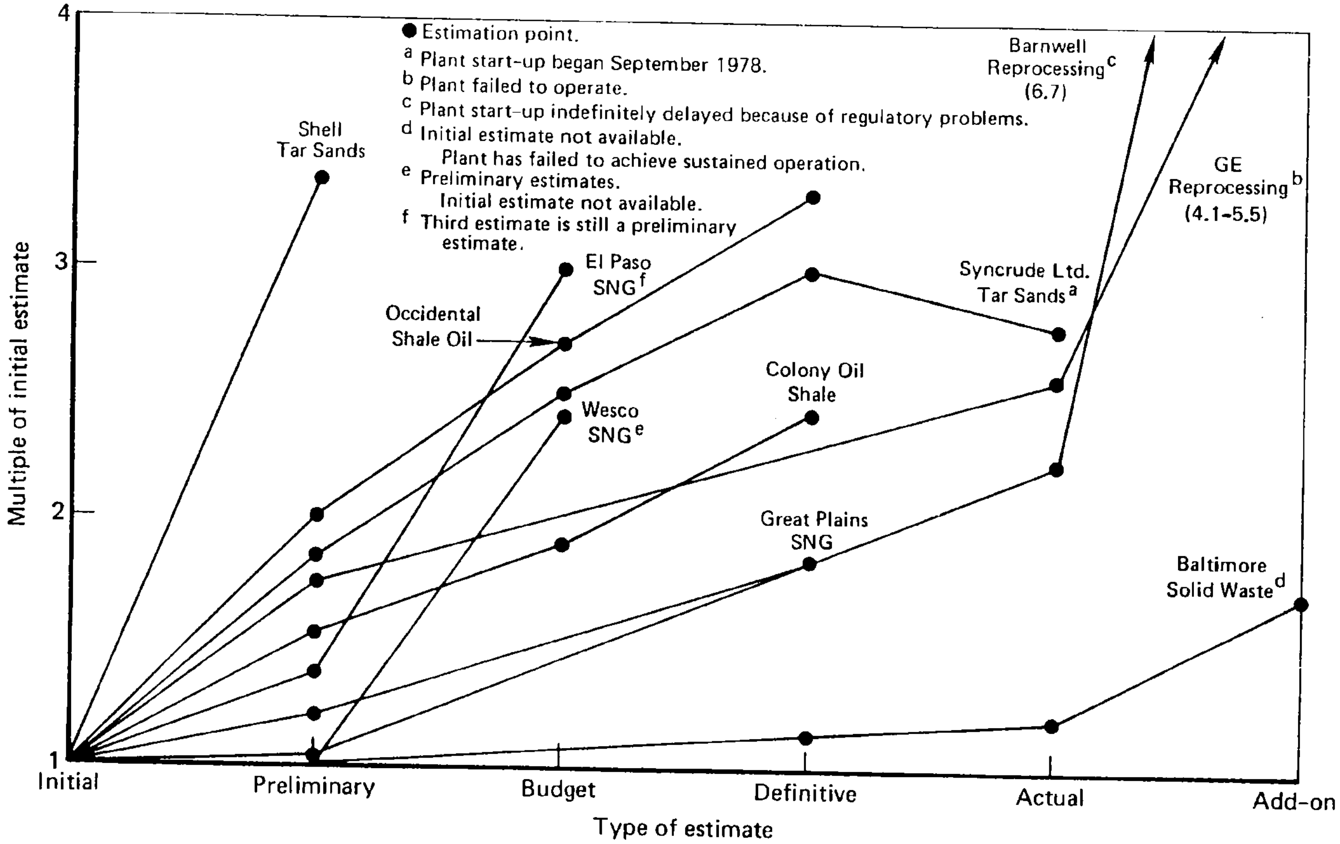

Fig. 1.1—Cost growth in pioneer energy process plants (constant dollars)

Table 1.1

COST ESTIMATE INCREASES FOR 10 ENERGY PROCESS PLANTS[a]
(1978 dollars)

| Estimate Category | Average Increase from Last Previous Estimate | Average Increase from First Available Estimate |
|---|---|---|
| Initial | -- | -- |
| Preliminary | 78% (N=7) | 84% |
| Budget | 31% (N=5) | 114% |
| Definitive | 37% (N=6) | 134% |
| Actual | 21%[b] (N=4) | 141%[b] |

[a] See Appendix for details.

[b] This understates cost growth because in three of the four cases additional capital expenditures would be necessary to make the plants fully operational.

Section IV reviews the published work on process plant cost estimation and incorporates the results of our discussions with industry cost estimators to date. Although there is a substantial literature discussing cost estimation problems for process plants, almost none of it builds upon a broad empirical base. The literature and our discussions do, however, suggest a number of possible causal factors that need to be considered in developing a model of cost growth in pioneer plants.

The final section discusses some of the problems that appear to be common to all efforts to estimate the capital costs of new major systems. The implications of the cost estimation experience in weapons systems, public works construction, and process plants for the Department of Energy's planning decisions conclude the section.

# II. COST ESTIMATES IN WEAPONS SYSTEMS ACQUISITION

Analysis of the costs of developing weapons systems has a number of lessons for those concerned with public policy choices that would in some way subsidize the development of new energy supplies. The development of both new weapons and new energy supplies is based upon the conception, development, and production of technically advanced systems, characterized by extraordinary amounts of technical uncertainty. But both are also characterized by nontechnical (external) uncertainty. In the case of weapons it comes from the variables discussed below—changes in externally generated technology, strategic requirements, and government policy. For energy development the external sources of uncertainties are similar with the addition that energy must be sold in private markets and is subject to all of the associated questions about future prices.

The principal characteristic that differentiates the military development experiences from those that are likely to occur in the energy development area concerns the question of differences in the market institutions. In weapons development the government pays for and buys the product emerging from the development. There is a sole buyer (the government) and once a contract is signed there is a vested interest on the part of both buyer and seller to complete the development of the product. In the case of energy, the government may subsidize development but does not buy the product. And with numerous potential buyers, the product must enter more conventional markets. The government can intervene in a couple of ways—it can directly subsidize the development of new energy sources in much the same manner as it purchases weapons, or it can indirectly subsidize the sources by subsidizing the price at which energy is sold to consumers (either by paying the difference between market prices and production costs or by allowing the higher prices to be averaged into the price of fuels, such as natural gas and electricity, where the prices are under governmental control).

Under this framework of uncertainty, institutional markets and possible government intervention, one must ask what can be expected about the nature of cost information that flows from the desire of private companies to develop new sources of energy. The purpose of this section is to review work on the costs of acquiring new weapons systems, emphasizing those pieces which are relevant to the issue of the nature of cost estimates, given the uncertainties and the market institutions that characterize the development process.

There are three sections. The first is a brief discussion of the development process and a framework that allows a systematic discussion of the cost estimating literature. Second, empirical analyses that attempt to quantify the effects of various factors on cost estimates are reviewed; and third, the relevance and lessons that the weapons cost estimating literature have for federal energy development policy are summarized.

## THE CONCEPTUAL NATURE OF WEAPONS DEVELOPMENT AND ACQUISITION

Development of weapons is basically an investment where the intended result is to provide a system with greater performance per unit cost and where the costs include development and production elements. Usefulness or value is determined by actual performance, the requirements for performance (taken from defense strategies and the capabilities of adversaries), and by costs. Obviously, decisions to undertake specific development projects depend critically upon the estimates of development and production costs and to the extent that cost estimates for planning are wrong, the decisions to undertake specific projects are questionable. Further, once a decision is made to undertake specific development projects, cost estimates play an important role in selecting contractors and monitoring contractor performance. Being able to identify overly optimistic cost estimates and to provide incentives to control costs during development and production are important elements of the government contracting process. Both depend heavily upon the quality of cost information.

In the remainder of this subsection we briefly discuss uncertainty and the institutional aspects of weapons development from a conceptual point of view, and we sharpen the discussion of the causes of cost growth.

### Uncertainty

In describing the factors behind the degree that the outcomes associated with weapons programs are unpredictable, Merton Peck and Frederic Scherer categorize uncertainties as internal and external. Internal (or technological) uncertainties relate to the possible incidence of unforeseen technical difficulties in the development of a specific weapon system while external uncertainties exist because of factors external to the individual project but affect the course and outcome of the project. External uncertainties originate in the pace of technological change in weaponry, changes in strategic requirements, and shifts in government policy.[1]

**Internal Uncertainty.** Peck and Scherer devote a lengthy discussion to the general character of solving technical weaponry problems and identify four development stages: (I) basic science, (II) applied research, (III) advanced engineering and development, and (IV) product engineering. They argue that basic and applied research are concerned with the notion of invention, i.e., the discovery of basic new knowledge about nature as the means of exploiting nature, and that an essential quality of invention is great unpredictability. (Inventive activities tend to have two-valued outcomes—either the problem is solved or it is not.) However, once inventions arise they are available to be utilized through primarily engineering activities, Steps III and IV, and uncertainty centers not on whether a problem can be solved but whether the cost, time of completion, and utility of the activities' outcome will be such as to make the efforts worthwhile (the two-valued outcome is replaced by a range of possibilities). In the engineering phases the relation between the quantity of resources allocated to the activity (the effort) and the nature of the outcome is less uncertain.[2]

Based upon a review of the history of the development of radar, Peck and Scherer conclude that: (1) there is a complex and unpredictable series of Steps I and II advances *underlying* the initiation of a weapons program and a program is not usually begun until enough progress in I and II has been made to establish that it is within the state of the art; and (2) the work in a weapons development is largely of a Step III (advanced engineering) nature but there may remain a few critical problems that require aid from Steps I and II advances for their resolution. However, they also argue that the technical problems associated with weapons system development are increasing and that two changes characterize post-Korean weapons development programs from earlier efforts. First, Steps I and II activities play a larger role but the bulk of the effort remains in Step III. Second, the effort at Steps III and IV has become more demanding. These conclusions are based on an examination of 12 weapons systems, of which the Atlas ICBM was one of the most extreme in terms of state-of-the-art advances.[3] [These comments were made during the early 1960s. A comparative analysis of the 1950s with the 1960s resulted in the conclusion that lower levels of techincal advance were sought in the 1960s.][4]

---

[1] Merton S. Peck and Frederic M. Scherer, *The Weapons Acquisition Process: An Economic Analysis,* Division of Research, Graduate School of Business Administration, Harvard University, Boston, 1962.

[2] Ibid., pp. 27-30.

[3] Ibid., pp. 36-39.

[4] Alvin J. Harman and Susan Henrichsen, *A Methodology for Cost Factor Comparison*

**External Uncertainty.** Weapons development programs do not occur in a vacuum. As they proceed, the external environment in terms of technology, enemy plans, and our own defense policies can change suddenly and unpredictably, possibly causing reorientation of the program or redesign of the weapons system. Such shifts in program plans could lead to substantial increases in development time and costs, and thus Peck and Scherer conclude that external as well as internal uncertainties may explain variances of actual program output from original predictions.

## Institutional Aspects of the Weapons Development Process

The performance of the weapons development process depends upon the institutional nature of the process. Peck and Scherer briefly touched on the subject and Scherer treats it in detail in his later work.[5] This subsection suggests the types of incentives and forces that are inherent to the process by discussing three basic attributes of weapons development. More precise quantification of the effects of these attributes requires empirical analyses, which are reviewed in the next subsection.

First, weapons development has many noncompetitive features. Peck and Scherer point out that (1) the buyer generally decides if a new weapons system is needed and directly finances most development (the seller does not offer a finished product which the buyer can accept or reject); (2) the price of the weapons system is not determined by market competition; instead it is largely determined by reimbursement of costs actually incurred plus a fee bargained for in advance. (A weapons system's price does not correspond to the price from a competitive market given that (1) the government is generally the only buyer and thus has the power of a monopsonist, and (2) most weapons systems are unique enough so that the seller, selected by the government, has some of the bargaining power of a monopolist.)[6]

A second aspect of weapons development which has important implications for incentives is the presence of significant amounts of both technical and external uncertainty—the potential for unforeseen problems, for changes in the scope of projects, and so on. In the presence of these risks one would expect that sellers either require the potential for

---

*and Predicton,* The Rand Corporation, RM-6269-ARPA, August 1970.

[5] Frederic M. Scherer, *The Weapons Acquisition Process: Economic Incentives,* Division of Research, Graduate School of Business Administration, Harvard University, Boston, 1964.

[6] Peck and Scherer, op. cit., pp. 55-60.

extraordinary rates of return or guarantees of a fixed return that reduce the risks associated with the unforeseen problems. Based on case studies, Scherer finds that cost reimbursement contracts have traditionally been preferred by contractors and that contractors generally are willing to trade their profit expectations for assured coverage of costs when substantial cost uncertainties are present.[7]

The final aspect of the weapons development market which has implications for incentives is the fact that once contracts are signed, maintaining development schedules and performance tends to receive much more emphasis than maintaining original costs. From his case studies Scherer concludes that quality maximization and lead-time minimization are consistently emphasized over cost reduction and he cites several reasons for this. First, contractors associate high penalties with quality and time sacrifices in terms of reduced follow-on development and production sales; second, contractor executives tend to overestimate follow-on production prospects (and thus the penalties associated with time and quality sacrifices); and third, contractors tend to emphasize organizational survival and growth for its own sake.[8] (It is important to realize that because there are no markets that establish the value of specific weapons development, the level of success of a development project is generally uncertain. Thus, it is not surprising that many proxy indicators of output—performance, reliability, development time, etc.—are emphasized.)

Given these institutional characteristics, the weapons cost literature touches on several reasons why cost estimates tend to be poor indicators of actual costs. Specifically, the literature attempts to quantify the effects that the following variables have on cost growth:

1. The degree of technological uncertainty
2. The length of development programs
3. The scope changes that occur
4. The amount of inflation during development

In addition, the literature touches on a couple of questions concerning the incentives and behavior that development contractors have:

1. Do they buy in on contracts by providing understatements of their best estimates of costs?
2. Have contract incentives been successful in controlling cost growth during development projects?

The next subsection reviews the literature looking for answers to these questions.

---

[7] Scherer, op. cit., p. 151.
[8] Ibid., pp. 154-162.

## REVIEW OF WEAPONS DEVELOPMENT ANALYSES

This subsection discusses two topics. First, we review the literature on the relationship of cost uncertainties to characteristics of the development—the amount of technological advance sought, the length of the development period, the amount of inflation that occurred, and the amount of scope changes that were made during the development. Second, we examine the studies that analyze the relationship between institutional contract arrangements and cost estimates.

### Cost Estimates and the Characteristics of the Development

The tradeoffs between costs, performance, and development schedules have been widely discussed in weapons development and acquisition debates, and it is generally accepted that greater performance implies greater costs and longer development times. These tradeoffs have implications for the nature of cost estimates. Development programs that call for large increases in performance have large amounts of technical uncertainty associated with them and if the uncertainty is underestimated, cost estimates for such programs are likely to be biased downward. The literature on the cost-performance-schedule tradeoffs attempts to quantify this bias and to identify factors other than technological advance that affect it.

The main lessons that can be learned from the experience are contained in four studies: Marshall and Meckling's early work, Robert Summers' report, Harman and Henrichsen's cost factor analysis, and Nelson and Timson's work on the relationship between technological advance and acquisition costs.[9]

The first two studies base their analysis on a sample of 22 "major" items of military equipment and compare the ratio of the latest available estimate of the cost of production to the earliest estimate available (called the cost factor). The ratios are adjusted for changes in price levels and for disparities between actual and contemplated output (quantities) at the time the early estimates were made.

Marshall and Meckling attempt to identify factors affecting cost ratios. However, they do not develop a regression model that describes the relationship between cost ratios and performance schedule. For the

---

[9] A. W. Marshall and W. H. Meckling, *Predictability of the Costs, Time, and Success of Development,* The Rand Corporation, P-1821, December 1959; Robert Summers, *Cost Estimates as Predictors of Actual Weapons Costs: A Study of Major Hardware Articles,* The Rand Corporation, RM-3061-PR, March 1965; Harman and Henrichens, op. cit.; J. R. Nelson and F. S. Timson, *Relating Technology to Acquisition Costs: Aircraft Turbine Engines,* The Rand Corporation, R-1286-PR, March 1974.

sample of 22 weapons systems they find that cost increases of 200 to 300 percent and development extensions of 1/3 to 1/2 are common, and state that the variability in the size of errors observed in individual cases comes from the differences in technological advance sought in different systems. (Measures of technological advance were based on the subjective evaluation by experts at Rand.) The errors tended to be larger for systems incorporating many new ideas and major improvements in performance.[10]

Summers develops a statistical relationship that explains cost ratios given measures of performance and schedule. Concerning the sample of 22 development projects, he states:

> The grosser differences between estimated and actual costs disappear when the estimated costs are adjusted (1) to refer to the actual quantities of item procured, and (2) to take account of the secular changes in the level of prices. But even these "adjusted" estimates exhibit great variability; in the sample studied they range from 15 percent to about 150 percent of actual costs. They are also systematically biased, about four-fifths of the adjusted estimates being below actual costs.[11]

Summers finds that early cost estimates for major hardware systems where the technological development is difficult and the program is long are likely to be low by a factor of two to three.[12] His estimates are based on using multiple regression to explain the ratio of actual to estimated costs:

$$F = \{11.929\}\,\{\mathrm{EXP}[.097t - .032tA - .311A + .015A^2 + .088L - .075(T - 1940)]\}v,$$

where F = ratio of actual cost to adjusted estimate

t = timing of the estimate within the development program as a fraction of program length

A = degree of technological advance required in the program (a numerical scale of 1 to 20 based on the judgment of experts at Rand)

L = actual length of the development period in months

T = calendar year

v = residual

The equation indicates that the ratio of actual cost to adjusted estimate is not far from unity for major hardware estimates (even when the estimates are made early in the development programs) when only minor technological advances are sought and the development time is

---

[10] Ibid.

[11] Summers, op. cit., p. v.

[12] Ibid.

short. But when there are major technological advances and the development time is long, the ratio is significantly different from unity.[13]

Besides the technological advance variable, Summers includes t as an indicator of the time within a development program that an estimate is made. (The later in a program that a cost estimate is made, the more likely the estimate will reflect the effects of such factors as technological problems and scope changes.) He also includes the length of the development, L, and the calendar year that the estimate was made, T, in his equation. The length of the development is included based on the belief that longer programs allow more time for the imposition of additional requirements (scope changes) which are relatively minor but which tend to increase costs. The calendar year is included because he believes that estimating methodology improved during the period that his data cover, 1947 to 1957. "Certainly toward the end of this period cost analysts generally received more complete and earlier basic data . . . As the techniques available to the cost analyst advanced beyond the use of the learning curve, their results should have improved."[14]

Summers points out that in general not adjusting cost estimates for bias will lead to a tendency for decisionmakers to choose higher technology systems excessively, and he correctly concludes that multiplying by a debiasing factor (derived from the regression analysis) will not make the estimates accurate; there is still the problem of variability (uncertainty). To assess the importance of removing bias and describing uncertainty, he examines three actual studies to determine if their conclusions would have to be changed. In one of the three studies the results suggest that a different conclusion would have been reached. In the other two studies the differences between the alternative systems were large enough to dominate the cost uncertainties.[15]

In the late 1960s a set of data was becoming available that made it possible to include the development program experience of the 1960s with those of the 1950s. Harman's work is quite similar to that done by Summers in that he estimates a regression model that explains the size of the cost factor using program length and requirement for advanced performance (leading to a large desired technological advance). Various structures or specifications of the models are tried and all indicate that both longer programs and larger technological advances lead to higher cost factors.[16] The main differences between Harman and Summers is that Harman uses both 1950s and 1960s data in his analysis and he attempts to develop a more complicated explanation of the effects of program length.

---

[13] Ibid., p. 9.

[14] Ibid., p. 31.

[15] Ibid., pp. 59-65.

[16] Harman and Henrichsen, op. cit.

The central idea underlying Harman's empirical work is that there is a unique development strategy of program length and development effort that will lead to minimum total cost of development and production, and that deviations from the strategy in terms of either longer or shorter development periods will increase cost. Basically he is arguing that for a given level of desired performance of a weapons system, a very short development period will result in performance being met but with a more costly weapons configuration than if more time is available for optimizing the configuration. On the other hand, too long a development period allows "accumulation of inefficient contractor performance or administrative laxity in controlling costs," He indicates that the procurement strategies range from "concurrency" of development (shorter programs where *all* components are developed concurrently with integration at the last stage of development) to "sequential" development (longer programs in which the essential parts are assembled and tested earlier in the development period.[17]

There are three variables in Harman's model: costs, technological advance, and development time. The problem with this formulation is that the length of time that it takes to develop a weapons system is affected by the size and complexity of a project in addition to technological advance and development strategy; thus including development time in the equation without controlling for these factors individually provides ambiguous results. (It is not clear whether variations in the length of the development period reflect differences in development strategies, technological advances, or size and complexity of projects.)

There is one piece of work that has something to say about the development strategy, and which avoids the problems that Harman had. Glennan provides a clear argument that development times are determined by a number of factors:

> The actual development time is not only determined by the desires of the military officials for rapid or more leisurely service introduction but also by the nature of the aircraft itself. Larger aircraft would seem to take longer to develop simply because a longer time is required for reasonable size development teams to accomplish all the tasks that are associated with the larger aircraft. Development time might be positively correlated with the comlexity of the aircraft for the same reason. Consequently, it seems inappropriate to introduce raw development times as an explanatory variable of development costs.[18]

---

[17] Ibid., p. 10.

[18] T. K. Glennan, Jr., *New Product Development: Some Observations Based on the Development of Military Aircraft,* Unpublished Ph.D. Dissertation, Stanford University, 1968, p. 100.

Glennan estimates the cost of development for 12 aircraft using weight and speed as explanatory variables, and, using basically the same logic as Harman, he argues that development strategies should affect costs. He develops a measure of development strategy by first estimating the length of the development using weight as an indicator of size and complexity. He calls the estimate a measure of "normal" development time and argues that differences between it and actual development times reflect whether or not aircraft were developed more quickly or less quickly than the "normal" time. Using the differences as a measure of development strategy, he concludes that "there is a negative relationship between development costs and development time but the relationship is not very strong and is not statistically significant.[19]

We find the evidence slightly more convincing. A comparison of the costs that are not explained by the weight and speed of the aircraft (the development-cost residuals) with the development time that is not explained by weight (development-time residuals—a proxy measure of the development strategy) shows an obvious correlation between shorter development periods and higher costs (see Table 2.1).

The final study that we discuss in this subsection illustrates some of the issues associated with measuring technological advance. The technological advance variable used by Summers and Harman is a subjective index based on an evaluation by a panel of experts. There are two problems with this index. First, it is not objective in the sense that two independent observers will always come up with the same value or A factor; second, because of the technological uncertainty (unforeseen technical problems) that is inherent in the development process, by definition it is unlikely that an expert will be able to provide a good estimate, early in the planning stages, of the amount of technological advance being sought in a particular program. Thus, the subjective index is not a useful input for assessing the cost growth that might occur in a program before the program has been carried out.

Work published in 1972[20] suggested a more objective index and Nelson adopted the method for his work that was published in 1974.[21] The technique quantitatively assesses the advances in technology sought in aircraft turbine engines in terms of the expected time of arrival (TOA) of a demonstrated level of performance. The quantitative measure of an engine's technology content was first developed by Alexander and Nelson and it is based on an assessment of the date when

---

[19] Ibid., p. 102.

[20] A. J. Alexander and J. R. Nelson, *Measuring Technological Change: Aircraft Turbine Engines,* The Rand Corporation, R-1017-ARPA/PR, June 1972.

[21] Nelson and Timson, op. cit.

## Table 2.1

## Distribution of 12 Development Projects by Development Time and Cost Categories

| Development Cost Category | Development Time Category: Actual was *longer* than estimate by more than 2% | Development Time Category: Actual was *shorter* than estimate by more than 2% |
|---|---|---|
| Actual was *higher* than estimate by more than 2% | 1 | 3 |
| Estimate was within plus or minus 2% of actual | 2 | 2 |
| Actual was *lower* than estimate by more than 2% | 3 | 1 |

NOTE: The estimates were parametrically derived using weight and speed as explanatory variables.

a turbine engine with a specific set of technical parameters should pass its 150-hour Model Qualification Test (MQT). Nelson's later work refines the results and applies them to estimated engine development and procurement costs.

The Alexander-Nelson study of turbine engine technology uses multiple regression to relate the date of an engine's successful completion of its MQT to certain technical characteristics. Basically, the regression estimates are predictions of what the state of the art will be at future points in time. Calculated dates are designated TOA. And while TOA is a measure of time, it is a function of the technological characteristics of turbine engines. Figure 2.1 indicates the relationship between the calculated TOA and the actual arrival at the 150-hour MQT date. The equation used to estimate TOA is given in the figure where TEMP is inlet temperature, TOTPRS is a pressure variable, WGT is weight of the engine, SFCMIL is a measure of fuel consumption per unit thrust, and THRMAX is maximum thrust.

The usefulness of this type of information is obvious. If a process or product such as jet engines can be described in terms of variables that reflect the technological state at any point in time, if we can assume

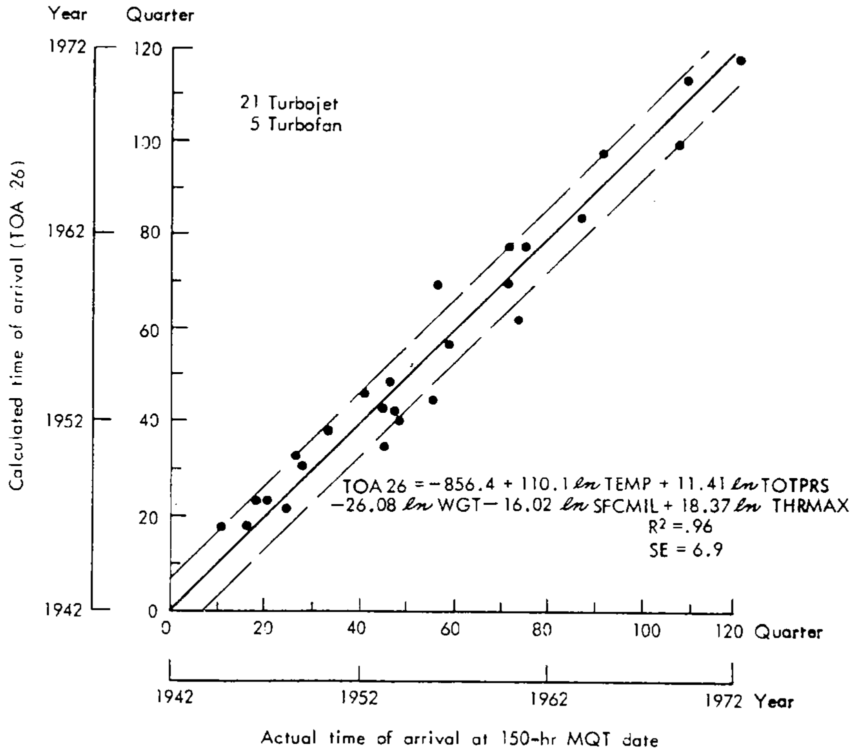

Fig. 2.1—Military turbine engine time of arrival (from J. R. Nelson and F. S. Timson, *Relating Technology to Acquisition Costs: Aircraft Turbine Engines*, The Rand Corporation, R-1288-PR, March 1974)

that the current state of the art hardware reflects the best effort of the industry, and if it is possible to predict the TOA with a level of precision statistically, then we have an objective method for measuring how close proposed programs are to the state of the art. [We do not want to downplay the importance of the conditions cited above and the reader should be aware that the validity of the TOA method depends critically upon them. The TOA approach requires close correlation between technological advance and objective indicators of performance; and it requires a fairly homogeneous set of data (such as that provided by turbine engines) for the correlation between technological advance and indicators of performance to hold.]

Nelson uses the TOA-derived estimates of "technological advance" to estimate aircraft turbine engine costs. His empirical examinations indicate that for all cases the inclusion of TOA and/or ΔTOA yields a cost-estimating relationship that is superior to the equations that use conventional variables from previous studies.

### Institutional Contracting Arrangements and Cost Estimates

Scherer argued, based on case studies, that once a contract was signed there are basic market forces that emphasize quality and development times rather than costs (the costs of quality and time sacrifices in terms of reduced follow-on sales are high and contractors tend to overestimate these costs). However, the fact that contractors do have incentives to maximize quality and minimize development time is not proof that they are inefficient or do not attempt to control costs.

The relationship between development time, the degree of technological advance sought, and costs provides some insight here. If there were no incentives to control costs during the weapons development process, then some cost growth should occur even when relatively small advances in technology are sought. However, the literature discussed in the previous section finds that there is almost no systematic bias in cost estimates until technological advances are high and all of the empirical work that we have reviewed supports this general relationship.

The recent work by Joseph Large on cost estimate bias and by Arthur Alexander on incentive contracting (App. B in R-2069-NSF) provides some evidence concerning the causes of the biased estimates.[22]

Large's work is motivated by the thesis that initial underestimates of costs can cause actual costs to be higher than necessary. He bases this hypothesis on the argument that insufficient funding imposed by low estimates can cause the occurrence of cost-increasing events such as program delays and undue economizing in engineering, tests, and quality control. He argues that ignorance of the technical pitfalls ahead and pressures of competition cause contractors to bid low. The lowest bids are accepted by the government based on the belief that the contractor with the lowest initial bid is more highly motivated to economize and find ways to reduce costs, i.e., cost growth may occur but it is assumed that final cost would have been even higher if the contractor had not been constrained by the low early estimate.[23]

---

[22] Joseph P. Large, *Bias in Initial Cost Estimates: How Estimates Can Increase the Cost of Acquiring Weapons Systems,* The Rand Corporation, R-1467-PA&E, 1974; Leland L. Johnson et al., *Alternative Institutional Arrangements for Developing and Commercializing Breeder Reactor Technology,* The Rand Corportation, R-2069-NSF, 1976.

[23] Large, op. cit., p. 1.

Large indicates that it is very difficult to test his hypothesis in a rigorous sense, and instead examines a sample of eight weapons programs where substantial cost growth has occurred to see what qualitative evidence can be found. He concludes that the evidence supports but does not prove his hypotheses.[24]

However, the main relevance of his work for our purpose is his conclusions about other causes of cost growth. For the eight weapons systems he finds that contractors were generally ignorant of how difficult it would be to develop the product. And in terms of "competitive zeal" he concludes that for five of the eight projects, contractors adjusted their estimates downward to obtain the contract. Large reports statistics for three projects where the company bids were 25 to 57 percent below the best internal estimate of costs while the final costs were over the best estimate by a factor of 2.0 to 4.0:[25]

| Internal Estimate | Company Bid | Final Cost |
|---|---|---|
| 1.0 | .75 | 2.2 |
| 1.0 | .43 | 4.0 |
| 1.0 | .45 | 2.0 |

Based on these results, he concludes that deliberate understatements of cost are a less important cause of cost growth than failure to appreciate the difficulty of the project.[25]

Arthur Alexander's research on incentive contracting provides insights about the effects of contract type on cost estimates for weapons development. In 1962 the Department of Defense revised its procurement regulation to encourage the use of incentive contracts, reflecting the fact that the CPFF contracts commonly used to acquire major weapons systems provided no positive incentives for firms to be efficient.

As a result of the policy change, there was a dramatic shift from CPFF contracts to incentive contracts of various types (CPFF contracts accounted for 37 percent of military prime contract awards in 1961 and less than 10 percent in 1965, while incentive contracts rose from 14 percent to more than 30 percent). Several studies analyzed the theory and outcomes of this shift and Alexander reviews these studies in an effort to understand whether the usual assumption that an incentive

---

[24] Ibid., p. 16.
[25] Ibid., p. 15.
[25] Ibid., p. 18.

contract does "constrain and influence" subsequent events is correct or whether the contract tends to get modified to reflect the "unfolding knowledge" derived from the ongoing project.[26]

Alexander finds consistent evidence to support the hypothesis that contracts tend to get modified (to follow rather than influence costs). Alexander notes that all contract types can be described by the algebraic relationship:

$$F = aC_t + b(C_t - C_f),$$

where $F$ = total fee to the contractor,
$C_t$ = estimated cost of the project (target cost),
$C_f$ = final or actual cost,
$a$ = target profit rate (as a percentage of target cost), and
$b$ = incentive sharing ratio.

The sharing ratio is 0 for CPFF contracts, 1 for firm fixed price (FFP) contracts, and is set between 0 and 1 for incentive contracts.[27]

For the incentive to affect company performance (to promote accurate cost estimates and to cause cost-minimizing behavior), a relationship should exist between the size of the sharing ratio and cost behavior (greater sharing ratios should be associated with smaller differences between $C_t$ and $C_f$). Alexander finds that sharing ratios have very little relationship with cost growth or overrun, but he does find that there is a strong incentive supplied by larger sharing ratios to rewrite contracts to reflect actual cost experiences. In addition, he finds evidence that R&D projects, being notably more uncertain than production projects, experience more adjustments of the contracts to reflect new cost information as it is generated. Finally, he finds that contract type is strongly related to cost growth and speculates that this is derived from an allocation of projects to contracts according to "prior expectations of uncertainty."[28]

## Summary of Principal Findings of Weapons Literature

The main findings that can be derived from the weapons cost research experience can be categorized into three areas: (1) the effects of technological advance, (2) the effects of the development program length, and (3) the effects of various incentives that are generated by institutional markets and contracting arrangements. The relevance of the first two areas for developing new energy supplies is not the quan-

---

[26] Johnson et al., op. cit., pp. 153-157.

[27] Ibid., p. 154.

[28] Ibid., pp. 159-166.

titative evidence that exists, although that is interesting. The more important contributions are (1) the approaches that are suggested for measuring concepts such as technological uncertainty and development strategy, and (2) the econometric approaches for estimating the effects that these concepts have on cost growth.

The main findings are summarized below:

1. Technological advance is an important determinant of cost growth, or more specifically, biased cost estimates, but it is not the only determinant. Perry et al., in their paper on system acquisition strategies, review the development of several major Air Force development programs and conclude that there are three main causes of cost growth. They attribute about one-third of observed cost growth and much of the deviation of system performance from that initially anticipated to technical uncertainty; approximately one-half of the cost growth is blamed on scope changes (changes in program objectives after the start of development) and the remainder is allocated to cost estimating inaccuracies.[29]
2. Weapons development work indicates that longer programs tend to have more cost growth than those with shorter development periods. This is rationalized largely on the grounds that in longer development programs there is greater chance for levying more demanding performance requirements on individual systems and thus increasing the scope of the projects.

   There have been attempts to use program length to capture the effects that program development strategies have on cost growth. Using Glennan's data, we find evidence that after the size of the project is accounted for, shortened development periods tend to be associated with greater cost growth. This is supportive of the hypothesis that concurrent development strategies tend to cause the cost of a weapons system to be higher than strategies which use a sequential approach.
3. There is some evidence concerning the effects of market institutions and contract incentives. First, defense contractors do appear to understate their estimates of costs in order to obtain contracts; but this appears to have a smaller influence on cost growth than technological uncertainty. Second, there is little evidence that incentive contracts have an appreciable effect on cost estimating bias. The specific reasons for this are not

---

[29] Robert Perry et al., *System Acquisition Strategies*, The Rand Corporation, R-733-PR/ARPA, June 1971, p. 16.

clear but the combined effects of technological and external uncertainty, deliberate understatements of costs, and lack of penalties for cost overruns (the willingness to rewrite the contracts) are the candidate causes.

## THE RELEVANCE OF WEAPONS DEVELOPMENT COST ANALYSES TO NEW ENERGY SUPPLIES DEVELOPMENT

The literature has touched on three main causes of bias and uncertainty of weapons systems development costs: (1) the uncertain nature of the development process and the tendency to be overly optimistic; (2) the tendency of sellers to understate costs to obtain contracts; and (3) the lack of incentives to control costs during the development and production of advanced systems.

The evidence is clear that the development of processes requiring large advances in the state of the art and long development times tend to have unforeseen technical difficulties, and cost estimates, especially those made during early stages of development, are biased in the low direction because of these unforeseen problems. We expect that energy development should experience similar problems.

The evidence is less clear concerning the other two sources of cost growth. Large found some indications that deliberate underestimates occur, but there was no conclusive or even weak evidence that the failure to control costs during development was a significant cause of cost growth in weapons systems. Scherer and others have argued that the primary focus of contractors in the weapons development process has been on quality and delivery schedules and that original cost estimates have been allowed to grow during development to accommodate the focus.

In the development of new energy supplies, not paying attention to costs may have significant implications for the efficacy of company performance and for the social desirability of government actions. Consider the following: (1) Energy must be sold in a market where alternatives exist, and thus significant cost overruns can reduce the *value* of large capital investments. As a result, the management focus should be more toward costs, and public policy should be oriented toward creating incentives to focus on costs (or at least to not create incentives that allow costs to be ignored).[30] (2) In energy, firms are not competing on a long-term basis for contracts to develop new energy supplies. They

---

[30] For example, granting an all-events tariff to a company that wishes to build a synthetic natural gas plant basically eliminates risk associated with cost uncertainties.

finance the development themselves and market the results in a competitive market. They have looked and will continue to look toward the government for funds to subsidize the development, and they will request intervention in competitive markets when there is risk that their product prices will be noncompetitive. Because the contract between the government and the firm doing the development tends to be a one-time affair, there are no incentives, if traditional defense approaches to contracting are followed, to provide unbiased cost estimates or to operate efficiently after the contract is signed.

# III. COST ESTIMATION ERRORS IN PUBLIC WORKS AND LARGE CONSTRUCTION PROJECTS

This section discusses the cost estimation experience for public works and some large private sector construction projects. Similar to the review of the military weapons acquisition experience in the previous section, this section is motivated by the expectation that cost estimation experience in this area will yield insights into the general cost estimating problem, and that elements that underlie cost estimation errors for these projects will be factors that could also contribute to costing errors in energy process plants.

The first part of this section inventories the available published work on estimating problems for large public and private construction projects. Second, the cost estimating experience for these projects is summarized. And third, factors that are suggested in the literature as contributing to estimate deviations from actual incurred costs are synthesized, outlined, and discussed.

## SUMMARY OF STUDIES

Of the literature available, the best and most comprehensive work has been done on the cost experience of federal water-resource construction agencies. Altouney has made a limited examination of the experience of the Bureau of Reclamation based on 1955 Bureau data. Hufschmidt and Gerin have examined the pre- and postwar experience of the Army Corps of Engineers, the Bureau of Reclamation, and the Tennessee Valley Authority (TVA), while Haveman has focused on the experience of the Corps of Engineers. In the non-U.S. experience, Healy has analyzed the cost experience of water control projects in India and has generated some useful findings.[1] Hufschmidt and Gerin have also assessed the work done by the Select Committee on Nationalized

---

[1] Edward G. Altouney, *The Role of Uncertainties in the Economic Evaluation of Water Resources Projects*, Institute of Engineering-Economic Systems, Stanford University, 1963; Maynard M. Hufschmidt and Jacques Gerin, "Systematic Errors in Cost Estimates for Public Investment Projects," in Julius Margolis (ed.), *The Analysis of Public Output*, Columbia University Press, New York, 1970, pp. 267-315; Robert H. Haveman, *The Economic Performance of Public Investments: An Ex Post Evaluation of Water Resources Investments*, Johns Hopkins Press, Baltimore, 1972; J. M. Healy, "Errors in Cost Estimates," *Indian Economic Journal*, Vol. 12, July-September 1964, pp. 45-52.

Industries in Great Britain (1957 and 1962) on cost experience in construction of hydroelectric power plants and the statistical study by two French engineers, R. Giguet and G. Moriat (1952), on bias toward underestimation of public works construction costs.[2]

Mead presents some provocative cost overrun figures for 12 large construction projects. However, while a "high level of uncertainty surrounding cost estimation" is suggested, the figures are not discussed outside of a contract-incentive context in reference to the proposed Alaskan Natural Gas Pipeline.[3] Other quantitative evidence includes two papers from a series of studies on the impacts of the Bay Area Rapid Transit (BART) system on transportation and related activities in the San Francisco Bay region. Merewitz and Sparks have made a disaggregated assessment of the BART cost overrun, while Merewitz examines and assesses the overall public works record including the findings of, among others, Hufschmidt and Gerin, and Tucker, and compares it to the BART experience.[4]

Other literature related to the cost estimation error problem for large public and private projects was either project specific (e.g., the Trans Alaska Oil Pipeline), or addressed to specific topics affecting estimation errors such as the problems inherent in assessing uncertainty, cost estimation experience and reliability historically and in varied contexts, contract/incentive issues as reflected in the federal contracting and technology development experience, and capital project management and control.

As may be apparent, little systematic analytic work has been published on the question of cost estimation error for public works and large private sector construction projects. Much raw cost information is apparently contained in federal, state, and local government agency files, but only limited information relating to public works has been collected, analyzed, and assessed as to the probable reasons behind variations of realized project costs from estimated costs, and the nature and extent of such variations. Private firms in many cases also fail to prepare and capitalize on such analyses for their own internal use, as

---

[2] Hufschmidt and Gerin, op. cit., pp. 268-269.

[3] Walter J. Mead with George W. Rogers and Rufus Z. Smith, *Transporting Natural Gas from the Arctic,* American Enterprise Institute for Public Policy Research, Washington, D.C., 1977, p. 84.

[4] Leonard Merewitz and Thomas C. Sparks, "A Disaggregated Comparison of the Cost Overrun of the San Francisco Bay Area Rapid Transit District," Working Paper No. 156/BART 3, Institute of Urban and Regional Development, University of California, Berkeley, May 10, 1971; Leonard Merewitz, "Cost Overruns in Public Works with Special Reference to Urban Rapid Transit Projects," Working Paper No. 196/BART 8, Institute of Urban and Regional Development, University of California, Berkeley, November 1972 (also available in *Benefit-Cost and Policy Analysis, 1972,* Aldine Publishing Co., Chicago, 1973, pp. 277-295); James F. Tucker, *Cost Estimation in Public Works,* Master of Business Administration thesis, University of California, Berkeley, September 1970.

aids in managing estimating and forecasting, and as the most reliable sources of cost information for future estimates.[5] Such private venture data and analyses that do exist, to our knowledge, have not been published and remain proprietary.

## COST GROWTH EXPERIENCE

Significant cost estimation errors and cost overruns appear to be the norm for water projects and for large construction projects in general. Projects unique in terms of previous design and construction experience appear to be particularly susceptible to large cost overruns.

### Water Resource Agency Performance

As noted above, the best and most thorough analytic work has been done on the cost experience of water-resource-related construction. The historical cost variation experience of the Army Corps of Engineers, the Bureau of Reclamation, and the TVA is summarized and reviewed briefly below.

The cost overrun experience of these agencies has varied, but has shown much improvement in the post World War II period, particularly for the Corps of Engineers and the Bureau of Reclamation. The TVA has the best record of the three agencies in terms of both size and frequency of overruns. Between 1933 and 1966 the TVA had an overall actual/estimated (A/E) cost ratio of .947, with about one-third of the projects showing overruns.[6]

The Corps of Engineers in a 1951 study revealed, for 182 rivers, harbors, and flood control projects, an overall A/E of 2.24, prior to adjustment for inflation, and an A/E of 1.3 subsequent to adjustment for price level changes. A later study performed in 1964 showed a significantly improved record, where for 68 projects completed between 1954 and 1965 the overall A/E was about unity in unadjusted dollars. After escalation adjustments, the ratio dropped to .766.[7] The frequency of overruns was 51 percent in original survey dollars, and 29 percent in escalated survey dollars.[8]

---

[5] John W. Hackney, *Control and Management of Capital Projects*, John Wiley & Sons, New York, 1965, p. 17.

[6] Hufschmidt and Gerin, op. cit., p. 274.

[7] It appears that the dramatic improvement in Corps' estimates in the 1954-65 period resulted from the inclusion of inflation/escalation factors. If not, then the Corps was seriously *over*estimating project costs in constant dollar terms.

[8] Hufschmidt and Gerin, op. cit., p 273.

A 1955 report by the Bureau of Reclamation was analyzed by Altouney.[9] The Bureau report indicated for 103 projects completed or in construction up to 1955 an unadjusted A/E of 2.77 with an overrun frequency of 89 percent. The adjusted ratio came down to 1.96, with an overrun factor of .86. A subsequent report in 1960 (similar to the 1964 Corps of Engineers' report) showed dramatic improvement for postwar projects, with an unadjusted A/E of 1.09 and a 52 percent overrun frequency. After adjustment, the A/E fell to .96 with a 35 percent overrun rate.[10] The figures are summarized in Table 3.1.

Overall, agency performance has improved significantly over performance before World War II and the 1940s. Hufschmidt and Gerin conclude, even with construction price level adjustments being made, that the recent program performance of the Corps of Engineers and the Bureau of Reclamation shows no significant bias toward underestimation of project costs. For the TVA, with the best record, recent estimates typically fall within 10 percent of realized costs, and the bias is toward overestimation.[11]

Both Haveman and Hufschmidt and Gerin suggest that the cost estimation procedures of the Corps and the Bureau of Reclamation are characterized by quite large inconsistencies in achieving accurate cost estimates for individual water resource projects, as can be seen in Table 3.2. As discussed in Sec. IV, the mean of a distribution of cost estimating errors is not nearly so important as the standard deviation, and wide ranges of percentage deviation of realized costs from estimated costs (to the extent not accounted for in project scope and design changes) indicate the potential for significant improvement in project planning and cost estimation performance; therefore, while the problem of bias in the estimates for water projects has been eliminated, the more important problem of error variance remains.

## Other Public Works and Large Construction Projects

Merewitz has compiled and analyzed data on general public works cost experience through 1972.[12] His summary of the cost estimation experience for public works is presented in Table 3.3. The figures have not been adjusted for unanticipated inflation or scope changes which could appreciably alter the results presented in the table.

On the basis of his gross data and a Wilcoxan signed rank test, Merewitz concludes that cost overruns have been smaller in water and

---

[9] Altouney, op. cit., pp. 102-105.

[10] These estimates also likely include inflation/escalation factors.

[11] Hufschmidt and Gerin, op. cit., pp. 279, 294.

[12] Merewitz, op. cit., pp. 17-40.

## Table 3.1

## COMPARISON OF WATER RESOURCE AGENCY PERFORMANCE

| | | | Actual/Estimated | | Overrun Frequency[a] | |
|---|---|---|---|---|---|---|
| Agency | Period of Record | No. of Projects | Original Estimate | Inflation Adjusted | Original Estimate | Inflation Adjusted |
| TVA | 1933-66 | | | | | |
| Dams | | 25 | 1.217 | (b) | 45[c] | (b) |
| Steam plants | | 9 | .904 | (b) | 0 | (b) |
| Total, TVA | | 34 | .947 | (b) | 34.4 | (b) |
| Corps of Engineers | | | | | | |
| 1951 Report | pre-1951 | 182 | 2.241 | 1.306 | (d) | (d) |
| 1964 Report | 1954-65 | 68 | .998 | .770[e] | 51 | 29 |
| Bureau of Reclamation | | | | | | |
| 1955 Report | pre-1955 | 103 | 2.770[f] | 1.960 | 89 | 86 |
| 1960 Report[g] | 1935-60 | 79 | 1.366 | 1.136 | 67 | 52 |
| 1960 Report | 1946-60 | 54 | 1.094 | .959[e] | 52 | 35 |

SOURCE: Adapted from M. M. Hufschmidt and J. Gerin, "Systematic Errors in Cost Estimates for Public Investment Projects," in J. Margolis (ed.), *The Analysis of Public Output*, Columbia University Press, New York, 1970, p. 278.

[a] Percent of projects.

[b] Because TVA included project price increases wherever possible in these estimates, no separate escalated estimates were provided. Very short time lags between survey completion and start of construction allow the TVA to base its estimates on short-term projected prices.

[c] Most of these overruns occurred on projects that were begun or built during World War II--when stoppages or accelerated construction was the rule.

[d] Not available.

[e] The original estimates are suspected to embody construction price level escalation factors.

[f] In most cases these costs were not final project costs, but current cost estimates for projects not yet completed.

[g] All projects exclusive of Colorado River Storage Project and Missouri River Basin Project.

Table 3.2

COMPARISON OF WATER RESOURCE AGENCY PERFORMANCE:
DISTRIBUTION OF ERRORS

| Agency | Period of Record | No. of Projects | Mean | Standard Deviation | Mode | Median | Maximum Overrun | Maximum Underrun |
|---|---|---|---|---|---|---|---|---|
| TVA | 1933-66 | 61 | .983 | .175 | .950 | .950 | 1.53 | .67 |
| Corps of Engineers | | | | | | | | |
| 1964 Report, original estimate | 1954-65 | 68 | 1.1066 | .45 | .875 | 1.034 | 2.16 | .43 |
| 1964 Report, inflation-adjusted estimate | 1954-65 | 68 | .9052 | .33 | .775 | .860 | 1.20 | .30 |
| Bureau of Reclamation | | | | | | | | |
| Original estimate | | | | | | | | |
| 1960 Report[a] | 1935-60 | 79 | 1.274 | .58 | 0.0 | 1.070 | 3.26 | .41 |
| 1960 Report | (b) | 63 | 1.258 | .42 | 0.0 | 1.030 | 1.65 | .41 |

SOURCE: Adjusted from M. M. Hufschmidt and J. Gerin, "Systematic Errors in Cost Estimates for Public Investment Projects," in J. Margolis (ed.), *The Analysis of Public Output*, Columbia University Press, New York, 1970, p. 280.

[a] All projects exclusive of Colorado River Storage Project and Missouri River Basin Project.

[b] Projects at least 50 percent complete, excluding two projects with overruns of 251 percent and 326 percent.

Table 3.3

SUMMARY OF PUBLIC WORKS COST OVERRUN EXPERIENCE

| Type of Project | No. of Projects | Actual/Estimated Cost |
|---|---|---|
| Highway | 49 | 1.26 |
| Water resources | 49 | 1.39 |
| Rapid transit | 8 | 1.51 |
| Building | 59 | 1.63 |
| Ad hoc[a] | 15 | 2.14 |

SOURCE: L. Merewitz, "Cost Overruns in Public Works with Special Reference to Urban Rapid Transit Projects," Working Paper 196/BART 8, Institute of Urban and Regional Development, University of California, Berkeley, November 1972.

[a] Ad hoc projects are essentially first- or one-of-a-kind projects, such as the Albany Mall (Albany, New York), the World Trade Center (New York City), the Long Beach Queen Mary, the Trans Alaska Oil Pipeline, and the New Orleans Superdome.

highway projects than for the overall public works experience. The cost overrun experience for ad hoc, building, and perhaps rapid transit projects, has been higher than the average public works experience. As can be observed from Table 3.3, ad hoc projects stand out significantly from the other types as being most prone to estimation errors.

Tucker examined the cost estimation experience of 107 civil works projects, 39 water resources projects, 39 highway projects, and 29 building projects.[13] The estimates used in the analysis, unfortunately, were those made just prior to project construction, rather than estimates upon which project authorization was based. Tucker found cost estimation error to be the greatest and most predictable in buildings, while water and highway projects experienced lesser, yet more eccentric, cost growth.

---

[13] Tucker, op. cit.

Tucker's regression equation is as follows:

$$R = .0233L - .0092(T - 1940) + .0019C - .0066t,$$

where $R$ = cost growth
$L$ = project length in years
$T$ = calendar year of estimate
$C$ = estimated project cost
$t$ = fraction of project length completed at the time of the cost estimate.

This equation indicates that longer, more costly projects have higher cost growth; over time, cost estimate growth has tended to become less of a problem; and estimates made later in the life of a project tend to be closer to actual costs.

We performed an analysis similar to Tucker's on the data summarized in Table 3.3 above. The limited data available could be used to explore the following questions:

1. Do longer projects tend to grow in cost more than shorter projects as indicated in both Tucker's results and the weapons systems cost analyses discussed in Sec. II?
2. With the duration of the project held constant, do larger (i.e., more costly) projects tend to display more cost growth than smaller projects?
3. Did cost estimation accuracy improve or at least not decline in the time frame covered by the data (pre-1972)?

Two sets of regression equations (Model 1 and Model 2) were estimated to examine these questions. In the first, the simple relationship between cost estimate growth and the time between the cost estimate and project completion is examined (a measure of the rate of cost growth). Table 3.4 below contains the results for a constant rate of growth equation of the form $\ln(C_a/C_e) = bt = \epsilon$, where $C_a$ represents the actual costs, $C_e$ is the cost estimate, and $t$ is the time between cost estimate and project completion (hereafter referred to as time).

All of the regressions in Table 3.4 support the argument that longer projects will experience more cost growth and the estimated growth rate parameters indicate greater cost estimate escalation for buildings and ad hoc projects (about 10 percent annual growth as opposed to 2 to 4 percent growth for the other projects.[14] Note that the constant cost growth model explains a large amount of the variation in total cost growth.

A major assumption underlying the first model is that "other things

---

[14] Because of the small number of observations for ad hoc and rapid transit projects, they are not discussed in the analysis that follows.

## Table 3.4

### MODEL 1: ESTIMATED REGRESSION PARAMETERS AND ASSOCIATED STATISTICS USED TO ESTIMATE COST GROWTH

| | Duration | | | |
|---|---|---|---|---|
| Type of Project | Estimate of b | Student's t-Ratio | Percent of Variation in Cost Growth Explained by Equation | Number of Observations |
| Water | .0227* | 5.74 | 40.7 | 49 |
| Highway | .0428* | 4.48 | 31.3 | 45 |
| Building | .1007* | 8.81 | 56.8 | 59 |
| Ad hoc | .1022* | 3.77 | 54.3 | 13 |
| Rapid transit | .0423* | 4.77 | 76.4 | 8 |

*Different than zero at the .01 level of significance.

are held constant." This assumption is critical if larger, more complex projects tend to have greater cost growth or if cost estimation techniques have tended to improve in more recent years. The equation used to model these effects is:

$$\ln(C_a/C_e) = b_1t + b_2t{*}C + b_3t{*}ESTYR + \epsilon,$$

where C is the final cost of the project and ESTYR is the year the cost estimate was made.

The results (given in Table 3.5) indicate that for water projects, the cost and estimate year of projects do not significantly affect the rate of cost growth. For highways, both cost and the estimate year influence the relationship between time and cost growth in the expected directions: higher cost projects have a higher rate of cost growth, and for the period covered by the data, the rate of cost growth has decreased. Buildings exhibit slightly different behavior: cost growth is strongly dependent upon the interaction of the cost of projects and time, and no improvement is manifested in more recent years.

These results should be viewed with some caution. Consistent with previous analyses, buildings exhibit greater cost growth than water or highway projects, and the growth is greater for larger undertakings. In addition, the cost growth problem in buildings appears persistent over time, which is at variance with Tucker's results. Finally, note that the three variables jointly explain a very large percentage of the cost growth (42 to 61.8 percent). This indicates that a large part of the

Table 3.5

MODEL 2: ESTIMATED REGRESSION PARAMETERS AND ASSOCIATED STATISTICS USED TO ESTIMATE COST GROWTH

| | Estimated Coefficients and t-Ratios | | | | | | |
|---|---|---|---|---|---|---|---|
| | Duration | | Duration by Cost | | Duration by ESTYR | | Percent of Variation in Cost Growth Explained by the Equation |
| Type of Project | b | t-Ratio | b | t-Ratio | b | t-Ratio | |
| Water | .0280* | 2.76 | .0000 | 0.59 | -.0000 | -0.72 | 42.0 |
| Highways | .0692* | 2.58 | .0002* | 3.43 | -.0012† | -2.11 | 48.8 |
| Buildings | .0288 | 0.35 | .0001† | 2.36 | .0010 | 0.73 | 61.8 |

*Different than zero at the .01 level of significance.

†Different than zero at the .05 level of significance.

causes of cost estimation problems are captured by these variables. However, our understanding of exactly what they are measuring is weak and a more complex model that more accurately reflects the phenomenan that underlie project cost, year of estimate, and time is needed before it will be possible to identify and control the causes of cost estimation error.

Mead also presents some evidence on cost overruns that include more recent, very large projects (see Table 3.6).[15] Adjustments made for unanticipated inflation and scope changes are presented along with the unadjusted A/E ratio, thus providing an indication of the potential importance of these factors. Mead's unadjusted weighted average A/E ratio is greater than any generated by Merewitz in Table 3.3. This may be due to a bias arising from the selection of the projects for analysis; to such factors as may be related to increasing project size and complexity; to technical and engineering difficulty; or to such other factors as the ones discussed below.[16]

---

[15] Mead, op. cit., pp. 88-89.

[16] No additional information was available for further assessment of these data.

## Table 3.6

## COST OVERRUN IN MAJOR CONSTRUCTION PROJECTS COMPLETED BETWEEN 1956 AND 1977, ADJUSTED FOR UNANTICIPATED INFLATION AND CHANGES IN PROJECT SCOPE

| Project | Initial Estimate | | Actual Result | | Unadjusted Ratio of Final to Initial Cost | Ratio After Adjustment | | Compound Annual Rate of Cost Overruns, After Adjustments (in percent)[a] |
|---|---|---|---|---|---|---|---|---|
| | Amount (millions) | Date | Amount (millions) | Date Completed | | For Unanticipated Inflation | For Change in Scope of Project | |
| Bay Area Rapid Transit Authority | $996.0 | 1962 | $1640.0 | 5/76 | 1.647 | 1.297 | 1.037 | 0.31 |
| New Orleans Superdome | 46.0 | 1967 | 178.0 | 7/75 | 3.870 | 3.219 | 3.219 | 15.73 |
| Toledo Edison's Davis-Besse nuclear power plant, Ohio | 305.7 | 1971 | 466.0 | 5/75 | 1.524 | 1.401 | 1.401 | 11.89 |
| Trans-Alaska Oil Pipeline (Alyeska) | 900.0[b] | 1970 | 7700.0[c] | 7/77 | 8.556[c] | 6.926 | 4.250 | 22.96 |
| Cooper Nuclear Station, Nebr. Pub. Power Dist. | 184.0 | 1966 | 395.3 | 74 | 2.148 | 1.748 | 1.748 | 7.23 |
| Rancho Seco Nuclear Unit No. 1, Sacramento | 142.5 | 1967 | 347.0 | 74 | 2.435 | 2.026 | 1.239 | 3.11 |
| Dulles Airport, Washington, D.C. | 66.0[c] | 1959 | 108.3[c] | 62 | 1.641[c] | 1.641[d] | 1.486 | 14.10 |
| Second Chesapeake Bay Bridge | 96.6[c] | 1968 | 120.1[c] | 6/73 | 1.243[c] | 1.104 | 1.104 | 2.00 |
| Frying Pan Arkansas Project | | | | | | | | |
| Ruedi Dam | 12.8[c] | 1962 | 22.9 | 72 | 1.789[c] | 1.636 | 1.145 | 1.36 |
| Sugar Loaf | 6.1 | 1962 | 10.2 | 73 | 1.672[c] | 1.500 | 1.500 | 3.75 |
| Boustead Tunnel | 9.2[c] | 1962 | 21.2[c] | 73 | 2.304[c] | 2.078 | 1.233 | 1.92 |
| Rayburn Office Building, Washington, D.C. | 64.0[c] | 1956 | 98.0[c] | 6/66 | 1.531[c] | 1.531[d] | 1.342 | 2.99 |
| Weighted average | | | | | 3.93 | 3.21 | 2.21 | 10.07 |

SOURCE: Walter J. Mead, with George W. Rogers and Rugus Z. Smith, *Transporting Natural Gas from the Arctic*, American Enterprise Institute for Public Policy Research, Washington, D.C., 1977, pp. 88-89.

[a] The compound annual rate expression is used only as a convenient method of comparing initial cost estimates with the sum of all actual costs at the termination of the project. This device permits a comparison of overruns on several projects having different construction periods.

[b] In May 1974, the Alyeska Pipeline Service Co. re-estimated capital cost at $4 billion; then in October 1974, costs were again estimated at $6 billion for the completed pipeline. By June 1975, the estimate was raised to $6.375 billion. In 1969, the $900 million cost estimate for Alyeska assumed a capacity of 500 mb/d. The scope was changed to permit a capacity of 1.2 million b/d. The cost of this change in scope was $700 million, raising the initial capital cost estimate to $1.6 billion.

[c] Does not include interest.

[d] Observed inflation was less than anticipated.

## FACTORS CONTRIBUTING TO ERRORS IN COST ESTIMATES

Many different factors have been ascribed as contributing directly or indirectly to experienced deviations of realized project costs from initial estimated costs. These factors can be grouped and discussed according to the general sources of significant estimation errors:

- Deviations of the actual project from the project as contemplated at the time of the estimate.
- Differences in management and organizational performance.
- Changes in the economic and institutional environment from the time of the estimate.
- Imperfections in estimating methods and limits on the estimating art.[17]

### Project Deviations from Estimate Scope

Scope and design changes, engendered by both exogenous and endogenous elements, are significant factors behind deviations of actual from estimated project costs. Inadequate anticipation at the time of an early estimate of all the physical installations and essential aspects necessary to fulfill the purpose of a project, and shifts in legal, administrative, and political conditions over time, are underlying causes of these changes.

**Scope Changes.** Changes in conceived project size between the original estimate and final design and construction correlate with time lag,[18] and are usually the result of changing exogenous conditions or demands made on the agency or firm performing the design. They are also related in some cases to poor project planning and management as discussed below.

**Design Changes.** Design modifications subsequent to an estimate can have a significant impact on costs, since such changes may engender "ripple effects" throughout an entire system of project cost relation-

---

[17] This framework (based on Hackney, op. cit., p. 81) provides a useful way of organizing the factors. It should be recognized, however, that some of the factors are not without ambiguity and could be correlative with contributory factors in the same and in other categories.

Further, two additional groupings which could contribute to deviations are (1) arithmetic errors and oversights, and (2) the occurrence of unforeseen events subsequent to the estimate—most generally, "acts of God." Systematic effects of such factors do not appear to be significant.

[18] For projects of the Corps of Engineers and the Bureau of Reclamation, 10 or more years may elapse between survey cost estimates and the initiation of construction due to administrative and funding procedures. Many regional and economic changes may take place in the interim.

ships. Design changes are sometimes the consequence of scope changes, and, as in the case of scope changes, correlate with time lag. They are often the result of changing exogenous conditions. In many cases such changes can be attributed to inadequacies and incompleteness in preliminary survey and design information, which can substantially affect estimation accuracy, and to poor project planning and management.[19]

Alternatively, it should be noted that scope and design changes are not always avoidable. As a project progresses into advanced stages, the scope and detailed requirements for a project become increasingly clear, and unforeseen technological and other problems may surface that could not have been foreseen in the best of preliminary surveys.[20]

Scope and design changes executed after construction has begun can have particularly large impacts on costs. When a project reaches this level of development it has accumulated a great deal of momentum, and substantial expenditures of money and time are likely to be required to implement changes.[21]

## Management and Organizational Performance

Project management is responsible for the organization, leadership, control, coordination, and integration of the efforts of the personnel and organizations involved in a construction effort; project management and organizational performance can have a considerable impact on whether significant estimation error and a cost overrun are experienced for a project. Many different factors relating to organizational performance are advanced in the literature, and while structural characteristics of project administering agencies and project management techniques utilized vary considerably across projects,[22] common factors appear across organizations experiencing estimation error and overrun problems. These factors are outlined and discussed below.

**Project/Organization Structure.** Appropriate project organizational structure and administrative procedures appear essential for controlling costs. The Trans Alaska Pipeline System (TAPS) illustrates the problems that can arise. According to an investigatory report, the project was virtually run by committees; it was structured with vertical

---

[19] A particular case in point is the Trans Alaska Pipeline System, which is discussed below.

[20] Merewitz, op. cit., p. 4.

[21] Hackney, op. cit., p. 16.

[22] A. Gravallese, P. Albin, and R. DiLuzio, "Northeast Corridor Improvement Program, Task 1: Management Survey, Summary Report," Dynatrend Inc., Massachusetts, December 1975, PB-259 984.

and horizontal duplication of supervision and decisionmaking, cumbersome decision chains, unclear lines of authority, and fragmentation of responsibility. Compounding this were significant communication, coordination, and liaison problems between project groups. The result of this duplicative management structure was paralysis of the project management decisionmaking process.[23] The inability of the TAPS owners to structure the organization appropriately was a significant factor leading to the experienced cost overrun.[24]

**Project/Organization Manning.** Manpower is required to plan, manage, supervise, and execute a project. The competence, expertise, historical experience, and efficient utilization of these personnel are factors influencing cost growth. These personnel may either be the direct staff of the agencies ordering construction, or contracted employees and organizations which may specialize in particular types or phases of projects.

A few very large organizations operate on a "force account," i.e., in-house construction force, basis. The TVA is a case in point, in contrast with the Corps of Engineers and the Bureau of Reclamation. The overall record of the TVA suggests that its use of force account has led to important economies for several reasons. It has been able to maintain relatively close control of its construction scheduling, thus being able to make economic use of its staff. It operates with relative certainty of labor costs and productivity levels, and has realized benefits from centralized management. This has further led to the accumulation of important administrative and technical expertise and historical experience within the organization.[25]

Contract construction constitutes the most economical and effective option for most construction projects. In addition to the greater efficiency of contract operations due to the competitive nature of the construction industry, contracting allows the availability and utilization for short periods of: (1) organizations and specialists with administrative and technical expertise, and historical experience not otherwise available; (2) large numbers of personnel without incurring costs associated

---

[23] Terry F. Lenzner, *The Management, Planning, and Construction of the Trans-Alaska Pipeline System,* Alaska Pipeline Commission, Anchorage, Alaska, August 1, 1977, Chap. II.

[24] The inappropriateness of project management by committee is further underlined by Hackney (op. cit., p. 273):

"... an organization which is planning a major capital project should designate a single person to manage and lead it. This comment would seem unnecessary if it were not for the repeated instances of organizations which have tried to execute engineering-construction or other capital projects under the direction of committees, or—even worse—as enterprises of organizational groups working in conjunction, with no specific leadership."

[25] Hufschmidt and Gerin, op. cit., pp. 290-291.

with employment, training, and separation; and (3) special physical equipment and facilities without incurring long-term expense and difficulties. Estimation accuracy associated with contract construction can vary with construction market activity, lower costs being experienced when construction work is slow.

In the case of either agency or contracted construction staff, the ability to retain competent and experienced personnel and organizations can be crucial for project outcomes. One example of this is the Albany Mall, where the project failed to obtain the services of contractors with levels of competence commensurate with the difficult construction tasks required by the designs. New York State's Office of General Services, which initially acted as construction manager, was also deficient in the requisite construction management expertise necessary to oversee such a complicated and difficult project. Both factors contributed significantly to the project's difficulties.[26]

**Project/Organization Leadership.** The suitable emphasis of project leadership is on enhancing project cost/time/value tradeoffs, and on liaison within and without the project.[27] Appropriate leadership emphasis is an important element in attaining satisfactory project completion and avoiding cost overruns. Projects where appropriate leadership is not exercised, perhaps due to staffing problems as discussed above, or is unbalanced, overly stressing rapid construction or large advances in the state of the art, are likely to experience cost escalation.

Construction schedules that are faster than normal experience difficulties in supervision and utilization of manpower, and material and engineering coordination problems become magnified. Since a project is composed of a series of interlocking and sequential events, construction is limited in the rate at which it may proceed. For every project there will be an optimum rate at which construction may proceed, and rates of progress slower or faster than this optimum will result in increased costs.

According to an investigatory report, TAPS is a case where the managers from the eight owner companies faced strong internal pressures for quick development.[28] This emphasis on compressing the project schedule, in conjunction with political considerations, caused construction to be initiated without: (1) adequate project planning and preparatory work; (2) a definitive project design; (3) a meaningful cost

---

[26] Eleanore Carruth, "What Price Glory on the Albany Mall?" *Fortune*, June 1971, p. 1966.

[27] Hackney, op. cit., pp. 271-273.

[28] Monte Canfield, Jr., "Statement before the Senate Committee on Energy and Natural Resources," United States General Accounting Office, Washington, D.C., September 26, 1977, p. 10.

estimate; (4) effective internal cost control systems; (5) adequate procurement and inventory control and distribution procedures; (6) adequate communication and information systems; (7) labor management mechanisms; and (8) adequate support facilities and logistics.[29] Failure to establish these systems and controls prior to construction coupled with the unbalanced high priority on construction progress resulted in a major impetus to cost overrun.

Similarly, particular emphasis on technological advance by project leadership can have negative cost and performance results if the jump is overly great. BART is a case in point. The goal of BART planners was to pioneer a transit system which would operate at the outer limits of the state of the art. This required the utilization of a large amount of unproved technology, unprecedented high performance standards, and a novel degree of complexity in transit construction.[30] This push on the state of the art, coupled with an emphasis on cost minimization in initial contracting, led to cost growth and performance deterioration.

**Project Planning.** The absence of the bases of control (good project survey work and planning, and an adequate design and cost estimate) and lack of effective utilization of management control techniques invite cost overruns. This was noted above for TAPS.[31] Healy, and Hufschmidt and Gerin, particularly cite the importance of gaining adequate geotechnical and engineering survey data for water projects in their initial stages if estimation errors are to be avoided.

Alternatively, the planning process can introduce estimation bias as a result of institutional contexts. Project planners, designers, and estimators may become project "champions" rather than remain objective evaluators, either through deep personal involvement with a project or because of environmental pressures.[32] Also, if a construction project is executed by an agency that does not have to return to a legislative or administrative body for funding or approval of future projects, this may allow an incentive to operate that can add to estimation bias.[33]

**Management Performance and Project Size.** Project size is a factor about which the literature is in some disagreement. Hufschmidt and Gerin's data show no conclusive evidence that project size for water

---

[29] Lenzner, op. cit.

[30] Charles G. Burck, "What We Can Learn from BART's Misadventures," *Fortune,* July 1975, p. 105.

[31] Lenzner (op. cit., p. II-16) suggests that the event with possibly the most adverse impact on costs for the project was the owner's refusal to allow Alyeska to enter into an outside planning contract with its eventual construction management contractor at a sufficiently early date.

[32] Hufschmidt and Gerin, op. cit., p. 290.

[33] This is an issue which has been of concern relative to the currently proposed Alaska Gas Pipeline.

projects (in terms of estimated cost) is related to frequency of cost overruns. Altouney found no such correlation in his analysis of projects in the 1955 Bureau of Reclamation study.[34] On the other hand, Merewitz suggests that very large projects may experience greater management problems due to complexity of administrative structure.[35] Hackney also notes that because of difficulties of coordination, very large projects usually experience poorer productivity than smaller projects.[36]

## Economic and Institutional Environment

Projects may not be constructed under economic conditions similar to those that existed at the time an estimate was made. Economic changes are difficult to forecast, and construction costs will vary in accordance with competitive construction market conditions and the general state of inflation (or deflation) in the national and world economy. Where inadequate allowances for construction industry price level changes are contained in project estimates, estimation error results.

It should also be observed that construction industry price level changes typified by construction cost indexes do not reflect the full costs incurred where projects are being constructed under tight market conditions, or the cost reductions which are experienced during slack periods. In periods of high construction and economic activity, extra costs may be incurred over direct increases in the costs of labor, materials, and equipment quality. In addition, delays and the resultant improper sequencing of work functions, decreases in work productivity and losses due to the time value of money, and the attraction of marginal workers to the industry all increase construction costs and are unlikely to be included in a project estimate.

In the case of water projects that were interrupted by World War II, changes in the general construction price levels between the original estimates and actual construction proved an important factor behind estimation error. Similarly, changes in land values were also important factors, particularly where long time lags between survey and construction were experienced. In general, where the length of time between the estimate and the completion of project construction is long, unanticipated construction price level changes are likely to be a factor behind estimation error.

---

[34] Altouney, op. cit., p. 48.
[35] Merewitz, op. cit., p. 2.
[36] Hackney, op. cit., p. 65.

Changes in legal and political conditions can impact project costs both directly and indirectly. Direct cost impacts have been observed to come through court and regulatory delays which cause cost growth through inflation and the time value of money. Indirect influences on costs can come through changes in legal and administrative criteria, contractual constraints, and sensitivity to political influences on the part of project leadership. Two recent cases in which court and regulatory delays have been named as factors behind cost escalation are BART[37] and TAPS.[38]

The Albany Mall and BART are two examples of the effect of contractual limitations on contractor selection. Carruth writes:

> A lot of the trouble on the Mall related directly to strictures surrounding New York State construction . . . Besides being in the trade, the only real eligibility requirement for a bidder is the ability to post a bond guaranteeing that the contract will be completed. The award must go to the lowest such bidder. . . .[39]

The contractors that were most qualified for the jobs refused to be involved. Furthermore, once a contractor won an award, state regulations made it almost impossible to fire the firm. This made management control on the project very difficult. Both of these factors invited cost growth and difficulties in project execution.

In the case of BART, the lowest "responsible" bid system required by law is imputed by Burck to be one factor behind the performance problems the transit system has experienced.[40] The contractual arrangements were inappropriate for a project which was being designed for a major advance in the state of the art.

In the case of federally funded demonstration projects, Baer, Johnson, and Merrow[41] identify political pressures as influences on project leadership. The passage of time for such projects renders them vulnerable to being killed or cut back due to changes in administration, congressional support, and budgets. These political facts make time very important, particularly in the case of large and highly visible projects. This may cause project managers to attempt to compress project schedules, particularly in the important early planning and design stages. This strategy was found to be associated with project failure.

---

[37] Merewitz and Sparks, op. cit., p. 19.

[38] Lenzner, op. cit., pp. III-7, 8.

[39] Carruth, op. cit., p. 168.

[40] Burck, op. cit., p. 163.

[41] Walter S. Baer, Leland L. Johnson, and Edward W. Merrow, *Analysis of Federally Funded Demonstration Projects, Final Report,* The Rand Corporation, R-1926-DOE, April 1976, p. 80.

TAPS is another example of project leadership being influenced by political considerations. At the time the TAPS owners were seeking congressional authorization to proceed with the project, they also chose not to fund necessary pre-construction planning efforts, hoping to obtain favorable action by Congress.[42] It is alleged by Lenzner that if planning had been initiated in the areas of design; cost control, procurement, inventory, and other systems when requested by Alyeska, the cost savings would have been substantial.[43]

## Limitations on Estimating Methods[44]

Merewitz and our reanalysis of his data demonstrate a correlation between project type and the accuracy of cost estimates for various types of public works projects.[45] Ad hoc, first-of-a-kind construction projects, which have large design and construction uncertainties surrounding them, were found to have the greatest deviations from estimated costs.

For water projects Haveman, and Hufschmidt and Gerin demonstrate that substantial differences exist in the cost estimation error experienced across types of projects. Corps of Engineers flood control projects have had a higher total and greater frequency of cost overruns than rivers and harbors projects. Frequency of overruns was least for dredging, locks and dams, and greatest for local protection works and reservoirs—flood control and multipurpose projects—where conditions not anticipated at the survey stage can increase costs significantly. Cost estimation involves few uncertainties and is relatively straightforward for dredging, while in the case of storage reservoirs, important elements found to lead to cost increases were geological and hydrological uncertainty.

A further contrast of estimation error experienced across project types is given by the TVA estimating experience for dams and steam plants. Table 3.1 shows that the A/E ratio for dams was 1.217 with a 45 percent frequency of overrun, while the A/E ratio for steam plants was .904 with no overruns. Hufschmidt and Gerin suggest that the relative freedom from estimating uncertainty is the important variable. The TVA gives the following reasons for the relative freedom from estimating uncertainty in steam plants as cited by Hufschmidt and Gerin:[46]

---

[42] Lenzner, op. cit., p. 2.

[43] Ibid., Chap. II.

[44] The reader is referred to Sec. IV for an in-depth discussion of estimating methods and limitations on the state of the estimating art.

[45] See Table 3.3.

[46] Op. cit., p. 286.

- Area and cost of land for site are fairly well known at the outset.
- Unforeseen foundation conditions do not greatly affect total costs.
- A large percentage of total cost is for off-the-shelf equipment (for which cost estimates are fairly firm).
- Good data are available on past experience for similar projects.
- Setbacks due to floods or bad weather are improbable.
- Good prospect of only small changes affecting costs between initial planning and final design.

From the above it is apparent that the presence of uncertainty as embodied in the type and complexity of projects, and associated limitations on estimation techniques, produce estimation error. In the water experience, Hufschmidt and Gerin observe that when the design or construction stage for a water project is reached, the reduction of uncertainty, through more complete geologic and hydrologic information, often results in sizable additional costs and only rarely in any lowering of actual from estimated cost. They conclude on the basis of their data that "the presence of physical uncertainty carries with it a bias towards underestimation of costs."[47]

Alchian studied the reliability of cost estimates using data from several sources.[48] His studies were concerned with items and methods of production that were "well known, well designed, and produced under standardized production methods." The four studies he conducted were:

| | | Average Error |
|---|---|---|
| Study 1: | Aircraft Wing Weight Estimates for 25 Aircraft Based on Various Design Criteria vs. Actual Wing Weights | ±10 |
| Study 2: | One Cost Estimator's Estimates for Aircraft Components Over a Two-Year Period vs. Actual Manufacturing Costs | ±23 |
| Study 3: | Public Engineer's Cost Predictions for 56 Public Works Projects vs. Winning Bids | ±15 |

---

[47] Ibid., p. 295.

[48] Armen A. Alchian, *Reliability of Cost Estimates—Some Evidence*, The Rand Corporation, RM-481, October 1950.

| | | |
|---|---|---|
| Study 4: | Variation Among Randomly Selected Bids vs. Lowest Bids on Various Public Works Projects . . . . . . . . . . . . . . . . . . . . . | ±15 |

The range of reliability which Alchian detected in the estimates was such that for actual costs to be captured in a 90 percent confidence region, upper to lower estimate intervals on the order of two to one were required. For estimates of new devices and nonstandardized items, Alchian suggests that the bracketing values of upper to lower estimates would be at least on the order of between 3 and 5 to 1. Some bias towards underestimation is observable in his data.

Others provide further insight into the question of estimation and estimation bias. Drawing on his own and others' research on how people perform judgments under conditions of uncertainty, Fischhoff writes:

> To provide valid estimates . . . the estimators must be experts in both the topic in question and in making probability estimates. There is no guarantee that these two forms of expertise go together—that is, that those who understand a system best are able to convert their knowledge into valid probability estimates and to assess the quality of their estimates . . . people who know the most about various topics are not consistently the best at expressing the likelihood that they are correct.[49]

Not only, however, is calibration[50] unaffected by levels of expertise, but overconfidence in making probability estimates has been observed as systematic, particularly for difficult-to-estimate items.[51] Capen has observed this tendency among technical people and notes an almost universal tendency to overestimate the precision of their own knowledge and contribute to decisions which lead to unwelcome financial surprises.[52]

---

[49] Baruch Fischhoff, "Cost Benefit Analysis and the Art of Motorcycle Maintenance," *Policy Sciences,* No. 8, 1977, pp. 177-202.

[50] A judge is perfectly calibrated if over the long run, for all propositions assigned the same probability, the proportion true is equal to the proportion assigned. Sarah Lichtenstein and Baruch Fischhoff, "Do Those Who Know More Also Know More About How Much They Know?" *Organizational Behavior and Human Performance,* No. 20, 1977, pp. 159-283.

[51] Sarah Lichtenstein, Baruch Fischhoff, and Lawrence D. Phillips, "Calibration of Probabilities: The State of the Art," in H. Jungermann and G. de Zeeuw (eds.), *Decision Making and Change in Human Affairs,* D. Reidel Publishing Co., Dordrecht, Holland, 1977, pp. 275-324.

[52] E. C. Capen, "The Difficulty of Assessing Uncertainty," *Journal of Petroleum Technology,* August 1976, pp. 843-850.

This tendency and correlative lack of proper appreciation for difficulties and uncertainties surrounding state-of-the-art advances, unproven construction techniques, and

A tentative conclusion which can be drawn on the basis of the above is that where a large degree of uncertainty is present in the cost estimation process, a bias toward underestimation of costs is likely to manifest itself.

## SUMMARY AND CONCLUSIONS

Published systematic and analytic work focusing on estimation error for public works and large private ventures is limited in nature and scope. This literature is sufficient, however, to allow for some important conclusions relating to the general cost estimating problem. These are:

1. The occurrence of cost estimation error is not atypical in public works and private capital ventures; indeed, it appears to be the norm.
2. The magnitude of estimation errors experienced in these projects correlates significantly with projects that have large design and construction uncertainties surrounding them.
3. The improvement of agency estimation performance in water construction lay in the fact that a debiasing of estimation errors was achieved over time, while no significant reduction of the variance in the errors around the mean of the estimates was achieved. This suggests that the reduction of variance is the more difficult problem of these two aspects of estimation error.

Project-specific assessments and other related literature complement the work focusing on assessing the broader public works estimating experience, and together they offer significant insights into the causes of estimation error. These factors can be summarized quickly:

1. Scope and design changes are important factors leading to deviations of actual from estimated project costs; the further a project has progressed in development, the greater the cost impact of the changes is likely to be.
2. Project management and organizational performance can have considerable adverse impact on a project's cost experience. The following are important to controlling project costs: (a) appropriate project organizational design; (b) competent and experienced project management and construction staff;

---

unique ventures were clearly significant factors leading to estimation error in the cases of BART, the Albany Mall, and TAPS.

(c) suitable project leadership emphasis (e.g., with respect to cost, time, performance tradeoffs); (d) accurate and complete project survey work and planning (including a sufficiently complete design and cost estimate); and (e) appropriate institutional arrangements.

3. Changes in the economic environment are difficult to foresee, and estimation error results if construction market conditions and price level changes vary from those assumed at the time an estimate is made. Pressures and changes in the legal and political environment, if unanticipated or not properly planned for, can have significant impact on project cost, schedule and performance.
4. The greater the degree of uncertainty present in the estimating process, as embodied in the type, complexity, historical precedent, and associated limitations on estimation techniques, the greater the likelihood that a bias toward underestimation of costs will manifest itself.

# IV. COST ESTIMATION FOR PROCESS PLANTS

In the preceding sections the extent of cost growth and some of the factors contributing to it in weapons systems and public works projects were reviewed. There is no completely analogous literature for process plants; published data on the frequency and extent of cost growth for process plants do not exist primarily because such data are proprietary. There is, however, a substantial literature discussing methodologies for and difficulties in estimating capital costs of process plants. In this section we will review that literature, first discussing the uses of capital cost estimates, then presenting a brief overview of how a process plant project takes shape and progresses and the points at which different kinds of estimates are made. We will then discuss in some detail the different types of capital cost estimates, the nature of estimation reliability, and finally factors that affect estimate reliability.

## THE USES OF CAPITAL COST ESTIMATES

Estimates of the capital costs of a process plant serve a variety of planning and management control functions. Estimates aid in research and development allocation decisions—to cut off or continue a program—in a decision to advance a project out of research and development to engineering, as well as in the decision to build a plant. Because capital spending budgets need to be planned several years in advance (especially in tight money markets), estimates are an important part of capital borrowing and spending plans. In managing a project, cost estimates serve as the framework for cost accounting and control during procurement and construction, and are the baseline against which cost performance of the constructors is measured. For the architect-engineering and/or construction firm, estimates can be the principal determinant of whether a profit or loss results on a project.

## AN OVERVIEW OF PROJECT DEVELOPMENT PHASES

Bringing a new process plant on-line evolves through a number of more or less well-defined stages:

- Research and development
- Project definition
- Engineering design
- Construction
- Start-up

The evolution of a process plant project described below is an idealization; different firms have somewhat different procedures and timing methods. The purpose of this overview is to explain the points in project development at which different types of cost estimates are made.

The organizational arrangements for bringing a new plant on-line vary from one extreme, in which each phase is performed by a separate firm, to all phases being performed by different departments of the same firm at the opposite extreme. Who actually performs the cost estimates may also vary substantially. However, in most cases at least the preliminary, budget, and definitive estimates will be made by the same cost estimating group. Sometimes the cost estimating group is part of the engineering department of the architect-engineering firm or plant owner; sometimes it is a separate entity within the architect-engineering or owner organization. Occasionally, independent experts will be hired on a consulting basis to study the plant design and cost estimates.

## Research and Development

Regardless of where the idea for a project originates, if the plant entails a new process or new equipment items, a research and development (R&D) group will take first responsibility for moving a project forward. R&D work may include gaining basic theoretical understanding of a reaction and proving out basic process feasibility, or working on a particular aspect of the proposed plant such as metallurgical difficulties or process safety. For a new process a process development unit (PDU) may be part of R&D. The PDU is generally a small batch unit that tests some portion of the process. During R&D a series of conceptual or initial capital cost estimates will be made. Alternative processes may be estimated for comparative purposes.

The principal function of initial estimates is screening. If initial estimate costs are relatively high, the project may be continued in R&D to see if solutions to high-cost aspects of the process can be found. Because the scope and basic design of a process are fluid during R&D, initial estimates may fluctuate a great deal over time.

## Project Definition

For a new product or new process to produce an old product, the most formidable hurdle is a decision to move the process out of R&D to engineering to begin the process of defining what a commercial plant would look like. This decision involves a commitment to spending enough money to define the scope of the proposed plant, basic plant layout, and process flow conditions. Most major equipment needs are defined at least in a preliminary way during project definition.

For a standard plant to which some modifications are being made, the project definition stage may be both short and simple. For a highly innovative plant, however, the project definition may require as much as six months and a large amount of high-priced engineering talent. For projects that have evolved from R&D, members of the R&D group will generally be involved with the process designers in defining the project.

In some cases it may be realized that additional R&D is necessary on a process as a result of the project definition exercise, in which case the project may be returned to R&D. If unknowns exist which can only be resolved through a larger scale test facility than a PDU, a request to authorize the construction of a pilot plant may be made. A pilot plant is distinguished from a PDU not only by size but by the fact that pilots are close to "scale-models" of at least some portions of a commercial plant. The size of a pilot is dictated by the kind of design information needed. If critical design questions center around scale-up, a pilot will be larger than if the problems center around, for example, process integration. The decision to build a pilot plant is made very carefully because even a small pilot is an expensive undertaking, the cost of which may render the overall economics of a project unfavorable.

An important product of the project definition phase is the "preliminary" or "phase I authorization" estimate. The preliminary estimate is based upon the design of the plant as formulated in the project definition stage rather than a PDU or pilot plant. Lab, PDU, and pilot data (if any) aid in the project definition and later in engineering. The cost estimator depends on quality and thoroughness of the project definition to compose the preliminary estimate.

The preliminary estimate is 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. *The decision to proceed to a full design is normally tantamount to a decision to construct the plant.* Design costs may be 10 percent or more of the total capital cost of the facility. For most relatively standard plants, the site preparation and other civil work may begin immediately. For innovative plants or plants with otherwise uncertain economics, the decision to begin actual construction may be deferred to the next step.

## 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. Potential problem areas are given special attention and procedures to cope with the problems worked out. Occasionally, problems will be encountered in design that cannot be solved without the construction of a pilot or more R&D work, in which case design work slows until the necessary information is produced. Procurement specifications and detailed construction phasing are also worked out during engineering. When engineering is well underway (30 percent or more complete), it is common to produce another capital cost estimate. This estimate, dubbed the "budget" or "phase II authorization" estimate, serves several important functions. The budget estimate serves as an important checkpoint for the project, especially if a pioneer plant is being built. If costs have increased considerably from the preliminary estimate, the project may be reexamined. As the name implies, the budget estimate is used as the basis for planning capital expenditures on the project over time. After the budget estimate is made and accepted by the management, the authorization of monies necessary to complete the project is generally made. A second function of the budget estimate is to establish the cost accounts that will be carried forward through the rest of the project. These cost accounts will later be used to control expenditures during procurement and construction. After the budget estimate is made, procurement generally begins in earnest. Specifications for equipment items are ready and can be put out for bids and subcontracts can be let.

From the moment that authorization is given to expend funds for actual plant construction, time becomes an increasingly valuable commodity because the rate of expenditures begins to rise rapidly. In addition to expenditures for procurement, site preparation work normally begins at this point if it has not been authorized earlier.

If the budget estimate is prepared relatively early in the design process (about 30 to 40 percent complete), a final-form "definitive" estimate will be prepared when engineering is 90 to 100 percent complete. As its data base this estimate has the advantage of a fully designed plant along with firm quotations on equipment and subcontracts. In addition, except in cases where the plant economics are marginal, considerable construction work will have been completed when the engineering design is completed and the definitive capital cost estimate prepared.

During the definitive design of the plant, the "critical path" for construction is finalized.[1] The critical path for a project is a series of

---

[1] The critical path method (CPM) was introduced in the late 1950s as a scheduling method. Later the technique was modified to include costs. As used here, the critical path

essential functions or steps that *must* be performed *serially*. If a step in the critical path is not performed, the project construction (or some significant part of construction) must halt until it is. In fact, the critical path begins long before construction commences. Design is part of the critical path, and in many cases, equipment orders for long-lead-time items will constitute the first pacing function many months, or even years, before plant site preparation begins.[2]

A "critical path failure" occurs either when an essential function is not completed on time (which then results in a delay of the project), or when the critical path has been misspecified. This latter type of critical path failure, while unusual, can be very costly if the error is not found soon after it occurs. For either type of critical path failure, the costs of the failure tend to be higher the later it occurs in the project because a larger investment has been made.

## Construction

As suggested above, when construction begins varies considerably from one plant to the next. For most standard plants construction will begin when design is less than one-half complete. For pioneer plants construction may not begin save for site preparation until the definitive engineering design has been completed.

Given a set of construction specifications, construction cost depends on effective control of materials and labor costs and maintaining the construction schedule. Most major purchasing is now performed by specialists in the home office of the constructor rather than in the field. A few major items such as concrete may be purchased locally, as well as bulk materials in which shortages develop.

The construction period for a process plant varies from less than one year for small plants to more than four years for the very largest complexes. Most leading construction firms are now using a network construction scheduling technique such as the Critical Path Method to minimize the time necessary to construct. The most common factors causing delays in construction schedules are late delivery of materials, labor unavailability, and poor labor productivity.[3] Inclement weather

---

refers generically to the essential pacing functions for a project. Long before CPM and other network scheduling methods were introduced, successful project managers were using some sort of critical path method, however informal.

[2] Necessary equipment lead-times vary considerably from one type of technology to another, and vary with market conditions. Lead-times for chemical process plant equipment items rarely approach those for nuclear power plant vessels.

[3] Henry F. Peters, "Field Construction," in Ralph Landau, *The Chemical Plant*, Reinhold Publishing Co., New York, 1966, p. 214.

and strikes can also significantly delay the completion of construction. Only in rare cases will construction be delayed by errors in the plant's design. Plant design problems that have not been caught in engineering will normally not he manifest until start-up.

## Start-up

When construction is completed the start-up phase begins immediately. Planning for start-up will have begun well back in engineering and first estimates of start-up costs will have been made with the preliminary capital cost estimate in most cases. The time allocated for start-up varies from about one month in the case of small standard plants to as much as one year for large, complex, and innovative projects. During start-up, operating and maintenance personnel are trained both in the classroom and with the plant itself.

The primary function of start-up, however, is to "debug" the plant. Equipment is operated using air, water, or other safe substances and inevitably a number of minor repairs and replacements are necessary. The plant is then tested at operating temperatures and pressures and finally tested with process materials. Delays in plant start-up are very expensive; the entire plant investment has been made, start-up personnel are highly paid engineers, shipments of raw materials may have arrived, and product orders may go unfilled.

Start-up problems have three primary causes:

- Equipment failures account for about 75 percent.
- Inadequate equipment accounts for another 20 percent.
- Process failures (i.e., improper design) account for the other five percent.[4]

In many cases a fair amount of time and expensive reworking may be necessary before the source of the problem is found. Of the three sources of start-up difficulties, process failures are by far the most serious. Process failures may result in substantial delays while design changes and added construction work take place, may entail considerable additional capital cost over and above the losses incurred by delays, and in some cases will result in the plant never operating at design capacity. Large profit losses are associated with poor performance because most process plants are more sensitive to poor service factors than to either additional capital or operating costs.[5] Major process failures are, of

---

[4] Manfred Gans and Frank Fitzgerald, "Plant Start-up," in Landau, op. cit.

[5] Roger F. de la Mare, "The Economic Implications of Plant Reliability," *Chemistry and Industry*, May 3, 1975, pp. 366-369.

course, most frequent for pioneer plants. No published data are available, however, on how frequently such failures occur in innovative facilities.

## TYPES OF CAPITAL COST ESTIMATES

In the section above, four types of capital cost estimates were mentioned: *initial, preliminary, budget,* and *definitive.*[6] In the section below we will define the estimates and discuss each in some detail.

- *Initial estimates* (sometimes also called "order-of-magnitude"[7] or conceptual estimates) are rough approximations based upon simple calculations and minimal engineering. Initial estimates are expected to be within about plus or minus 40 percent of actual costs for known technologies. Initial estimates are used to screen and compare alternative processes and to aid corporate management in R&D allocation decisions.
- *Preliminary estimates* are generally based upon completed development work, and some engineering. Preliminary estimates are usually the first submitted to management for a decision on whether to continue the project into plant design. The cost of a preliminary estimate varies with the degree of accuracy sought, the size of the plant, and the conventionality of the proposed plant technology. A confidence interval of 20 to 25 percent in generally sought for preliminary estimates.
- *Budget (or control) estimates* are generally made when plant design is well underway and engineering is 30 to 70 percent complete. Budget estimates are generally based on nearly complete equipment specifications, and at least some quotes from equipment vendors. As the name implies, budget estimates are used by management as the basis upon which to allocate capital to the project. Depending upon the goals of the firm and the conventionality of the process technology, a confi-

---

[6] There is no generally accepted set of definitions for capital cost estimates. Some firms and authors employ a threefold set, while others use as many as six. More confusing, the same labels are sometimes used to represent quite different kinds of estimates. Several different criteria have been used to form different typologies of cost estimates for chemical process plants and other major plant construction. Categories have been devised using level of effort or cost of the estimates, size of confidence interval sought for the estimate, function of the estimate and methodology employed in developing the estimate. We have chosen the fourfold set because it appears sufficient to cover almost all estimates.

[7] The term "order-of-magnitude" is used in a loose sense here rather than in its strict mathematical definition.

dence interval between plus or minus 10 percent to plus or minus 15 percent will be sought.

- *The definitive estimate* is generally made after project engineering is complete, vendor quotes have been received, schedules have been finalized, and construction is ready to begin or is underway. Definitive estimates are expected to be within plus or minus five percent of actual plant costs.

Table 4.1 summarizes the differences between various estimate types. The chief distinguishing feature of the estimate types is the stage of development or design when the estimate is made rather than whether the process has had process development unit or pilot testing. Cost estimates for a commercial plant are developed from the design with lab results, PDUs, and pilots providing data for the design rather than cost data for the commercial plant. Many chemical process plants, including some that are pioneer plants, are never piloted because the cost of constructing even a small pilot plant is very high.

The confidence intervals for different estimate types are those generally reported in the literature as the target for estimates. For pioneer plants the interval is widened to about minus 40 percent, plus 75 percent for initial estimates, and minus 25 percent, plus 30 percent for preliminary estimates. The literature is not clear whether the intervals are goals or if they are routinely achieved. Discussions with industry engineers suggest that for pioneer plants they are usually goals.

### Initial Estimates

Initial estimates, also called conceptual or order-of-magnitude estimates, are made prior to project definition. Therefore, unlike any subsequent estimates, initial estimates include no site characteristics. In general, initial estimates are inexpensive to perform, requiring no more than a few days to complete using simple ratio methods to estimate the basic process portions of the plant from an approximation of the plant's major equipment costs. In most cases no attempt is made to estimate plant costs beyond the battery limits. If the balance of plant investment is estimated, it is done by applying a factor rather than by individual estimation of various items.

When initial estimates of standard plants are made, the results can be quite accurate *if the plant built is the one estimated.* It is often the case, however, that significant changes will be made in the scope, design, and even product mix of a plant during project definition. For pioneer plants, such major changes are the norm during project defini-

## Table 4.1

## SUMMARY OF ESTIMATE TYPES

| Estimate Type | When Performed | Confidence Interval Sought | Methodology | Data Base | Usual Private Sector Use |
|---|---|---|---|---|---|
| *INITIAL* (also conceptual, "order of magnitude," factored) | Repeatedly during process development | ±40% | Cost-capacity curves, analogy | Lab results, PDU[a] analogous plants | General information purposes, R&D allocation |
| *PRELIMINARY* (also first phase, initial authorization) | Project definition complete | ±20-25% | Cost-capacity curves (standard plants), analogy, some equipment costing | Pilot plant (if any) plot plant, flow sheet, major equipment list, building sizes | Prepared for management decision on whether to proceed with full plant design |
| *BUDGET* (also second phase, control, detailed)[b] | Design and engineering 30-70% complete | ±10-15% | Equipment costing, installation ratios, takeoffs | Complete equipment list, some quotes, detailed site-specific costs, engineering drawings for some takeoffs | Authorization to start site prep., firm up equipment orders, construction capital allocation |
| *DEFINITIVE* (also detailed)[b] | Design and engineering 90-100% complete, site preparation may be well under way | ±5% | Full cost quotes on all equipment, firm subcontractor bids, take-offs from completed drawings, all code and regulatory requirements, fees, detailed labor requirements and cost | Completed design | Construction cost control, final construction decision in rare cases |

[a] Process development unit.

[b] Note that "detailed" is sometimes applied to either budget or definitive estimates by different firms. In the latter case, the "detailed estimate" is a refinement of the definitive estimates made during construction with a ± 3% target confidence range.

tion. Initial estimates of pioneer plants often attempt to say how much it costs, before knowing what *it* is.

Initial estimates are often used for comparative purposes; two or more alternative processes can be quickly costed out to see if one is clearly superior or to eliminate clearly inferior options. The estimate can also give the potential purchaser some indication of how much money would have to be set aside from earnings or borrowed if the project were continued.

For pioneer plants a series of initial estimates is typically made during research and development to roughly cost out different process configurations and scopes. As the research and development process progresses, more should be known about the ultimate configuration of the commercial plant and one would therefore expect the accuracy of the estimates to improve.

## The Preliminary Estimate

The preliminary estimate is the first cost estimate made after project definition. The principal difference between an initials estimate and the preliminary estimate is not methodology; in both cases various types of ratio methods are employed. The key difference is that for the preliminary estimate one is estimating a particular plant of a particular size and basic configuration to be constructed in a particular place and time. Preparation of a preliminary estimate may entail as little as a few weeks or up to several months of preparation. When the plant being estimated is a straightforward scale-up of an existing process, reliable preliminary estimates may be obtained using cost-capacity curves or the "rule of six-tenths." The rule of six-tenths is that costs will increase at 0.6 times the rate of increase in capacity. This rule of thumb has been derived empirically for the chemical and other industries.[8]

Of course, the six-tenths rule must be used with caution. Some types of major plant components do not follow the 0.6 rule (e.g., pumps and compressors), and, of course, the rule is nullified as one moves beyond the limits of a single train. The usefulness of rules of thumb, such as the 0.6 rule, in the chemical industry may be declining over time because of practical and economic size limits.[9] Second, the advent of wide-ranging and continuously changing government environmental and safety regulations has forced numerous design

---

[8] L. F. Williams, "Capital Cost Estimating From the Viewpoint of Process Plant Contractor," *AACE Bulletin,* Part I, December 1972.

[9] D. E. Chaulkey, "Is Bigger Really Better," paper presented at 1975 meeting of ICI. Some of the difficulties of using the 0.6 factor are discussed below.

changes in what would otherwise have been standard plants. Prior plants, therefore, are increasingly less reliable bases against which to estimate larger facilities. Even in the case in which a near duplicate or modest scale-up of an existing plant is involved, a preliminary estimate will incorporate as many adjustments for the particular plant being built as data and time will allow.

For new processes, the preparation of a preliminary estimate may prove extremely difficult, and the uncertainty surrounding the estimate may remain large even if the best available information is used with care and skill. In order to prepare a preliminary estimate for a new process, it is necessary to develop a plot plan, flowsheet, major equipment list, and building sizes.[10] Estimation then commonly proceeds on the basis of a combination of analogy, some equipment costing, and rules of thumb.

Estimation by analogy entails defining a series of process steps and estimation on the basis of cost of such steps for other plants and the number of steps involved. Major equipment costing is generally only considered for a preliminary estimate if the required equipment is standard and prices are known. If nonstandard major equipment items are necessary, then rules of thumb or a computer cost model will be used to estimate their costs at this stage. More detailed costing would require more expense than is usually justified at this stage.

After major equipment items have been estimated, a number of different techniques are available to arrive at total plant costs.[11] The most common method is the "equipment installation cost ratio." For given types of equipment the costs of fully installing the item including foundations, erection, and connections can be estimated by multiplying the purchase price by a factor derived from past experience. If derived from identical or analogous equipment and if carefully applied, equipment installation factors can provide reasonable accuracy (i.e., plus or minus 20 percent). Another ratio method uses factors for plant components as a percentage of total cost rather than equipment items. Similar methods are available for estimating the cost of outfitted structures and piping, valves, and instrumentation. Some of the dangers of ratio methods will be discussed in a later part of this section.

## The Budget Estimate

The budget (or control) estimate is not generally made until after

---

[10] O. Mendel, "Types of Estimates: Their Reliability and Basis as Used in Conjunction with Cost Controlling Techniques,' *AACE Bulletin,* August 1974, pp. 107-110.

[11] See O. T. Zimmerman, "Capital Investment Cost Estimation," in F. C. Jelen (ed.), *Cost and Optimizaton Engineering,* McGraw-Hill, New York, 1970, pp. 311-334.

engineering is under way. As the name implies, this estimate is used to set the project budget, not only on an overall basis, but also into various categories.

The decision to proceed with the project has usually been made by the time the budget estimate is complete, but this estimate can serve to stop projects, or modify plans, if it shows costs to be noncompetitive. (In some cases, even if the control estimate shows costs to be noncompetitive, engineering work will continue through the definitive design, so that the design is available for future use. Once the engineering is well underway, a process design team has been assembled, which represents a substantial cost.)

Unlike the preliminary estimates, in which factor multipliers play a central role, the budget estimate is usually based primarily on information that is specific to the plant in design. The scope has been fully defined, a construction schedule set and quotations have usually been received for key pieces of equipment. In addition, site-specific factors, such as wage-rates and productivity, availability of utilities, and site-related construction problems can be included.[12] At least preliminary piping and electrical system drawings can be used.

A number of uncertainties remain after a budget estimate is completed, and as in the case of preliminary estimates, the range of uncertainty is greatly influenced by the "newness" of the process.

After the budget estimate is completed, several factors may routinely affect costs:

- *Changes.* Late changes in scope or design.
- *Exclusions.* Sometimes the budget estimate does not include all capital cost items (e.g., working capital, owner's expenses, start-up costs, etc.).[13]
- *Escalation.* Especially since 1973, even preliminary estimates have included an escalation factor to account for increases in equipment and labor costs. This factor is subject to error, especially when long construction times are involved.
- *Schedule delays.* Delays in the construction and start-up schedules can result from a number of factors, such as permit delays, environmental and legal problems, changes in market conditions, labor problems, equipment shortages, and assorted technical difficulties.

The accuracy sought for a budget estimate varies between about plus or minus 7 percent and plus or minus 15 percent, depending upon the novelty of the plant and the accuracy demanded by the purchaser.

---

[12] Mendel, op. cit., p. 108.

[13] Ibid., p. 109.

## The Definitive Estimate

The definitive estimate (sometimes also called the detailed estimate) is not performed until engineering is nearing completion. The definitive estimate has a target accuracy range of plus or minus five percent. The preparation of a definitive estimate is expensive. Two to five thousand engineering man-hours are required for the preparation of a definitive estimate for a typical chemical process plant.[14] (The engineering costs for a chemical plant will typically range from a low of about 5 percent of capital costs for a repeat plant, to about 15 percent for a first-of-a-kind plant. This includes both engineering and purchasing, but not profit to the engineering firm.)[15]

The definitive estimate is based on completed process and engineering flow sheets, designs, and often firm quotes for major equipment items, designs for all structures, construction specifications, and a well-defined engineering and construction schedule, usually based upon an extensive analysis of the critical path.

Because the process and engineering flow sheets are available, takeoffs[16] of piping, values, foundation work, instrumentation, structural steel requirements, and electrical costs can be made. Although considerable data are available for the preparation of the definitive design, arriving at an accurate cost figure is by no means mechanical. Extensive records of costs of past projects and accurate current price lists must be used.[17] Even if all major equipment prices are quotes received from vendors, many items must be estimated.

One of the most difficult-to-estimate areas is piping and valves. Piping and valves typically constitute 15 percent to 20 percent of the total capital cost of a chemical plant. Unlike most major equipment items, piping and valves must be estimated from takeoffs even for the definitive design.[18]

---

[14] J. H. Lutz, "Cost Control and Estimation," in Ralph Landau, *The Chemical Plant*, Reinhold, New York, 1966, p. 258.

[15] Ibid., p. 263.

[16] A "takeoff" is an estimte derived from engineering flow sheets. The amount of pipe, for example, is "taken off" the diagrams. Takeoffs are sometimes made for budget type estimates from whatever flow sheets are available at the time. The cost derived from a takeoff has to be adjusted (upward in most cases) by reference to previous experience. Although takeoffs can be very accurate, they are nonetheless estimates, and if the plant being estimated is a pioneer, prior experience may not be an accurate guide.

[17] In the past 10 years, the computer has been of increasing importance in design, project scheduling, and cost estimation. The use of computers to keep track of price changes has become common among larger firms.

[18] L. F. Williams, "Capital Cost Estimating From the Viewpoint of Process Plant Contractor" *AACE Bulletin*, Part II, February 1973, p. 6. Piping costs vary significantly with the type of pipe installed. For example, welded stainless steel may run three to four times as much installed as welded carbon steel. The takeoffs for piping and other bulk materials used in field construction always require adjustment.

Another difficult area is field construction cost. Even if field fabrication is unnecessary, field construction may amount to about one-fifth of capital costs, and even for repeat plants, is subject to a number of vicissitudes (e.g., shortages of skilled craftsmen, labor troubles such as strikes, schedule problems, etc.). Even when such "random" factors are excluded, field construction costs are difficult to estimate because these costs vary considerably from site to site and the unit of work is difficult to define. In addition, the type of materials used in the plant and the error tolerance of construction influence field costs.[19]

In summary, each type of capital cost estimate has a different knowledge basis, employs a different methodology, and is expected to have a different level of accuracy. In the next section, we will examine more closely what the term "estimation accuracy" means.

## THE NATURE OF ESTIMATION ACCURACY

What is meant by accurate estimation depends upon point of view. To management, accurate estimation probably means something similar to common usage: an accurate estimate is one that is about equal to actual costs. To the cost estimator, however, estimation accuracy is viewed over a number of projects, and is essentially probabilistic. "Good cost estimation" by an individual cost engineer or firm consists of being "reasonably" close to the actual cost a *large* portion of the time over a series of estimates. The definition of reasonably close depends upon the type of estimate being performed, which, as discussed above, depends upon the amount of information available to the cost estimator.

### Confidence Intervals

All cost estimates are accompanied by a range from some percentage below the estimate to some percentage above the estimate. The precise meaning of the range is unclear in the literature and from our discussions with cost estimators. There is agreement that over a series of estimates the mode of actual costs should be the estimated cost (i.e., the estimated dollar cost should be the most likely actual cost). In cases in which the confidence interval is symmetrical, the means of estimated and actual costs should be the same (and, obviously, equal to the mode, i.e., a normal distribution). But it is not clear what percentage of estimates is expected to fall within the given range. Some authors seem to imply that *all* estimates should be expected to fall within the confidence

---

[19] Peters, op. cit., p. 215. A good example of the cost effects of very high quality standards is the Alaskan oil pipeline welds, many of which had to be redone.

interval.[20] In other cases, two standard deviations (i.e., 95 percent) are assumed, and in still others another figure such as 80 percent is suggested.[21] In addition, it is unclear whether the confidence intervals are normative or empirical rules of thumb. Discussions with industry estimators strongly suggest that they are the former but that is never stated explicitly.

### Types of Errors in Estimates

If one is examining a set of estimates, three parameters that are descriptive of the distribution of estimation errors may in principle be used:

- Bias
- "Spread"
- Multi-modality

A set of estimates containing only bias is probably indicative of basically sound estimating technique, but with some systematic error. It is also possible that bias results from incentives on the part of the estimators to overestimate or underestimate. The source of biased estimates (be they incentives, systematic errors, or both) may be very difficult to trace. If the bias is consistent, however, it may be possible to adjust (debias) the estimates after sufficient observations have been made.[22]

A more difficult type of estimating error is "spread" (or variance). If in a set of estimates, a large number are outside the confidence interval or if the distribution is flat, then the estimates are unreliable and the cost estimates or the basis for the estimates is being done poorly.

The third type of problem is present when a set of estimates has two or possibly three modes. Industry estimators suggest that bimodal distributions are not uncommon. When a set of estimates has more than one mode, it is likely that some important differentiating characteristic(s) of the plants forming the groups has been missed. A problem for the analyst attempting to understand the sources of error in cost estimates is that bias, spread, and multimodality usually exist together for a set of estimates at least to some extent.

---

[20] M. Rosenthal and E. O. Green, "Discussions of Estimating Methods," *AACE Transactions*, pp. 343-348.

[21] Hackney, op. cit., Appendix B.

[22] Ibid.

## FACTORS AFFECTING ESTIMATE RELIABILITY

Cost estimates are predictions of the future. Like all such predictions, they are subject to the possibility of being wrong. In this section we discuss the factors mentioned most prominently in the literature and in discussions with industry as causes of unreliable cost estimates. We have arranged the factors into four areas:

- Plant and Process Uncertainty
- Estimation Methodology
- Project Organization
- Exogenous Effects on Cost

### Plant and Process Uncertainty

Cost estimators prepare estimates on the basis of the information available about the process and particular plant. Estimators are dependent upon the designers and engineers for information that is as complete and accurate as possible given the stage of development.

**Scope.** A clear definition of the *scope* of the plant is often cited as the first critical information for cost estimation. Changes in scope are a leading factor in estimation error. Scope consists of what the plant will produce and at what rate. But as McCabe points out, scope is subject to varying interpretations. The interpretation of the meaning of a specified plant capacity may differ substantially among the design engineers, operators, and cost estimators.[23] Capacity is a function not only of plant size, but also of expected downtime for maintenance and product changes. Thus, realized capacity (and hence scope) are affected by the amount of redundancy built into the plant design as well as operating procedures. As mentioned above, the economics of a process plant are very sensitive to assumptions about plant average output over time.

During the course of a project, plant scope may be changed for a variety of reasons. Change in market conditions for the plant's output may induce either an increase or a scaling-down of the plant scope. The product mix may be changed, thereby changing the scope. Scope may be reduced if unexpected technical problems are encountered with equipment items during design. Conversely, the scope may be increased if, during design, technical opportunities to reduce unit cost are seen. Changes in scope may also result from changes in environmental and safety standards applicable to the plant. A change in air quality stan-

---

[23] William P. McCabe, "Project Scope Definition," paper presented at Pittsburgh Section Meetig of AACE, October 1964.

dards may necessitate the addition of gas scrubbers, for example. The failure of local authorities to issue a waste discharge permit may necessitate the addition of an effluent treatment plant at significant additional cost. If the plant scope is changed, cost estimates must necessarily also be adjusted, and major scope changes may require that cost estimates be substantially redone.

**Design Changes.** Design changes not involving plant scope can also invalidate a cost estimate. One of the primary reasons that initial estimates are sometimes highly inaccurate is that the plant estimated has changed significantly as the project moves through project definition and engineering design. At some point, sometimes as early as the end of project definition, the basic design of the plant will be frozen (i.e., no additional major design changes will be allowed, even if such changes would improve the plant). After the design has been frozen, only changes that are necessary for technical reasons or changes that are so beneficial that cost of redesign and estimation are exceeded will be considered by the project manager. Prior approval becomes necessary before any significant amount of time may be spent by engineers considering design changes.[24] The later in the project that design is frozen, the more tentative are estimates made before that time.

**Products Specification.** A source of low bias related to the scope problem in nondefinitive estimates is incomplete or incorrect products specification.[25] For example, if the preliminary estimate is based upon 97 percent product purity and this is later changed to 99 percent to meet market demands, major design changes involving significantly increased capital costs may be necessary. This difficulty is especially prevalent in pioneer plants incorporating a new process.

A point made strongly in discussions with industry engineers who have designed pioneer process plants is that even with extensive theoretical, laboratory, and even pilot plant work, there is some amount of residual uncertainty about exactly what will come out of the back end of a new chemical process when operated at commercial scale. This is because the precise nature of the chemical reactions taking place is in some cases unknown. This problem is especially common where organics are involved because of the complexity of the chemical reactions.

**Scale-Up.** A factor *not* mentioned in the literature as being related to estimate accuracy is any possible effect of having constructed a pilot plant or demonstration facility prior to design. The reason for this is that a pilot or demonstration facility does not normally figure *directly* in cost estimation. Rather, such a facility is constructed to aid the

---

[24] Russel G. Hill, "Project Engineering and Management," in Landau, op. cit., p. 169.

[25] Lutz, op. cit., p. 264.

proper design of a commercial plant. To attempt to estimate commercial plant costs by factoring from a pilot plant can introduce major errors. Even if a pilot is in some sense a scale model of a process, it is not a scale model of a commercial plant. In the chemical industry, pilot plants are typically very small relative to the commercial plant (1/1000th or less). Therefore, the equipment is in no sense comparable to a commercial facility. Demonstration plants (i.e., plants using commercial or near-commercial scale equipment but with smaller than commercial scale plant capacity) are rarely built by the oil and chemical industries.[26] With careful adjustments, such plants may provide a reasonable basis for direct extrapolation of the costs of a commercial facility. In such cases the result may be a high-quality initial estimate.

Of course, if (in retrospect) a pilot plant should have been built but was not, or if a larger pilot should have been constructed, then the probability of design failure increases and with it the probability of cost growth.

If one is making an initial estimate of a new plant based upon a scale-up of an existing commercial plant using cost-capacity curves, then the literature does suggest that the degree of scale-up influences estimate reliability, but in general, one is as likely to overestimate as to underestimate the costs.[27]

**The Effect of Pioneer Plants 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 plans toward entirely new processes.[28] Confidence intervals are relaxed and a larger contingency is built into the estimates. In addition, schedules tend to be longer, especially in design and start-up, and construction generally begins later in design than for conventional plants.

For pioneer plants both bias (in this case, underestimation) and spread appear relatively common.[29] The primary reason that pioneer

---

[26] When a demonstration type facility is constructed, it is usually as an add-on to an existing plant rather than a "green field" project. The usual reason for building a demonstration facility is to test the market for a new product rather than testing the technical or economic feasibility of a new process. For market testing, large quantities of the new product may be necessary, in which case they could not be supplied from pilot plant output.

[27] Zimmerman, op. cit., p. 311.

[28] See, for example, Peters, op. cit., Williams, op. cit. (1972, 1973), and Zimmerman, op. cit.

[29] Unfortunately, no empirical investigations of cost estimation accuracy in pioneer process plants have been published. Discussions with industry suggest that inaccuracy is common, especially for early estimates. This accords with findings reported in Secs. II and III above as well as for energy process plants.

There are several possible reasons for the deficit in the literature. The first is obvious: pioneer plant data are proprietary in most cases so that a data base is difficult to assemble within the industry. Second, whenever a project seriously overruns, the causes of the plants are more subject to estimation errors than more standard plants is obvious: *ceteris paribus,* less is known about first-of-a-kind processes. This translates into all of the factors mentioned above—scope change, design change, and inadequate product specifications—being more likely to operate in the case of pioneer plants than standard plants.

## Estimation Methodology and Practice

Methods for estimating the capital costs of process plants have evolved considerably during the past 20 years. Use of the computer has become commonplace not only for information storage and retrieval but also to undertake complex statistical analyses of equipment costing[30] and venture profitability.[31] Nonetheless, a number of problem areas exist.

First, it is critical to match the methodology employed to the information base available. As discussed above, the amount of information available is first and foremost a function of how far the project has progressed when the estimate is made. A very carefully implemented, time-consuming, and therefore costly estimate based upon highly uncertain plant characteristics will result in an estimate that is little better in terms of real confidence range than an initial estimate performed quickly, but may be subject to misinterpretation as a hard estimate.[32]

Initial estimates even with wide ranges of uncertainty may be subject to major reliability problems.[33] This is especially true for any plant that does not lie close to the "duplicate" end of the technological change continuum.[34] For "repeat plants," of course, one may have the advantage of actual cost data, in which case a "quickie" estimate may be both reliable and accurate. But if good data are not available on the

---

overrun are investigated and the causes found. Once found, those particular reasons for an overrun will not likely be repeated by the estimating firm for similar plants. The difficulty is that the next pioneer plant will often not have the same potential difficulties, but a new set dissimilar except in an abstract way from previous plants. Because the causes of cost overrun are seen as being either unique to a plant or tied to some exogenous factor such as inflation, there is little incentive to aggregate the data in order to search for underlying factors that influence cost in a systematic way.

[30] For example, see John W. Hackney, "Some Practical Aspects of Regression Analysis of Cost Data," paper presented at AACE meeting, July 1967.

[31] Edward G. Ward, "Evaluation of Risk in New Capital Projects," paper presented at AACE meetings, 1969.

[32] See E. W. Merrow, *Constraints on the Commercialization of Oil Shale,* The Rand Corporation, R-2293-DOE, September 1978, Sec. II, for an extended discussion of this problem.

[33] W. O. King, "Abolish the Quick Estimate," *AACE Bulletin* 6 (2), 1964.

[34] Williams, 1972, op. cit., p. 178.

previous plant, or if considerable time has elapsed, or if local conditions are different, problems may arise.

**Problems with Ratio Methods.** As discussed above, initial and preliminary estimates are generally prepared using some form of ratio-estimating methodology. Initial estimates are often developed from a simple cost-capacity relationship, such as the six-tenths rule mentioned above. Use of the six-tenths rule, however, is quite risky when the scale-up (or down) is large. Table 4.2 illustrates the error that can be introduced into an estimate if the six-tenths factor is used inappropriately. If, for example, a 0.6 factor—considered the "norm" for chemical process plants—is used when the actual factor is 0.9 and the scale-up factor is 10, plant costs will be underestimated by 50 percent. Measured cost-capacity factors vary from 0.33 to 1.39, but average about 0.6.[35] The variations are usually attributed to differences in plant type,[36] but at least part of the observed variation in cost-capacity factors is undoubtedly due to the fact that factors other than size affect costs.

Table 4.2

POTENTIAL ERROR FROM USE OF SIX-TENTHS COST-CAPACITY FACTOR

| | Actual Cost-Capacity Factor | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
| | Percent Error | | | | | | | | |
| Scale-up x 5 | +89 | +61 | +37 | +17 | 0 | -16 | -28 | -39 | -48 |
| Scale-up x 10 | +150 | +100 | +59 | +26 | 0 | -21 | -37 | -50 | -60 |

SOURCE: Zimmerman, op. cit., p. 311.

Other ratio methods—equipment installation ratios, plant cost ratios, and plant component ratios, can suffer analogous problems. *Every empirically derived multiplier is in fact a probability distribution rather than a single point, so that expected costs should be expressed as a range.* To assign a reasonable confidence interval, one must know not only what the distribution is, but what the confidence interval is

---

[35] Cecil H. Chilton, "Six-Tenths Factor Applies to Complete Plant Costs," *Chemical Engineering*.

[36] See ibid., and Zimmerman, op. cit.

around the base number—usually equipment costs—to which the factor will be applied. Distributions are usually assumed to be normal, but Williams suggests that at least for plant cost ratios, this is not the case,[37] and Zimmerman shows that equipment installation factors and plant component factors have very wide ranges.[38]

It should be clear why ratio methods are more likely to lead to serious misestimation for pioneer plants than for more standard plants. Ratio methods are predicated upon the assumption that past experience is an accurate guide to the costs of the next plant. By definition, the more innovative a plant is, the less it will follow prior experience.

**Incomplete Estimates.** Most initial estimates and some preliminary estimates are confined to the "battery limits" of the plant. The battery limits are the basic process portion of the plant (i.e., from the point that the raw materials enter the process until the final product first emerges). Not included are utilities, nonprocess buildings, access roads, raw material and product transportation facilities, and many other cost items such as engineering, purchase, or personnel costs, overhead and the like. Then, if total capital investment is desired, either a factor or a cursory estimate of the balance of plant costs can be made. This procedure may introduce significant error into the estimate. The battery limits cost of a process plant may be less than one-half of total capital investment. While the balance of plant costs are generally considered standard, easy-to-estimate items, surprises can and do occur that upset the estimates even for standard plants. Examples mentioned in discussions with industry estimators are the need to provide rather than buy utility services, the need for unanticipated access roads, and the need to provide waste treatment facilities.

**Difficult-to-Estimate Items.** The state of the art of estimation methodology is not consistent across all aspects of a process plant. In the past decade considerable progress has been made in estimating the cost of specially fabricated major equipment, in maintaining up-to-date cost lists, and in effective estimates of project scheduling and engineering costs. Several areas, however, are particularly hard to estimate, the most important of which are piping, valves, and instrumentation (PVI), and items requiring field fabrication.

PVI and field fabricated items are difficult to estimate accurately even at the definitive design stage. There are several related reasons for the difficulty. First, these items are frequently unique to a particular plant, even if the plant is quite similar in most respects to a previous plant. Slight changes in plant layout can require significant changes in PVI. Second, PVI and field fabrication are not subject to the kind of

---

[37] Williams, 1972, op. cit., p. 178.

[38] Zimmerman, op. cit., pp. 312-315, 318.

cost and quality control obtainable in the shop. Both are very dependent on the quality of the labor pool for the plant's construction.

A more interesting question is why these difficult-to-estimate items should give rise to a low bias in many estimates. On the basis of discussions with industry cost estimators, we hypothesize that the reason for low bias is the manner in which uncertainty is treated in estimation. The cost estimator forecasts costs for items that he can see, define, and unitize. When uncertainty is known to exist, this is usually expressed by a confidence interval. But the estimator has to document and justify each element in his analysis, especially as the project progresses beyond the preliminary estimate. To adjust the midpoint of an estimate for PVI upwards by some percentage is difficult to justify in the absence of clearly relevant historical data. If the data for a contingency do not exist, then it is unlikely that the contingency will be added to the particular item. Cost estimation supervisors are careful not to allow contingencies to be added for individual items without justification because of the danger that contingencies would be piled upon contingencies, making any project unattractive or the architect-engineering firm's bid noncompetitive.

## Project Management

This section discusses how process plants are organized and managed, and reviews key problems and principles of effective project management mentioned by people in the industry.

**Organizational Arrangements.** As outlined at the beginning of this section, a process plant project moves through a series of stages: research and development for a pioneer plant or design and engineering for a standard plant, followed by detailed engineering, construction, start-up, and finally, commercial operation. Companies vary enormously in the degree to which they themselves perform these steps or assign them to outside contractors; and the relationships between contractors working on the same project also vary. At one extreme, a few large companies use their own personnel to perform every step from research and development through operation (ownership), for at least some plants. At the other extreme, a company may do no more than supply the capital and take possession of an operational plant. Each step along the way may have been performed by a separate firm. In many cases, an architect-engineering or process development firm develops and markets a new process design, and serves as main contractor for the project. Sometimes specialized construction management firms are hired to supervise construction performed by yet another firm. This variety of practices is good evidence that no one holds a clear comparative advantage in the market.

In general, however, it appears that pioneer plant projects are less likely to involve a large number of separate firms than are standard plant projects. One important reason is that the "hand-off" problem is more severe for innovative projects. "Hand-off" is the transfer of responsibility for a project from one stage and group of specialists to another. It is commonly believed that hand-off is easier when the groups of specialists work for the same organization. A hand-off failure occurs when essential project information is lost or distorted during this process. All process plant projects are subject to difficulty in making the transition from engineering to construction and from start-up to operation. In the first case, the problem is to translate a set of designers' drawings into a physical plant. Accuracy is achieved by having design engineering personnel present during all phases of construction, constantly monitoring the match between the drawing and the work. In the second case, the problem is to educate the operators, who must understand the functioning of the plant well enough to operate it efficiently and deal with malfunctions. An incorrect response to an operating problem can seriously damage equipment and catalysts in many process plants.[39] The usual practice is to involve key operating personnel in the project as early as the design stage.

Pioneer plants ordinarily have more difficulty with both hand-offs than do standard plants, because less is known about a pioneer plant at each project stage. The pioneer plant has a third difficult hand-off that standard plants do not confront: the transition from research and development to engineering. The transition from the laboratory to successful project definition by a design staff is a formidable hurdle. Process ideas, tested under very restricted conditions, have to be translated into a plan for a plant that may be several thousand times the size of the process development unit or pilot plant. Teamwork between research and development and engineering is essential for pioneer plants; in some cases, the research and development team remains with a project through start-up.

**Management Principles.** Two management principles recur in the process plant project literature:

- The invariant need for a single project manager with overall responsibility for the project's success.
- The quality and experience of a few key personnel.[40]

---

[39] See Gans and Fitzgerald, op. cit.

[40] For extended discussions, see Russel G. Hill, "Project Engineering and Management," in Landau, op. cit., and Hackney, op. cit., Chapters 22-24.

The project manager is usually drawn from the staff of the purchasing firm, but may be appointed by the architect-engineering contractor in cases of turnkey contracts. The manager almost always has complete responsibility for directing the project from design through start-up. There are obvious advantages to having a single project manager instead of a manager for each stage or a committee management. A succession of managers would be hard put to execute hand-offs effectively. Conflicts over authority at the transition stages would be very likely. In addition, the concurrent design-and-construct strategies employed for most projects ensure that the project has more than one manager at certain points. A committee management system is even more frowned upon in the literature. Timely decisions are particularly important for a project once detailed design has begun, and committees are notorious for being unable to make decisions rapidly.

The other management variable often cited as important is the quality and experience of key project personnel. Key personnel are usually the project manager, the chief design engineer, the construction supervisor, and the chief operating engineer who supervises startup.[41] In the case of a pioneer plant, the research and development team leader is an important figure who may remain with the project throughout.

That the quality of project management can and does routinely affect ultimate project costs is widely assumed. Unfortunately, no studies have even attempted a quantitative analysis of management effects on process plant costs. Factors such as personnel experience and continuity could be included in an examination of estimation error, as discussed in Section V below.

## Exogenous 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 cost and delivery date, one would wish to adjust the figures to remove exogenous factors, at least for some purposes.

**Inflation.** There are two components to cost-inflation in chemical process plants: inflation of the dollar, and real increases in the costs of constructing a process plant. For the past decade, the inflation in plant construction has generally exceeded overall inflation by one or two percent. Inflation can affect cost estimates in two ways. First, unan-

---

[41] Gans and Fitzgerald, op. cit.

ticipated inflation (i.e., inflation that is not assumed in the cost estimates) will increase the nominal dollar costs of the plant. The relationship of plant construction costs to general inflation during the period between estimation and actual costs may reflect an increase in real cost as well. Second, differential inflation can lead to estimation error. Most initial and preliminary estimates are based on ratio methods, which prior rapid inflation may have rendered invalid. For example, if one is using major equipment installation ratios, then greater inflation in equipment costs than in labor costs will necessitate a downward revision of the ratio to obtain an accurate installed-cost figure. Conversely, relative increases in labor costs will entail an upward revision. If prices have been changing rapidly, the information necessary for revising the ratios will probably not be available for a time. This is particularly true if the inflation is concentrated in equipment items, because process plant construction price indices are relatively insensitive to short-term equipment price changes.

**Regulatory Standards.** Since the beginning of the 1970s, changes in environmental and safety regulations imposed by all levels of government have become an important cause of added capital cost and low bias in cost estimates for the chemical and oil industries.[42] If a standard is already in effect when a plant is designed and estimated, but the costs of meeting it are misestimated, the fault lies with an endogenous plant and process factor (a design and/or estimation failure); it is not an exogenous perturbation of costs. But when standards change after an estimate is made, project personnel cannot be faulted justifiably.

**Other Exogenous Factors.** Other exogenous factors include bad weather, labor strikes, and failure of a vendor to deliver pacing equipment items as promised. If construction is well under way, such factors can inflict serious cost increases that estimators could not reasonably be expected to anticipate.

## SUMMARY AND CONCLUSIONS

Cost estimating difficulties in chemical process plants are directly relevant to the Department of Energy's problems in accurately estimating the costs of energy process plants. Although energy process plants are expected to be considerably larger than even the largest chemical plants, many in the chemical industry see few differences in principle between the types of plants and the estimation problems that arise.

Unfortunately, at the present time less information about the fre-

---

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

quency and magnitude of cost estimation errors is available for chemical process plants than for either major weapons systems or public works projects. Despite the lack of "hard" data, a number of conclusions can be drawn from discussions with industry, the anecdotal literature and works on estimation methodology.

Capital cost estimation errors are a persistent and serious problem for the process industries. No two projects are ever exactly the same, even if the same process technology is being employed. The differences will usually have implications for capital costs that are impossible to forecast with perfect precision.

The most important factor causing estimation error in constant dollar terms appears to be the level of process and project definition when an estimate is made. Process definition—the degree to which the technical characteristics of a plant are known—depends in turn upon the extent to which a proposed plant will depart from previously used technology. The level of project definition is the extent to which a particular plant in a particular time and place have been defined when an estimate is made. A low level of project definition can cause significant estimation error even in standard plants.

While cost estimation methodology has clearly become more sophisticated over the past 20 years or so, there is little to indicate that it has become more successful. Process plants have become progressively more complex over time, and exogenous factors such as escalation in construction costs, materials and services shortages, and continuing changes in environmental, health, and safety regulations have conspired to make capital cost estimation more difficult.

A few major chemical and oil firms have begun to augment cost estimation techniques based upon engineering designs with statistical approaches similar to that being developed in this study. The general acceptance of statistical approaches to cost estimation will depend, obviously, upon demonstration of their usefulness. In any case, smaller firms and firms with a narrow range of historical experience in estimation will have difficulty obtaining sufficient data to employ statistical models of cost estimation error.

# V. CONCLUSIONS AND IMPLICATIONS

This report has reviewed cost estimation problems in four areas: major weapons systems, public works and large construction projects, energy process plants, and chemical process plants. Statistical findings in the first three areas and anecdotal evidence in the last suggest that difficulties in estimating the capital costs of major projects are widespread, and in at least some areas pose serious problems for decisionmakers, both public and private. Despite wide differences in the items estimated and in market structures, the empirical findings are similar in important respects: Capital cost estimates tend to display a low bias, and there is considerable variance in the cost estimation errors. In addition, cost estimates for first-of-a-kind or one-of-a-kind systems display greater bias and variability than do estimates for more standard systems. Table 5.1 allows a comparison of cost estimate errors in the various areas covered in this report.

The importance of whether a system involves new technology or nonstandard design has been demonstrated for weapons systems: The apparent improvement in cost estimation between 1950s and 1960s systems is accounted for by lower levels of technological advance and shorter program duration for 1960s systems.[1] The effect of incorporating new technology or nonstandard designs in other areas can only be inferred. In the public works category, "ad hoc projects" were mostly first-of-a-kind or one-of-a-kind projects and exhibited a large cost-growth factor. All of the major construction projects surveyed by Mead[2] were in that category. Finally, all of the energy process plants that we have surveyed are pioneer plant projects.

## COMMON ELEMENTS IN COST ESTIMATION ERROR

Given the similarities in the results, it is not surprising to find that many of the same factors were cited as sources of cost estimation difficulties in all areas reviewed. The factors can be usefully (if not precisely) divided into two categories: factors that change costs, and factors that affect estimation accuracy.

---

[1] Robert Perry et. al., *System Acquisition Strategies,* The Rand Corporation, R-733-PR/ARPA, June 1971, p. 14.

[2] See Sec. II. Unfortunately, Mead's sample selection criteria are not known.

## Table 5.1

### SUMMARY OF COST ESTIMATING EXPERIENCE

| Items Estimated | Mean of Actual to Estimated Cost | N | Standard Deviation |
|---|---|---|---|
| Weapons, 1950s | 1.89 | 55 | 1.36 |
| Weapons, 1960s | 1.40 | 25 | .39 |
| Public works | | | |
| Highway | 1.26 | 49 | .63 |
| Water projects | 1.39 | 49 | .70 |
| Building | 1.63 | 59 | .83 |
| Ad hoc | 2.14 | 15 | 1.36 |
| Major construction | 2.18 | 12 | 1.59 |
| Energy process plants | 2.53 | 10 | .51[a] |

SOURCES: *For weapons:* R. L. Perry et al., *System Acquisition Strategies*, The Rand Corporation, R-733-PR/ARPA, June 1971, pp. 6, 11.

*For public works:* L. Merewitz, "Cost Overruns in Public Works with Special Reference to Urban Rapid Transit Projects," Working Paper No. 196/BART 8, Institute of Urban and Regional Development, University of California, Berkeley, 1972, p. 35.

*For major construction:* W. J. Mead, with G. W. Rogers and R.Z. Smith, *Transporting Natural Gas from the Arctic*, American Enterprise Institute for Public Policy Research, Washington, D.C., 1977, pp. 88-89.

*For energy process plants:* Data reported in Sec. I and the appendix to this report. Because so few energy process plants have been constructed, the mean and standard deviation were calculated on the basis of the inflation-adjusted ratio of the last available estimate to the first available estimate. This probably results in a significant understating of the mean for these plants.

[a] It is unknown how the standard deviation is affected by using the ratio of the last available estimate to the first available estimate instead of actual to originally estimated costs.

## Factors that Change Costs

This report has focused on cost estimation difficulties. Discrepancies between estimated and actual costs, however, are not explainable solely by the quality of the estimating method. Even the best executed estimates must make assumptions about the state of the world as it affects project costs, and about the quality of project management.

The following factors are mentioned most often in the literature as those that drive up the costs of major capital projects:

- *Externally imposed scope changes.* The buyer "changes his mind" about the size, characteristics, or numbers of an item being produced. Scope changes are more common for long projects because they allow more time for such changes and greater probability that the buyer's needs will change. In some cases, especially for process plants, repeated scope changes reflect management deficiency. Numerous scope changes cost more than any benefits that can be reasonably expected. The later "freezing" of design caused by repeated scope changes is widely believed to cause higher than necessary costs.
- *Deviations from the "appropriate" schedule.* Presumably, every project has an optimal schedule. While the relationship between long schedules and schedule slippages and cost increases has been established in some areas, the relationship between overly tight, compressed schedules and increased cost is difficult to establish for methodological reasons. Logic and anecdotes, however, strongly suggest that compressed schedules can cause both higher cost and poor system performance.
- *Management and organization.* A number of management-related factors have been cited as reasons for increased costs. The one mentioned most prominently in the process plant literature is diffuse decisionmaking responsibility for a project. It is part of the general wisdom for major construction projects that one person needs to be given broad authority for all routine project decisions and a reasonable scope for fairly important decisions on schedules, allocation of monies, and all but major modifications.

  The logic behind the conventional wisdom is compelling. Any major process plant, and especially one that incorporates new technology, is a complex and highly integrated undertaking. A large number of decisions must be made, made on a timely basis, and made in light of how the decision will affect other items in the critical path for the project. Standard industry practice is to appoint a project manager—in the case of a pioneer plant project, a project manager of long experience—who is responsible for the undertaking from shortly after the time that the project emerges from development until an operating plant is on-line. Top management's role is to ensure that careful preparation for the project was done initially, and to review the project at a few established checkpoints. Frequent review or top management intervention in project decisions is widely believed to increase the costs of the project significantly. When joint venture or consortia arrangements are used to finance the construction of a plant, it is common practice to designate one company as the "lead" and appoint a project manager from that company.

If the conventional wisdom is correct, it has some important implications for DOE's approach to pilot, demonstration, or first commercial plant projects funded by the government in conjunction with the private sector. First, careful initial planning and review for a project should substitute for direct involvement in project decisionmaking when private sector firms manage a project. Second, if the government will for whatever reasons be intimately involved in project level decisions, it is probably better to acknowledge that fact by making DOE the "lead" partner, and appointing a project manager who is responsible to DOE.

- *Exogenous factors.* A large number of factors outside the control of project management can increase costs over original estimates, e.g., greater than anticipated escalation; shortages of labor, materials, and services; and changes in various regulatory standards. Although some factors are consistently cited as sources of increased costs, with the exception of escalation, there is little quantitative information to gauge the effect of exogenous factors.[3]

## Factors that Affect Estimation Accuracy

The principal factor cited as a source of error in cost estimation is the degree of definition for the project's scope and design. Changes in scope have been a constant source of estimation error for weapons programs, especially those of long duration. Many such changes are due to the purchaser's effort to improve the size, quality, or number of items

---

[3] Studies to quantitatively assess the costs of regulatory changes on chemical plant costs have been recently begun by industry groups. See, for example, "Cost of Federal Rules to Firms Detailed," *Chemical and Engineering News,* March 26, 1976, p. 6.

to be delivered. The changes may vitiate the earlier estimates but do not reflect their quality. Many other changes are required, however, because the system envisioned cannot be effectively produced at the scope initially specified. This commonly occurs for a pioneer technology before system design parameters have been worked out. For process plant technologies, such parameters include the heat and materials balances for the plant, process conditions, and knowledge of the major equipment items. In addition, large increases in estimates are often associated with *project* as well as *process* definition. Project definition refers to the development of specific plans for a plant at a particular site, governed by a particular schedule.

Another factor mentioned frequently in weapons acquisition and occasionally in other government purchases is deliberate misestimation of costs—usually underestimation. Discussions with planners and engineers in the chemical and oil industry reveal that for process plants such deliberate underestimation (or at best excessive optimism and enthusiasm) is most often associated with process developers' claims for new systems. A number of industry officials have also stated that unless discipline and monitoring are maintained, plain sloppy cost estimates can occasionally sneak through. As noted in Sec. II, there is some evidence of deliberate underestimation of costs for weapons systems; but even in those cases, technical uncertainty was a more important factor in total cost growth.

## IMPLICATIONS FOR DOE

All of the factors cited in this report as contributors to estimation inaccuracy can be grouped conceptually as the results of uncertainty. This is true not only for actual uncertainties (e.g., about scope, design basis, new equipment items, etc.) but also for problems of deliberate misestimation of costs and for sloppiness. In the absence of uncertainty, any incentives to understate costs are vitiated unless they motivate *both* seller and buyer. Sloppiness in estimation is not only less likely (because the task itself is easier) when uncertainty is low, but is also much more likely to be quickly recognized and corrected.

Most of the cost estimates that must be used by DOE planners and managers, however, will of necessity be based upon somewhat uncertain system designs, unproven processes, and in some cases upon major development events that may or may not occur. Under such circumstances, DOE planners might adopt the following principle in considering cost estimates:

- *Optimism tends to expand to fill the scope available for its exercise.*

The scope for optimism is a function not only of the uncertainties associated with the technology, but the incentives on the part of process developers, potential operating companies, and DOE program managers to obtain accurate estimates. If it is not possible to penalize inaccurate estimation, or if inaccuracy is actually rewarded, the scope for optimism increases. The ability to penalize for inaccurate estimation is largely a function of how far into the future a technology's commercial readiness lies. In addition, the ability to bestow appropriate reward for accurate estimation requires being able to distinguish among deliberate misestimation and sloppiness, the effects of poor management, exogenous factors, and inadequacies in the estimating state of the art for new technologies.

In these circumstances, what options are or might be made available to DOE to cope with uncertainty? The following three approaches, which are not completely mutually exclusive, are suggested with the knowledge that DOE is already beginning to implement some of them, at least in part:

- *Downplay the importance of or disregard cost estimates* when the uncertainties surrounding the technology are very high. The initial estimates for energy process plants discussed in Sec. I and the Appendix were so inaccurate as to be worthless in the absence of methods to adjust them. A "confidence interval" of +50 percent to +400 percent offers no guidance for decisionmaking. Furthermore, treating such early estimates as if they were even roughly accurate guides to system cost is probably more misleading than ignoring costs altogether. If early estimates are to be disregarded, R&D allocation decisions will have to be made by other criteria, such as the theoretical energy-conversion efficiencies for the technology, the resource base employed, and perhaps environmental or institutional factors. Such factors already play an important role for technologies that are seen as being far in the future and are included along with cost in more near-term technologies. Given the importance of cost, there is an understandable desire to include it as the central criterion as quickly as feasible. When uncertainty is very high, however, there is the danger that a cost estimation will engender false hopes and inappropriate R&D allocation decisions.

A distressing feature of the estimates for energy process plants discussed in Sec. I is that many of the technologies were at an advanced stage of technical development when estimates were made—estimates that in many cases turned out to be well over 100 percent too low. This strongly suggests that factors other than technical feasibility and pilot plant experience must be employed when assessing the uncertainty in an estimate.

- *Attempt to control the scope for optimism.* A number of operating chemical companies and architect-engineering firms with whom we have discussed cost estimation problems for process plants have adopted standards and procedures to help control both enthusiasm and carelessness on the part of process developers and cost estimators both within and without their firms. Such procedures include standard quality requirements for the scope, process, and project definitions underlying an estimate; standards for the completeness and thoroughness of estimates; and the use of independent consultants to review process design and/or cost estimates. A number of companies employ such means in conjunction with complete or partial disregard of estimates made early in R&D. Attempting to check excessive optimism, while undoubtedly useful, is no panacea. Such checks work best when they are least needed, i.e., when technical uncertainties are fairly low.
- *Adjust for uncertainties.* Most process plant cost estimates, and all such estimates for plants involving significant amounts of new technology, include contingencies intended to cover the costs of unforeseen problems. Such contingencies rarely exceed 30 percent of total plant cost and are generally in the range of 10 to 20 percent. Such routine contingencies clearly do not begin to cope with the kind of uncertainty seen in many energy process plant cost estimates.

At present, the weights of different factors that cause error in early cost estimates for new energy process plant technologies are not understood well enough to enable estimators to debias the estimates or to place a confidence interval around them. In other words, it is currently possible to distinguish between an estimate to which normal engineering confidence intervals should apply (i.e., a standard technology) and one to which such intervals cannot be expected to apply. There is insufficient knowledge, however, to distinguish between a technology that will ultimately increase 100 percent in cost and one that will increase 400 percent in cost from the same estimating stage. The current

> study of which this report is the first publicly available product is directed toward developing empirically the information necessary to categorize and, if possible, place statistical confidence intervals around the expected cost growth for new energy process technologies. The required data are being acquired through the cooperation of chemical, oil, and architect-engineering firms.

It is our hope that the results of this effort will provide some fresh insights for both DOE and industry into uncertainties in cost estimation for new process plant technologies.

# APPENDIX: COST GROWTH IN ENERGY PROCESS PLANTS

This appendix presents capital cost estimates made at different stages of project development for 10 pioneer ("first-of-a-kind") energy process plants. The purpose of gathering these data is to illustrate the phenomenon of cost growth, i.e., increases in estimated capital costs, as energy projects progress from early conceptual stages through design and construction.

## SELECTION CRITERIA

The following criteria guided the choice of plants included in this report:

- Actual or proposed projects were included, rather than technologies. For example, the report includes the Colony Development Operation's proposed plant at Parachute Creek, Colorado, but excludes estimates for a *hypothetical* TOSCO II surface oil shale plant. This criterion was employed because we wished to trace cost growth from conceptual stages toward actual plant construction, rather than being limited to precommercial design estimates.
- Published data had to be available for three or more estimates made at different stages of project development. Three data points per plant were felt to be the minimum necessary to establish a pattern for a plant. Only publicly available data could be used, because plants are identified.

## METHODS AND DEFINITIONS

Data were assembled from published sources. Whenever possible, we then discussed the data by telephone with one or more project officers of the plant-purchasing firm or its architect-engineering firm to check the accuracy of the estimates and the stage of project design when the estimates were made. In a few cases, estimates were adjusted to a uniform plant scope, and in a few others it was not possible to check the accuracy of an estimate. All estimates are reported in 1978 dollars using the GNP price deflator,[1] a practice that understates the cost growth actually experienced in some cases. This occurs whenever the estimates assume an inflation rate rather than a "build today, operate today" basis. In such cases the proper adjustment is not for inflation, but for *unanticipated* inflation. Unfortunately, only in a few cases do we know whether an inflation rate was assumed in the estimates.

Estimates are placed into categories according to the stage of project development and commercial design at which the estimates were completed. The types of estimates employed are defined as follows:[2]

- *Initial estimates* are based on engineering concepts rather than a commercial design. They rarely if ever are based upon conditions at a particular site and are sometimes based upon a scope significantly different from that of the plant actually designed and constructed. In most cases the scope in the initial estimate was the same as that for the commercial design.
- The *preliminary estimate* is made after design for the plant has begun. Plant scope and basic layout including major equipment are set, and design is generally 5 to 10 percent complete. The preliminary estimate is also known as a "phase I authorization" or "factored" estimate.
- The *budget* (or control) *estimate,* also known as the "phase II authorization," is generally made when design is at least 30 percent and usually 50 percent complete. When the budget estimate is made late in design (50 percent to 70 percent complete), it may be the last formal estimate for a project. It will then be refined as engineering is completed and construction begins.
- The *definitive* estimate is made when project design and engineering are 90 to 100 percent complete. Site preparation and possibly even construction may have begun on the plant when the definitive estimate is complete.
- *Actual costs* are reported capital costs when the plant is started up.
- In a few cases we have added a sixth category—"*Add-on.*" These are estimated additional capital costs necessary for the plant to operate as expected or necessary to meet regulatory requirements.

---

[1] We considered it inappropriate to use a construction price index such as the Handy-Whitman or Du Pont Index, because changes in real (i.e., constant dollar) construction costs are a causal factor in cost growth.

[2] See Sec. IV for discussion.

## INTERPRETING THE DATA

Table A.1 presents the data for the plants. In some cases more than one cost estimate is given within a particular estimate category; this is because an estimate may be updated subsequently to reflect input price changes and better design information, without constituting a new estimate type.

The data suggest (but only suggest) one of several potentially important explanatory variables: improved estimates due to increased design detail. In some cases we are confident that other equally important factors were at work. For example, in the Barnwell nuclear fuel reprocessing plant, changes in regulatory standards had a major impact on costs, and labor productivity was less than expected. The GE reprocessing plant saw an attempt to substantially and rapidly advance the technological state of the art.[3] In the coal gasification and surface oil shale plants, for which we have conducted thorough analyses,[4] real increases in construction costs and changes in environmental standards contributed to cost growth along with improved design and engineering information. We caution, therefore, that although these data strongly suggest that early capital cost estimates may be sharply biased low, *one cannot conclude with confidence what factors contributed to the bias* nor why some plants were subject to much greater cost growth than others.

For the plants in Table A.1, the estimates tend to increase as the development projects progress. Attempts to describe this behavior with mathematical functions can be based on the general functional form:

$$C_a = f(C_e, t). \qquad (1)$$

Specifically, actual costs, $C_a$ are described as a function of estimated costs, $C_e$, where cost estimates approach actual costs as the project progresses from its inception ($t = 0$) toward completion ($t = n$). The estimates improve because information on the product or process increases as engineering progresses beyond the initial phase, through preliminary, budget, and detailed design. As development proceeds, the product takes on progressively greater detail, and technical problems are uncovered and dealt with.

Many mathematical functions could be used to describe cost estimate behavior, but currently none stands out as the most desirable or most representative of the real world. One function, however, is easy

---

[3] See R. Gillette, "Nuclear Fuel Reprocessing," *Science* 185, August 1974, for a discussion of the attempt to advance the technology rapidly.

[4] W. F. Hederman, *Prospects for the Commercialization of High-BTU Coal Gasification,* The Rand Corporation, R-2294-DOE, April 1978; and E. W. Merrow, *Constraints on the Commercialization of Oil Shale,* The Rand Corporation, R-2293-DOE, October 1978.

# Table A.1

## Cost Estimate Data for Energy Process Plants

## (In million 1978)

| Plant | Estimate Type |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Initial |  | Preliminary |  | Budget |  | Definitive |  | Actual |  | Add-on |  |
|  | Year[a] | $ | Year | $ | Year | $ | Year | $ | Year | $ | Year | $ |
| Midwest Reprocessing | 1967 | $37.7^{1}$ | 1968 | $65.2^{2}$ |  |  |  |  | 1974 | $97.1^{2}$ | 1974 | $117\text{-}169^{2}$ |
| Barnwell Reprocessing |  |  | 1968 | $127^{3}$ | 1972 | $152^{3}$ | 1974 | $283^{3}$ | 1976 | $400^{3}$ | 1976 | $567^{4}$ |
| Solid Waste |  |  | 1973 | $23.0^{5}$ |  |  | 1974 | $26.0^{6}$ | 1975 | $27.4^{7}$ | 1977 | $12.8^{8}$ |
| Colony Oil Shale | 1972 | $379^{9}$ | 1973 | $583^{10}$ | 1974 | $721^{10}$ | 1978 | $925^{10}$ |  |  |  |  |
| Occidental Oil Shale | 1975 | $204\text{-}272^{11}$ | 1977 | $473^{12}$ | 1978 | $650^{13}$ | 1978 | $800^{14}$ |  |  |  |  |
| WESCO SNG |  |  | 1973<br>1974<br>1975 | $583^{15}$<br>$582^{15}$<br>$1017^{15}$ | 1976<br>1977 | $1361^{16}$<br>$1390^{17}$ |  |  |  |  |  |  |
| El Paso SNG | 1971 | $392^{15}$ | 1972<br>1973 | $536^{15}$<br>$706^{15}$ | 1975 | $1191^{15}$ |  |  |  |  |  |  |
| Syncrude Oil Sands | 1971<br>1973 | $784^{18}$<br>$1106^{19}$ | 1973 | $1437^{20}$ | 1974 | $1953^{21}$ | 1974 | $2384^{22}$ | 1978 | $2170^{23}$ |  |  |
| Great Plains SNG | 1974 | $482^{24}$ | 1975<br>1975 | $588^{25}$<br>$602^{26}$ |  |  | 1978 | $890^{27}$ |  |  |  |  |
| Shell Canada Oil Sands | 1973 | $1006^{19}$ | 1974<br>1976<br>1978 | $2604^{28}$<br>$3401^{29}$<br>$2900^{30}$ |  |  |  |  |  |  |  |  |

SOURCES: References to Table A.1 are found on p. 109. The superscript beside each estimate refers to the number of the reference.

[a] Indicates year in which estimate was made. All costs are adjusted to 1978$ basis.

# Table A.1—continued

## REFERENCES TO TABLE A.1

1. B. Wolfe and R. Lambert, "The Back End of the Fuel Cycle," n.d., General Electric Company, San Jose, California.

2. R. Gillette, "Nuclear Fuel Reprocessing," *Science*, Vol. 185, August 1974.

3. Data supplied by company.

4. J. A. Buckham, "Why Reprocess Nuclear Fuels?," *Chemical Engineering Progress*, Vol. 71, No. 3, pp. 21ff.

5. U.S. Environmental Protection Agency, *Baltimore Demonstrates Gas Pyrolysis*, EPA/530/SW-75.i, 1974.

6. Ibid., update, 1975.

7. E. Zulver and E. Stewart, "A Full Scale Refuse System for Baltimore, Maryland," paper presented at First International Conversion of Refuse to Energy Conference, Montreux, Switzerland, November 1975.

8. B. Peterson, "Baltimore's Trash Plant is Costly Failure," *Washington Post*, March 20, 1977.

9. J. A. Whitcombe, "Oil Shale Development: Status and Prospects," *Journal of Petroleum Technology*, January 1976, pp. 16-20.

10. Synthetic Crude and Minerals Division, Atlantic Richfield Company, Los Angeles, California.
    Only the capital construction costs for the mine and other on-site facilities that were the responsibility of the A/E are included in these estimates.

11. *Petroleum Economist*, July 1975. Based on early pilot plant work on DA shale property. Adjusted by straight line extrapolation from 50K b/D.

12. *Modified Detailed Development Plan for Tract C-b*, Ashland Oil Co. and Occidental Petroleum Co., 1977.

13. *Oil and Gas Journal*, 1978. Estimate and design basis checked with company.

14. Company announcement, January 1979.

15. Comptroller General of the United States, *Status and Obstacles to Commercialization of Coal Liquefaction and Gasification: Report to State Committee on Public Works*, May 5, 1976.

# Table A.1—continued

16. "Synfuels Development in U.S. Dealt New Setback," *Oil and Gas Journal*, October 4, 1976.

17. "Navajos Reject WESCO SNG Offer," *Oil and Gas Journal*, March 6, 1978.

18. Robert T. Tippee, "Tar Sands, Heavy-Oil Push Building Rapidly in Canada," *Oil and Gas Journal*, January 30, 1978, pp. 87-91.

19. "Shell Tar-Sand Profits Tied to Better Prices," *Oil and Gas Journal*, September 10, 1973, p. 52.

20. "Syncrude Clears Tax Hurdle to Building of Tar-Sands Plant," *Oil and Gas Journal*, December 17, 1973, p. 23.

21. "Cost of Shell Tar-Sands Plant Triples," *Oil and Gas Journal*, December 3, 1974, p. 47.

22. "Syncrude Slows Tar-Sand Work While Hunting for New Partner," *Oil and Gas Journal*, January 13, 1975, p. 20.

23. "Syncrude's Tar-Sands Plant Going on Stream in Alberta," *Oil and Gas Journal*, July 3, 1978, pp. 51-74.

24. Federal Power Commission: ANR Gasification Properties Co. and PGC Coal Gasification Co., Docket No. CP75-278, et al., Exhibit No. REB-1. [This estimate was adjusted from an estimate for a 275 MM cfd plant. According to project personnel, the plant has few economies of scale except for oxygen production. Therefore, a 0.9 exponent was used to extrapolate the cost. In addition, power generation costs of $42 million were subtracted from the estimate to achieve comparability with later estimates.]

25. Ibid., Exhibit No. REB-12. [Power generation costs of $45 million were subtracted.]

26. Ibid., Exhibit No. REB-18.

27. Federal Energy Regulatory Commission: Great Plains Gasification Associates, successor to ANR Gasification Properties Co. and PGC Coal Gasification Co., et al., Docket No. OP-S-391, et al., Exhibit No. REB-21.

28. "Cost of Shell Tar-Sands Plant Triples," *Oil and Gas Journal*, December 2, 1974, p. 47.

29. "Soaring Costs Stall Athabasca Plant," *Oil and Gas Journal*, March 29, 1976, p. 80.

30. "Ten Firms to Join Shell in Tar-Sands Plant Development," *Oil and Gas Journal*, March 6, 1978, p. 43.

to estimate and provides some insights about the data. Suppose actual costs are approximately related to estimated costs times a constant growth rate (1 + r) per unit time, t:

$$C_a = C_e(1 + r)^t E, \tag{2}$$

where E is an error term that is multiplicative. By dividing by $C_e$, taking natural logarithms and letting (1 + r) = B, Eq. (2) becomes

$$\ln(C_a/C_e) = t\ln B + \ln E. \tag{3}$$

Further simplifying by setting lnB = b and lnE = e, we get an equation that is easily estimated and that describes cost estimating error as a function of time:

$$\ln(C_a/C_e) = bt + e.$$

Because only 4 of the 10 projects in our data hve been completed, not enough data are available to estimate Eq. (4) using actual costs. Instead, three equations are estimated: The first uses time, t, to estimate cost growth between the preliminary and initial estimate, $C_p/C_i$; the second examines the effect of time on cost growth between the budget and initial estimate, $C_b/C_i$; the third examines cost growth between the budget and preliminary estimates, $C_b/C_p$; and the fourth and fifth equations examine the cost growth between the definitive and preliminary, $C_d/C_p$, and definitive and budget, $C_d/C_b$, estimates, respectively. Table A.2 summarizes the results. For all of the equations, a large amount of the variation is explained by the constant growth rate model and the estimated annual growth rates are high, ranging from 17 to 37 percent.

The reader is cautioned not to misinterpret the very high proportion of variation of cost growth that is explained by time t—70 to 98 percent—summarized in Table A.2. These statistics reflect the ability to explain variations in cost growth among the energy process plants in the sample; they do not reflect the ability to estimate the absolute levels of cost growth for individual plants. Although the statistical fit using a constant growth rate by time is extremely good, we caution that the number of observations is very small. Table A.3 reports the percentage errors using Eq. (4).

A further indication of the degree of statistical uncertainty and precision associated with the estimating equations in Table A.2 is illustrated by placing 95-degree confidence intervals around the estimated growth rate parameters. These are provided in Table A.4. Note that the uncertainty about the growth rate parameters, as measured by the confidence intervals, is fairly high. For example, the estimated annual growth rate between the initial and preliminary estimates is 37 percent, but the confidence interval is 14 to 64 percent.

## Table A.2

## SUMMARY OF ESTIMATES OF COST GROWTH USING THE EQUATION (4) SPECIFICATION

| Equation | Dependent Variable | Estimate of Growth Rate Parameter (1 + r)[a] | t-Ratio for Estimate of Growth Rate Parameter | R Square | Number of Observations |
|---|---|---|---|---|---|
| 1 | $\ln (C_p/C_i)$ | 1.37 | 4.19[b] | .75 | 7 |
| 2 | $\ln (C_b/C_i)$ | 1.32 | 11.60[b] | .98 | 4 |
| 3 | $\ln (C_b/C_p)$ | 1.19 | 3.41[c] | .70 | 6 |
| 4 | $\ln (C_d/C_p)$ | 1.17 | 5.57[b] | .86 | 6 |
| 5 | $\ln (C_d/C_b)$ | 1.33 | 5.13[b] | .90 | 4 |

[a] Calculated as EXP(b), where b is the estimated parameter from the regression equation.

[b] Indicates that the parameter (1 + r) is statistically different from 1.0 at the .01 level of significance.

[c] Indicates that the parameter (1 + r) is statistically different from 1.0 at the .05 level of significance.

## Table A.3

## ACTUAL VERSUS ESTIMATED COST RATIOS USING THE FOURTH EQUATION TO ESTIMATE COST GROWTH

| Observation | Cost Ratio |  | Percentage Error |
|---|---|---|---|
|  | Observed | Predicted |  |
| Barnwell Reprocessing | 2.23 | 2.56 | +15 |
| Baltimore Solid Waste | 1.13 | 1.17 | +4 |
| Colony Oil Shale | 1.59 | 1.37 | -14 |
| Occidental Oil Shale | 1.69 | 1.17 | -31 |
| Great Plains SNG | 1.51 | 1.66 | +10 |
| Syncrude Oil Sands | 1.66 | 1.37 | -18 |

### Table A.4

### THE STATISTICAL UNCERTAINTY OF THE ESTIMATED GROWTH RATE PARAMETERS AS REPRESENTED BY 95-PERCENT CONFIDENCE INTERVALS

| Equation | Dependent Variable | Estimate of Growth Rate Parameter $(1 + r)^a$ | 95-Percent Confidence Intervals for the Growth Rate Parameters |
|---|---|---|---|
| 1 | $\ln (C_p/C_i)$ | 1.37 | 1.14 to 1.64 |
| 2 | $\ln (C_b/C_i)$ | 1.32 | 1.22 to 1.42 |
| 3 | $\ln (C_b/C_p)$ | 1.19 | 1.04 to 1.36 |
| 4 | $\ln (C_d/C_p)$ | 1.17 | 1.09 to 1.26 |
| 5 | $\ln (C_d/C_b)$ | 1.33 | 1.12 to 1.58 |

## PLANT DESCRIPTIONS

The section below briefly describes each energy process plant. Fuller descriptions can be obtained from the references for the cost estimates provided in the cost table for each plant. Four of the ten plants were completed through actual construction, although only two are actually operating: the Baltimore Gas Pyrolysis plant and the Syncrude, Ltd. Oil Sands plant. The last plant is still in start-up and total capital costs can be expected to increase. The Colony surface oil shale plant is in indefinite suspension; the modified in situ plant on Colorado Tract b is proceeding toward start-up in the early 1980s, although one of the partners recently withdrew, citing higher costs; the WESCO and El Paso plants have been cancelled; the Great Plains SNG plant is in suspension awaiting a regulatory ruling; and Shell Canada Oil Sands was seeking partners at this writing.

### The Midwest Fuel Recovery Plant

The Midwest Fuel Recovery plant, employing a new process developed by GE, was intended to extract fissile uranium and plutonium from spent fuel rods of light water nuclear reactors. Construction of the plant started in 1968 after more than four years of intensive development work on the process. The plant was expected to cost $36 million upon completion in 1970. After six years, the last two of which had been spent attempting to debug the plant, GE announced in 1974 that the plant, as designed, could not be made to work and that an additional expenditure of $90 to $130 million would be required if the plant were to be redesigned and operated. Construction of the plant started before known technical problems had been solved. "Special designs" to work out technical problems were in process during construction but were unsuccessful. This appears to be a case in which a major technological advance was attempted, including a jump from the laboratory to a commercial plant, using a concurrent development strategy.

### Barnwell Nuclear Fuel Plant (BNFP)

BNFP was constructed by Allied-Gulf Nuclear Services (a venture jointly owned by Allied Chemical and Gulf General Atomic) to recover (i.e., "reprocess") fissile uranium and plutonium from spent light water reactor fuel. Construction started in 1971, but was plagued with delays, low construction productivity, changes in scope, and new regulatory requirements. By 1975, $250 million had been expended, about 2.5 times the estimate when construction started, but the plant could not begin operations because new safety regulations required installation of facilities to solidify both plutonium and radioactive wastes. In addition, the economic viability of the plant came into question when the Nuclear Regulatory Commission failed to approve the use of recycled plutonium in light water reactors at the present time. The cost of the necessary ancillary facilities was estimated at between $500 and $650 million in 1975.

BNFP employed the Purex process, which had been successfully used at the same scale in military applications for many years. Even though a number of modifications to the technology were made to reprocess power reactor fuel, BNFP entailed far lower technical risks than those of the smaller GE plant. As with the GE plant, however, some technological difficulties were expected but not fully worked out before construction started, particularly in waste treatment. The most serious problems for Barnwell, however, have been regulatory rather than technical.

### Baltmire Gas Pyrolysis Solid Waste Recovery Plant

This plant was designed to produce steam for sale by the pyrolysis (heating in the absence of oxygen) of municipal refuse. The process was developed and the plant designed by Monsanto Enviro-chem, a subsidiary of the Monsanto Chemical Company. Although the plant was constructed with the aid of an EPA demonstration project grant in the amount of $6 million, Monsanto sold the plant on a commercial turnkey basis to the City of Baltimore, complete with penalties for late delivery or poor performance.

Plant construction began in early 1973, although design was not completed until early the next year. Monsanto's confidence that the plant could be scaled up easily from their 35 ton/day pilot to a 1000 ton/day pioneer commercial plant proved to be misplaced. As of February 1977, two years after the plant was supposed to be in full operation, plant operation had not exceeded 50 percent of design capacity and no sustained operation had been achieved. Monsanto withdrew from the project, and city officials estimated the capital cost necessary to bring the plant to design capacity to be an additional $12 million.

The technological advance sought appears to be the primary culprit in cost growth for this plant. An interesting additional note, however, is that this plant, like the GE reprocessing plant, was organized with a concurrent construction/design strategy. The plant was fully one year into construction before design was completed. While this practice is common for state-of-the-art plants, it can be risky for first-of-a-kind facilities.

## The Colony Development Operation Surface Oil Shale Plant

Colony, an oil shale development consortium headed by Atlantic-Richfield, had funded the development of TOSCO II surface retorting technology for several years before it was decided in 1973 to press forward with the first commercial plant. Colony hired C. F. Braun to replace Ralph Parsons as its architect-engineer, and the commercial design was begun in late 1973. Braun's preliminary estimate, made shortly after design began, was over $400 million, 60 percent higher than an initial estimate made by Parsons. When the definitive design was completed 10 months later, the cost estimate had risen to over $700 million. The Braun estimates included only those portions of total plant investment that were the responsibility of the architect-engineer. When offsites, ancillary facilities, and other costs were included, total plant cost approached $1 billion. As a result of this cost growth, Colony announced in September 1974 that it was indefinitely suspending its plans.

Cost growth in the Colony plant can be attributed to four factors: inflation, real increases in equipment and construction costs, the factoring-in of environmental costs, and better knowledge of costs gained during design. Of these factors the last appears to have been the most important.[5]

### Modified In Situ Oil Shale Plant on Tract C-b

The Occidental Petroleum Company has been the foremost developer of modified (mine-assisted) in situ oil shale retorting technology. Compared with conventional surface plants, modified in situ requires only about one-fourth as much mining, a third as much water, and, hopefully, less capital outlay per barrel of daily capacity. Occidental began experimental and pilot plant work on the private DA property in Colorado in the early 1970s. Shale quality on this property is low, and Occidental was an unsuccessful bidder for higher-quality acreage leased by the government in 1974.

In 1977, however, Occidental was approached by Ashland Oil, the sole remaining leaseholder of federal oil shale tract C-b. In exchange for Occidental's technology, Ashland granted a one-half partnership in the tract. The preliminary estimate of capital costs was $442 million for a 57,000 barrel per day facility. The budget estimate released in 1978 showed costs nearly 50 percent above the preliminary estimate due to better information acquired during design, and to some inflation. The definitive estimates completed in 1978 showed capital costs as having risen to $800 million for the plant. This estimate was instrumental in Ashland Oil's decision to withdraw its 50 percent share from the project. Occidental has announced that it plans to proceed with the venture despite Ashland's decision. Design is being undertaken by the Ralph Parsons Company of Los Angeles.

### WESCO SNG Plant

Western Gasification Co. (WESCO) is a joint venture between subsidiaries of Pacific Lighting Service Co. and Transwestern Pipeline Co. The project was intended to supply high-BTU gas to the Pacific Coast and Midwest markets. Original plans called for the phasing-in of three or four 250,000 scfd SNG plants that would draw on the large deposits of sub-bituminous coal near Farmington, New Mexico. Economic studies in 1971 found the project very promising, with original plant cost placed at $406 million. WESCO's plans by 1977 had been reduced to one or two plants, and in March 1978 they were abandoned altogether, with

---

[5] See Merrow, op. cit., Sec. II.

refusal by the Navajo Tribal Council to grant a lease agreement and construction permit.

The cost estimating and design for the plants were handled by Fluor Engineers and Constructors, Inc. Fluor based its estimates on Lurgi-provided preliminary plant design information, prices for all major machinery and equipment (some quoted and some from the Fluor data bank), estimation of site preparation work, and flowsheet takeoffs for offsites and utilities. The later estimates are essentially refinements of the first estimate based on Lurgi design changes, environmental requirements imposed on WESCO, and construction price changes. Fluor also made use of its South African experience with SASOL II in refining the estimates. The specific factors behind the tripling of the estimates between 1973 and 1977 have not been determined, but appear to have been preliminary design changes and construction inflation.

### El Paso SNG Plants

El Paso Natural Gas Co. plans originally called for the construction of two 288,000 scfd SNG plants at the Burnham, New Mexico, site. Similar to the WESCO plans, the proposed plants were to use Lurgi technology with methanation units to increase the heating value of the gas-to-pipeline quality levels to supply Western markets. Coal for the operation was to have come from a coal mining operation near Burnham.

From 1971—when the project was first estimated—through 1975, the cost estimates for the SNG facility escalated four times. The causes probably were similar to those in the WESCO case. According to El Paso sources, the main factors behind the escalating costs were inflation in construction and equipment compounded to design changes.[6]

### The Great Plains Coal Gasification Plant

The Great Plains plant, slated for North Dakota, is the most advanced project in the U.S. for producing synthetic natural gas from coal. Sponsored by a natural gas company consortium, the plant is currently being considered by the Federal Energy Regulatory Commission. It employs Lurgi technology and has a rated capacity of 137.5 million cubic feet per day (MMcfd) output, i.e., about half the size of most proposed Lurgi plants. The plant was originally planned for twice its

---

[6] Comptroller General of the United States, "Status and Obstacles to Commercialization of Coal Liquefaction and Gasification," Report to the Senate Committee on Public Works, May 5, 1976.

current proposed size, but plant purchasers do not believe that the small scale economies above 137.5 MMcfd justify the added capital expenditure.

Design has proceeded further than for any other proposed high-BTU gasification plant. Definitive engineering design was recently halted by Great Plains because of delays in a ruling by FERC. The suspension limits losses in the event of an adverse ruling. Whether the plant is actually constructed will depend primarily upon how FERC treats the plant and upon the ability of the parties to raise capital.

### Syncrude Oil Sands Plant

In 1974, when construction began for the Syncrude Oil Sands Plant, the Syncrude consortium consisted of Imperial Oil Ltd., Atlantic-Richfield Canada Ltd. (ARCAN), Canada-Cities Services Ltd., and Gulf Canada Ltd. During 1974, design progressed toward more definitive stages and the cost estimate increased to $2 billion—4 times the initial estimate of $500 million. Deciding that the economic risk was too great, ARCAN withdrew, placing severe financial pressure on the remaining members of the consortium. The project would have been terminated if three Canadian governments (the provincial governments of Alberta and Ontario, and the federal government) had not come forward with $600 million in financial assistance, and if the remaining participants had not doubled their investment.

The plant is considered to embody first-generation technology. It was developed in conjunction with the designers of the first Canadian oil sands plant built by Great Canadian Oil Sands Ltd. (in operation since 1967). The Syncrude plant was originally scheduled to come on stream in 1977; this slipped to September 1978. Cost escalation appears to be a consequence of more detailed design and the receipt of actual quotations for materials and equipment, with a resulting refinement of the overall estimate, and to a lesser extent, escalation of construction costs. The Syncrude plant is still in start-up as of this writing. Total capital costs will not be known until start-up is completed.

### Shell Canada Ltd. Oil Sands Project

When world oil prices escalated in 1973, Shell Canada estimated costs for a 100,000 b/d oil sands project of $700,000. In late 1974, Shell Explorer Ltd. withdrew from its partnership with Shell Canada, attributing its move to rising development costs and uncertainties over government energy policies. By December 1974, estimated development costs were triple the original $700,00O; by March 1976, they had more than quadrupled, whereupon Shell Canada suspended the project.

In September 1978, Shell was seeking partners to share an estimated $2.9 billion (1978 dollars) investment for a 125,000 b/d plant, the conceptual design of which is very similar to that of the Syncrude facility. Shell expects to decide whether to proceed sometime in 1979.

# BIBLIOGRAPHY

Alchian, A. A., *Reliability of Cost Estimates—Some Evidence,* The Rand Corporation, RM-481, October 1950.

Alchian, A. A., and W. R. Allen, *Exchange and Production Theory in Use,* Wadsworth Publishing Company, Inc., Belmont, California, 1964.

Alexander, A. J., *R&D in Soviet Aviation,* The Rand Corporation, R-589-PR, November 1970.

Alexander, A. J., *Weapons Acquisition in the Soviet Union, United States and France,* The Rand Corporation, P-4989, March 1973.

Alexander, A. J., and J. R. Nelson, *Measuring Technological Change: Aircraft Turbine Engines,* The Rand Corporation, R-1017-PR, June 1972.

Altouney, E. G., *The Role of Uncertainties in the Economic Evaluation of Water Resources Projects,* Institute of Engineering-Economic Systems, Stanford University, 1963.

Armstrong, B. E., *Avionics Data for Cost Estimating,* The Rand Corporation, P-5745-1, March 1977.

Baer, W. S., L. L. Johnson, and E. W. Merrow, *Analysis of Federally Funded Demonstration Projects: Final Report,* The Rand Corporation, R-1926-DOE, April 1976.

Blue Ribbon Defense Panel, *Report to the President and the Secretary of Defense on the Department of Defense* (Appendix E, Staff Report on Major Weapon Systems Acquisition Process), Washington, D.C., July 1970.

Boehm, G. A. W., "Helping the Executive to Make Up His Mind," *Fortune,* April 1962.

Boren, H. E., Jr., *A Computer Model for Estimating Development and Requirement Costs of Aircraft (DAPCA-III),* March 1976.

Burck, C. G., "What We Can Learn from BART's Misadventures," *Fortune,* July 1975.

Canfield, M., Jr., *Statement Before the Senate Committee on Energy and Natural Resources,* United States General Accounting Office, Washington, D.C., September 26, 1977.

Capen, E. C., "The Difficulty of Assessing Uncertainty," *Journal of Petroleum Technology,* August 1976.

Carruth, E., "What Price Glory on the Albany Mall?," *Fortune,* June 1971.

Chai, D. K., "A Practical Approach to Using the C.O.M.E. Project on Complex Items," *AACE Transactions,* 1972.

Chairman of the Armed Services Committee, House of Representatives, "The Soviet Threat," Congressional Record, 31st Congress, 2nd Session, Washington, D.C., September 28, 1970.

Chow, W., *Treatment of Missing Values,* The Rand Corporation, P-6153, July 1978.

Clark, F. D., "How to Assess Inflation of Plant Costs: Cost Control for Process Plants from the Owner's View," *Chemical Engineering,* July 7, 1975.

Clark, F. D., and A. B. Lorenzoni, *Applied Cost Engineering,* Marcel Dekker, Inc., New York, 1978.

Clune, J. L., "A Quantitative Discussion of Capital Cost Indexes Used in the Chemical Process Industry," *AACE Transactions,* 1973.

Comptroller General of the United States, "Survey of Publications on Exploration, Development, and Delivery of Alaskan Oil to Market," Report to the Senate Committee on Interior and Insular Affairs, January 14, 1977.

*Cost of Government Regulation,* The Business Roundtable, New York, 1978.

Cowan, J. C., et al., "Cost Comparisons with Competition," Panel discussion transcript, AACE National Meeting, 1962.

De la Mare, R. F., "The Economic Implications of Plant Reliability," *Chemistry and Industry,* May 3, 1975.

Dreyfuss, D. J., *Estimated Costs of Extended Low-Rate Airframe Production,* The Rand Corporation, R-2243-AF, March 1978.

Dryden, J., and J. P. Large, *A Critique of Spacecraft Cost Models,* The Rand Corporation, R-2196-1-AF, September 1977.

Eckstein, O., *Water-Resource Development: The Economics of Project Evaluation,* Harvard University Press, Cambridge, Mass., 1958.

Enyedy, G., Jr., "AACE's Cost of Major Equipment (C.O.M.E.) Project: A Report to the Membership," *AACE Transactions,* 1972.

Enyedy, G., Jr., "Preliminary Estimates of Process Plant Investments Can Be Realistic," *AACE Transactions,* 1975.

Faltermayer, E., "The Hyperinflation in Plant Construction," *Fortune,* Novembr 1975.

Fisher, I. N., *A Reappraisal of Incentive Contracting Experience,* The Rand Corporation, RM-5700-PR, July 1968.

Glennan, T. K., Jr., "New Product Development: Observations Based on the Development of Military Aircraft," Unpublished Ph.D. Dissertation, Stanford University, 1968.

Glennan, T. K., Jr., et al., *The Role of Demonstrations in Federal R&D Policy,* The Rand Corporation, R-2288-OTA, May 1978.

Gravallese, A., P. Albin, and R. DiLuzio, "Northeast Corridor Improvement Program, Task 1: Management Survey, Summary Report," Dynatrend Incorporated, Massachusetts, December 1975.

Gruenstein, P., "Waste: The Real Problem with the Alaska Pipeline," *The Washington Monthly,* Vol. 8, No. 1 January 1977.

Guthrie, K. M., et al., *Managing Capital Expenditures for Construction Projects,* Craftsman Book Co., Solano, California, 1977.

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

Hackney, J. W., "Some Practical Aspects of Regression Analysis of Cost Data," paper presented at the American Association of Cost Engineers 11th National Meeting, Cleveland, Ohio, July 10-12, 1967.

Hall, G. R., and R. E. Johnson, *Aircraft Co-production and Procurement Strategy,* The Rand Corporation, R-450-PR, May 1967.

Harman, A. J., *Measurement of Technological Innovation by Firms,* The Rand Corporation, P-5496, September 1975.

Harman, A. J., assisted by S. Henrichsen, *A Methodology for Cost Factor Comparison and Prediction,* The Rand Corporation, RM-6269-ARPA, August 1970.

Haveman, R. H., *The Economic Performance of Public Investments: An Ex Post Evaluation of Water Resources Investments,* Johns Hopkins Press, Baltimore, 1972.

Healy, J. M., "Errors in Project Cost Estimates," *Indian Economic Journal,* Vol. 12, July-September 1964.

Hederman, W. F., Jr., *Assessing Technology Assessment,* The Rand Corporation, P-5391, February 1975.

Hederman, W. F., Jr., *Prospects for the Commercialization of High-BTU Coal Gasification,* The Rand Corporation, R-2294-DOE, April 1978.

Heely, G. T., *Time, Cost, and Architecture,* McGraw-Hill Book Company, New York, 1975.

Hufschmidt, M. M., and J. Gerin, "Systematic Errors in Cost Estimates for Public Investment Projects," in J. Margolis (ed.), *The Analysis of Public Output,* Columbia University Press, New York, 1970.

Jelen, F. C. (ed.), *Cost and Optimization Engineering,* McGraw-Hill Book Company, Inc., New York, 1970.

Johnson, L. L., et al., *Alternative Institutional Arrangements for Developing a Commercializing Breeder Reactor Technology,* The Rand Corporation, R-2069-NSF, November 1976.

Katell, S., and L. G. White, "Economic Comparison of Synthetic Fuels Gasification and Liquification," *AACE Transactions,* 1976.

Keating, C. J., "Predesign Estimation of Process Plants," *AACE Bulletin,* September 1961.

Kirschke, R. H., K. Singh, and C. Chen, "Good Cost Estimating: More Important Than Ever," *AACE Transactions.*

Klein, B. H., "The Decision-Making Problem in Development," in *The Rate and Direction of Invention Activity,* Princeton University Press, Princeton, New Jersey, 1962.

Klein, B. H., T. K. Glennan, Jr., and G. H. Shubert, *The Role of Prototypes in Development,* The Rand Corporation, RM-3467-1-PR, April 1971.

Kneese, A. V., and C. L. Schultze, *Pollution, Prices, and Public Policy,* The Brookings Institution, Washington, D.C., 1975.

Kraar, L., "Electric Boat's Whale of a Mess: The Trident Sub," *Fortune,* July 31, 1978.

Landau, R., "Role of American Engineering Design Companies in the Chemical Process Industry," *Chemical Age of India,* January/February 1962.

Landau, R. (ed.), *The Chemical Plant: From Process Selection to Commercial Operation,* Reinhold Publishing Corporation, New York, 1966.

Large, J. P., *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.

Large, J. P., H. G. Campbell, and David Cates, *Parametric Equations for Estimating Aircraft Airframe Costs,* The Rand Corporation, R-1693-1-PA&E, February 1976.

Large, J. P., et al., *A Critique of Aircraft Airframe Cost Models,* The Rand Corporation, R-2194-AF, July 1977.

Lenzner, T. F., *The Management, Planning, and Construction of the Trans-Alaska Pipeline System,* Alaska Pipeline Commission, Anchorage, Alaska, August 1, 1977.

Lichtenstein, S., and B. Fischhoff, "Do Those Who Know More Also Know More About How Much They Know?," *Organizational Behavior and Human Performance,* Vol. 20, 1977.

Lichtenstein, S., B. Fischhoff, and L. D. Phillips, "Calibration of Probabilities: The State of the Art," in H. Jungermann and G. de Zeeuw (eds.), *Decision-Making and Change in Human Affairs,* D. Reidel Publishing Co., Dordrecht, Holland, 1977.

Lovell, J. F., "Feasibility Studies," paper presented at the American Association of Cost Engineers Pittsburgh Section Meeting, Pittsburgh, Pennsylvania, September 9, 1964.

Ludwig, E. E., *Applied Project Management for the Process Industries,* Gulf Publishing Company, Houston, Texas, 1974.

Lutz, J. H., "Cost Control—The Importance and Difficulty of Knowing Where You Are," paper presented at the American Association of Cost Engineers 11th Annual Meeting, Cleveland, Ohio, July 10-12, 1967.

Marschak, T. A., T. K. Glennan, and R. Summers, *Strategy for R&D:*

*Studies in the Microeconomics of Development*, Springer-Verlag, New York, 1967.

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

McCabe, W. P., "Project Scope Definition," paper presented at the American Association of Cost Engineers Pittsburgh Section Meeting, October 14, 1964.

McKee, G., Jr., "Problems in Construction Cost Control," *AACE Bulletin*, June 1963.

Mead, W. J., G. W. Rogers, and R. Z. Smith, *Transporting Natural Gas from the Arctic*, American Enterprise Institute for Public Policy Research, Washington, D.C., 1977.

Mendel, O., "Types of Estimates: Their Reliability and Basis as Used in Conjunction with Cost Controlling Techniques," *AACE Bulletin*, August 1974.

Merewitz, L., "Cost Overruns in Public Works with Special Reference to Urban Rapid Transit Projects," Working Paper 196/BART 8, Institute of Urban and Regional Development, University of California, Berkeley, November 1972.

Merewitz, L., "Cost Overruns in Public Works," in *Benefit-Cost and Policy Analysis 1972*, Aldine Publishing Co., Chicago, 1973, pp. 277-295.

Merewitz, L., and T. C. Sparks, "A Disaggregated Comparison of the Cost Overrun of the San Francisco Bay Area Rapid Transit District," Working Paper No. 156/BART 3, Institute of Urban and Regional Development, University of California, Berkeley, May 10, 1971.

Merrow, E. W., *Constraints on the Commercialization of Oil Shale*, The Rand Corporation, R-2293-DOE, 1978.

Mooz, W. E., *Cost Analysis of Light Water Reactor Power Plants*, The Rand Corporation, R-2304-DOE, June 1978.

Nelson, J. R., and F. S. Timson, *Relating Technology to Acquisition Costs: Aircraft Turbine Engines*, The Rand Corporation, R-1288-PR, March 1974.

Ostawald, P. F., *Cost Estimating for Engineering and Management*, Prentice-Hall, Englewood Cliffs, New Jersey, 1974.

Patton, E. L., "Comments on Trans-Alaska Pipelines Costs," *Alaska Construction & Oil*, July 1977.

Peck, M. J., and F. M. Scherer, *The Weapons Acquisition Process: An Economic Analysis*, Harvard University Press, Cambridge, Massachusetts, 1962.

Perry, R. L., et al., *System Acquisition Experience*, The Rand Corporation, RM-6072-PR, November 1969.

Perry, R. L., et al., *System Acquisition Strategies*, The Rand Corporation, R-733-PR/ARPA, June 1971.

Rapier, C. P., "Toolmaking for Better Conceptual Estimates," *AACE Transactions.*

Rigatti, J. F., "Capital Cost Estimates," paper presented at the American Association of Cost Engineers Pittsburgh Section, March 10, 1965.

Rosenthal, M., and E. O. Green, "Discussion of Estimating Methods," *AACE Transactions.*

Rudelius, W., "Methods of Analyzing the Impact of Program Stretchouts," National Aeronautics and Space Administration, November 1967.

Sawyer, J. E., "Entrepreneurial Error and Economic Growth," *Explorations in Entrepreneurial History,* Vol. 4, No. 4, 1951-52.

Scherer, F. M., *The Weapons Acquisition Process: Economic Incentives,* Harvard University Press, Cambridge, Mass., 1964.

Sherman, A., "Impact of Technology on Cost Decisions in a Dynamic Industry," *AACE Transactions,* 1970.

Sides, C. M., and D. K. Dodson, "Escalating Costs of Process Plant Construction," 1975 Transactions, American Association of Cost Engineers, Morgantown, West Virginia.

Summers, R., *Cost Estimates as Predictors of Actual Weapon Costs: A Study of Major Hardware Articles,* The Rand Corporation, RM-3061-PR, March 1965.

Thorne, H. C., and R. O. Carlson, "Acquisitions and Joint Ventures," *AACE Transactions.*

Tucker, J. F., "Cost Estimation in Public Works," Master of Business Administration thesis, University of California, Berkeley, September 1970.

Tuersky, A., and D. Kanheman, "Judgment Under Uncertainty: Heuristics and Biases," *Science,* September 1974.

U.S. Department of the Interior and U.S. Department of Transportation, "Alaska Natural Gas Systems, White House Task Force Lead Agency Report on Constructon Delay and Cost Overruns," July 1, 1977.

Ward, E. G., "Evaluation of Risk in New Capital Projects," *AACE Transactions,* 1969.

Williams, L. F., "Capital Cost Estimating from the Viewpoint of Process Plant Contractor," *AACE Bulletin;* Part I, December 1972; Part II, February 1973.

Zimmerman, O. T., "Capital Investment Cost Estimation," in F. C. Jelen (ed.), *Cost and Optimization Engineering,* McGraw-Hill Book Company, Inc., New York, 1970.