A Quantitative Assessment of R&D Requirements for Solids Processing Technology

Edward W. Merrow

Rand

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PREFACE

This research was funded as Task 7 of Rand's program of analysis on Nonrenewable Energy Resources under contract with the U.S. Department of Energy's Office of Fossil Energy. The Advanced Research and Technology Division was the research sponsor. The project was also supported under the Process Industries Agenda of Rand's Private Sector Sponsors Program. That program consists of an agenda of research supported by companies in the process industries.

The purpose of the project was to better understand the sources of performance difficulties in solids processing facilities and to determine which R&D areas ought to be most vigorously pursued to reduce future performance difficulties. The Department of Energy's interest in this research stems from the solids processing character of many of the technologies that the Department supports.

The report should be useful to those who have a practical interest in setting R&D priorities for solids processing and those involved in making the technology for processing solids, including synthetic fuels, more cost-effective. The approach described here should also interest those concerned with the general problem of establishing effective R&D priorities.

SUMMARY

Plants that process or produce solid materials, such as metal-ore processors, resins plants, calciners, and synthetic fuels plants, consistently have poorer performance than plants that process liquids and gases. The failure of many solids processing plants to perform efficiently has been uniform over time—new plants show no tendency toward better performance. The present study was undertaken to attempt to identify the reasons for poor performance of solids processing plants and thereby to suggest priorities for research and development (R&D).

We began by expanding an existing database on solids processing facilities to include information on 40 commercial plants, including data on the R&D programs that preceded the design of the facilities. We then performed a statistical analysis of plant performance and the relationship between plant performance and the R&D programs. This approach has several significant advantages over the more conventional method of simply soliciting expert opinion:

- It assures that the R&D priorities will be determined by the problems actually experienced, rather than by academic interest.
- It is considerably less subjective than expert opinion, and the results are therefore less likely to be biased.
- It is reproducible and tied to an explicit figure of merit, plant performance.

Our analysis revealed that the key performance problems in solids processing plants result from physical and mechanical difficulties rather than problems of process chemistry. The R&D needs in the process chemistry areas are being identified and tackled successfully, but problems associated with materials handling, corrosion and abrasion, and solids behavior are not being resolved. The failures in the area of waste handling are particularly pronounced and have led to a number of complete plant failures.

The failure of solids plants performance is closely correlated with incomplete knowledge of heat and material balances, that is, the equations that establish heat and mass flows throughout a plant for design purposes. Poor knowledge of these balances in solids processing is related to difficulties in applying prior experience to new facilities, and this in turn reflects a poor state of basic knowledge about solids

behavior relative to knowledge about the behavior of liquids and gases. This lack of knowledge is especially pronounced in plants that use solid feedstocks and plants that have experienced R&D and design problems in waste handling. Poor knowledge of the heat and material balances was manifested most dramatically in 12 plants that had one or more incorrectly sized major process steps.

A curious aspect of the chronically poor performance of solids plants is the long-standing failure of the R&D system in these industries to correct their problems. We believe that this failure can be laid largely to the strong orientation toward chemistry in the process industries that has developed at the expense of physics and mechanical engineering. Because the problems of solids processing plants tend to be related not to the chemical processes but to the more "mundane" problems of handling, materials transport, etc., those problems have tended to take a back seat to issues that are more professionally rewarding to chemists and chemical engineers.

ACKNOWLEDGMENTS

This report is the result of the work, cooperation, and patience of a number of people. First, I thank Richard Bergmann of the Advanced Research and Technology Division of DOE for his support and for his comments and suggestions, which materially improved the quality of the research and the report. My Rand colleagues Bernard Aboba, Ronald Hess, and Christopher Myers acquired, checked, and followed up the data from industry with thoroughness and care. My special appreciation is extended to Ronald Hess, who organized a good deal of the data collection, and to Bernard Aboba, who also assembled hundreds of process descriptions and references to help target the plants we needed for the analysis. Toshi Hayashi and Kip Fisher assisted in the statistical analysis. My thanks to William Krase for his careful and insightful analysis of the results of expert panels.

Thirty-two companies in the process industries in Canada and the United States provided the data on 40 projects for this study. My special thanks are offered to the individuals at those companies who dug back through old records, called and wrote current and former colleagues, and then patiently assembled a full picture of the projects for our analysis.

Rand colleague John Birkler reviewed an earlier draft of the report and improved its quality in virtually every section. Ralph Shangraw of Syracuse University also critiqued the report, and his comments helped to sharpen the focus in Section I and to draw out the implications of the research.

My thanks to Richard Pei for his helpful comments on the project throughout and his excellent liaison with the sponsor, and to Janet DeLand for her skillful editing of the report.

I owe the greatest debt of gratitude to my Rand colleague Mary Vaiana, for spotting weaknesses and ambiguities in the argument and forcing their resolution and clarification. Her patient and astute reviewing of several early drafts played the key role in the presentation of the research results.

Any errors or omissions are, of course, the sole responsibility of the author.

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I. INTRODUCTION

The economics of chemical process plants are dramatically affected by how well the plants perform, that is, how much they produce relative to expectations. Although this relationship is well known, there is a whole class of plants—those that process solid materials—that have performed poorly compared to other plants, *and no progress appears to have been made toward improving their performance over time.*[1] This finding raises the following questions:

- Why hasn't the R&D system in the process industries addressed and effectively coped with the difficulties associated with processing solid materials? The failure to do so is particularly striking in view of the prominence of R&D in the process industries over the past 25 years, the very high costs of poor performance, and the generally good record of R&D success in other process industries. Moreover, the failure to successfully address solids processing problems has important negative implications for the future transition to synthetic fuels, all of which require solids processing facilities.
- Are there important areas for R&D attention in solids processing that have been neglected?
- If so, what are they?

In attempting to answer these questions, we developed an approach to establishing R&D priorities for solids processing that we believe has important advantages over traditional methods.

Our primary goal was to find ways to improve the setting of R&D priorities. R&D needs must be correctly assessed if R&D resources are to be properly allocated. Identifying the appropriate problems for R&D to address is not easy. By its very nature, R&D is a search for information. It is exceedingly difficult—and perhaps impossible—to establish *ex ante* how valuable the information is. In general, the more "basic" research is (that is, the less immediate commercial application it has), the harder it is to predict either the outcome of a particular R&D project or the value of the results.

Typically, the R&D manager faces an array of potential projects, the total costs of which would far exceed his budget. He must therefore

[1]Edward W. Merrow, Kenneth E. Phillips, and Christopher W. Myers, *Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants*, R-2569-DOE, The Rand Corporation, September 1981, Sec. V.

select projects to pursue that will satisfy some goal or set of goals. In the private sector, the goals are usually related to maximizing return on the R&D investment.[2] But the R&D manager has few objective clues as to which projects are likely to succeed; moreover, it is seldom known whether a "successful" R&D project will ultimately prove to be a good investment. In the extreme case, it may not be possible even to know what "success" means for a project.

An effective R&D approach must therefore take into account resource limitations, interactions between basic and applied research, and uncertainty. We suggest that an allocation methodology should therefore have the following features:

- It should include *both basic and applied R&D,* permitting the relationship between basic and applied requirements to be examined.
- It should maximize the use of *objective measures and procedures* and minimize the use of idiosyncratic measures.
- It should, in principle, include *all fruitful research avenues* within a particular technical area—that is, it should have no inherent biases or blind spots.
- Its results should be *reproducible,* so that corrections can be made when uncertainties are reduced.
- It should *tie research priorities to some figure of merit.*
- It should produce *clear priorities,* preferably with a meaningful interval scale for ranking alternatives.

The ability of economic theory to provide specific guidelines for R&D priorities in a particular area is very limited. Lacking useful theoretical guidance, R&D managers have usually fallen back on expert opinion to guide allocation decisions. In government, it is common to appoint panels of experts to provide R&D priorities; the practice is widespread in industry as well, although industries tend to employ single experts rather than formal panels.[3]

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[2]The goals of an R&D program, taken as a whole, may be difficult to rationalize. Public sector R&D managers, in particular, are likely to have complex and conflicting objectives. For example, Betz et al. contend that public sector R&D managers have an important responsibility to "the national R&D system," and that this responsibility must be included in their decisions. (Frederick Betz, L. Vaughn Blankenship, Carlos Kruytbosch and Richard Mason, "Allocating R&D Resources in the Public Sector," in Burton V. Dean and Joel L. Goldhar (eds.), *Management of Research and Innovation,* New York: North-Holland Publishing Company, 1980, p. 242.)

[3]We use the term *expert panels* for all ranking of R&D priorities by means of expert judgment. In some cases, rankings based on expert judgments are structured and quantified using some scoring method, but we group any approach that has expert judgment at the root of its assessment of priorities under the rubric of *expert panels.*

THE USE OF EXPERT OPINION

An expert panel is exactly what the name implies: a (generally small) group of scientists and research managers whose work in a particular field is widely recognized as outstanding. With few exceptions, expert panels are temporary teams tasked with examining an R&D agenda at a single point in time. After reporting their results, they are disbanded.

The expert-panel approach clearly meets our first criterion: Experts can examine both basic and highly applied R&D requirements. Indeed, their ability to provide guidance on long-term, basic research needs is one of their most valuable functions.

Unfortunately, expert panels are far less successful in meeting the remaining five criteria:

- First, the conclusions of an expert panel are necessarily highly subjective. Even if some systematic aggregating technique is used, the conclusions of a panel will reflect a set of unknown and essentially unknowable individual beliefs, assumptions, and premises. Even if the method of aggregating and filtering the expert judgments is very rigorous, the basic subjectivity of the approach remains.
- Second, our review of expert panel assessments of synthetic fuels technologies revealed *no* cases in which any clear priorities were established. The difficulties of establishing priorities by committees are well known and substantial. Any priority must, by implication, downplay the importance of one or another panelist's work—unless, of course, there is little divergence in the accomplishments of the panel members. The failure to establish priorities can be reconciled only by making an implicit assumption that unlimited funding would be available for virtually all technical approaches.
- Third, the results of any panel discussion depend on the composition of the panel. One becomes an expert by successfully developing a particular line of research, and it is illogical to expect a panel to produce results that encompass a broader range of possibilities than the lines of research represented. Thus, by their very nature, expert panels tend to ensure that the research agenda consists in some degree of "more of the same." *Disciplinary blind spots are automatically perpetuated.*
- Fourth, the results of expert opinion are not reproducible, and this can make the results difficult to defend. Moreover, they cannot be used to improve the ranking of future R&D projects

because such results are not cumulative and the assumptions on which they are based are not explicitly stated.

- Finally, none of the expert panel assessments we reviewed attempted to estimate how the proposed program of research would affect cost, performance, or any other figure of merit for commercial systems.[4]

A PARAMETRIC APPROACH TO ASSESSING R&D NEEDS

An alternative to using expert opinion for R&D allocation is parametric analysis. Parametric analysis statistically links the characteristics of entities, such as R&D projects, to some defined outcome measure(s), such as commercial plant performance. The statistical links are derived from historical experience, e.g., a database describing many projects. Once the empirical links have been identified, parametric analysis enables predictions to be made of the value of the outcome measure for some *new* entity that resembles the entities in the database. Thus, this approach makes it possible to derive generalizations about an entire class of entities by examining a limited set of them.

The parametric-analysis approach to R&D allocation meets our criteria quite well:[5]

- First, a statistical method is applicable to both long-term R&D requirements and near-term, development-oriented applications. Such an approach also makes it possible to discover relationships between development-oriented requirements—e.g., improved steel hardening to resist erosion—and the need for better theoretical understanding—in this case, of corrosion processes. If a development-oriented problem is common to a set of situations, this is probably indicative of a weak underlying theoretical basis. (We discuss several such situations in Section IV.)
- Because statistical analyses rely on systematically obtained historical evidence, rather than the judgments of individuals, they are usually less subjective than expert panels. However, this

[4]It was clear, on the other hand, that none of the R&D items were considered essential to technical feasibility, because immediate commercialization of first-generation technologies was consistently recommended.

[5]The present discussion focuses on the extent to which statistical analyses can, in principle, meet our criteria. The details of the statistical approach used in this study and its limitations are discussed in Section II.

does not mean that all subjectivity can be removed; there is likely to be some inherent subjectivity in the data collected.

- To the extent that the data collected are free of bias, the results of a statistical analysis will be free of blind spots. However, new directions with few historical antecedents will not be picked up in the data and will therefore be excluded.[6]
- Statistical analyses are reproducible and correctable because the basis for the conclusions is clearly stated.
- Because of the way in which the statistical models are derived, parametric analyses can be linked to a measure of value or merit.
- Because they use statistical reasoning and quantitative measures, statistical analyses are likely to provide *clear, quantitative ranking of priorities.*[7]

In sum, a parametric approach to assessing R&D requirements is very appealing in principle. It provides rigor, replicability, and a quantitative rationale for establishing priorities. We have used such an approach in this study in exploring how to allocate R&D resources to achieve successful commercial introduction of new chemical processes and new chemical processing equipment.[8]

EXPLORING R&D IN SOLIDS PROCESSING FACILITIES

Plants that handle and process solid materials show considerably poorer performance than plants that process only liquids and gases.[9] This is of considerable concern to the Department of Energy (DOE) and to industry, for several reasons:

- Performance is an extremely important factor in determining product costs.

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[6]It is not clear that expert panels are better in practice than parametric analyses, but in principle they could be.

[7]This, of course, assumes that there is agreement as to what should constitute the figure(s) of merit. R&D situations with multiple goals that cannot be defined in terms of a common figure of merit may not yield consistent priorities regardless of the approach selected.

[8]The results of statistical analyses could be used to complement expert-opinion-based results. An interesting and potentially very informative exercise would be a systematic comparison of the results of this analysis with those of several expert panels dealing with related subject areas, e.g., synthetic fuels. Unfortunately, such a comparison is beyond the scope of the present study.

[9]See Merrow, Phillips, and Myers, *Understanding Cost Growth and Performance Shortfalls.*

- The differences between performance of solids processing plants and that of liquids/gas processing plants are large and statistically convincing.
- The processing of solids is an increasingly important part of the process industries' plant portfolio and an overwhelming part of DOE's R&D portfolio.

We have attempted to identify the reasons for the poor performance of solids processing facilities and to determine whether the difficulties encountered in such plants could be related systematically to research areas that government and industry might then address.

To support our analysis, we substantially expanded the number and variety of solids processing plants in Rand's Pioneer Plants database.[10] The original sample of 15 facilities was sufficient to establish the performance differences between liquids/gas processing and solids processing, but it was inadequate to establish the reasons for the difference and the relationship between performance problems and R&D needs. We therefore collected data on 25 additional solids processing plants that varied considerably in type and degree of innovation.

As a figure of merit for an R&D effort, we used the expected improvement in commercial plant performance.[11] With this figure and the additional data, we were able to address statistically the following questions:

- Is our original finding that solids processing plants display relatively poor performance sustained by analysis using the expanded database?
- What kinds of performance problems are most common for solids processing plants?
- What is the relationship between the R&D problems and areas worked on prior to opening the first commercial plant and the performance of the pioneer (first-of-its-kind) plant?
- Based on the historical evidence, does it appear that any R&D areas are being systematically ignored or worked on unsuccessfully by the process industries?

[10]See Merrow, Phillips, and Myers, *Understanding Cost Growth and Performance Shortfalls*, Sec. III, for a detailed description of the Pioneer Plants database as it existed in 1981.

[11]Although we believe that plant performance is the appropriate figure of merit in this case because it is a major factor influencing product costs and it is particularly problematic for solids processing, other aspects could be used. For example, improved environmental characteristics, thermal efficiency, or reduced operating and maintenance costs could, in principle, be the measures of merit in a statistical analysis of this sort. It would also be possible, although much more difficult methodologically, to use more than one measure of value at once.

- Based on the answers to the questions above, can we fashion a reliable, empirically based tool for allocating R&D budgets for solids processing technologies?

We summarize the answers to those questions as follows:

- The differential performance between solids and non-solids processing plants is equally apparent and strong using the larger database.
- The key performance problems in solids processing plants are associated with mechanical and physical difficulties rather than with process chemistry.
- R&D related to process chemistry is generally successful; other problems are not successfully resolved because they are not well integrated into the research paradigm that goes from improvements in basic knowledge of chemistry to improved processes and products in the marketplace. These problems—feedstock characterization, corrosion, abrasion, and material handling—have not received the degree of attention that is appropriate, *given the dramatic effects of failure in these areas on plant performance and thus product costs.*
- Our analysis permits us to rank the R&D areas that have been neglected in terms of product cost reductions that could have been achieved by more successful R&D.

ORGANIZATION OF THE REPORT

Section II of this report describes our parametric approach in detail and explains its strengths and limitations. In Section III, we review the characteristics of our database, including a discussion of the types of facilities represented. Sections IV and V describe our analysis and our conclusions, respectively.

II. APPROACH AND METHODOLOGY

A CONCEPTUAL MODEL OF THE APPROACH

The ranking of R&D projects for funding might be approached in the following way. Assume that the value of a project is equal to the increased value it would bring to some commercial venture if it is successful.[1] We can express this as

$$V_i = \Delta V_{CP} \times PS_i$$

where V_i is the value of an R&D project; ΔV_{CP} is the increased value the project (if successful) would bring to a commercial venture; and PS_i is the probability that the effort will be successful.[2] The probability of success of an R&D project is determined primarily by (1) the difficulty of the chosen task, and (2) the abilities of the R&D performer. We can control for the first component, but unfortunately, we have no measures of the second and therefore cannot consider it.

Figure 2.1 shows how we approached this equation. We can define the difficulty of a particular R&D project in a variety of ways, e.g., in terms of the amount of new technology represented in the plant design, the number of process steps that are new, or the degree of difficulty encountered in the R&D process along the dimensions shown in Fig. 2.1. We wished to forge a statistical link between the increased value of a commercial project and the nature of the R&D program that preceded it, using plant performance as our measure of increased value.

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[1]All values must be adjusted by a discount rate that reflects the time value of resources. This factor can become extremely important for R&D projects whose potential payoffs are far in the future. For example, if a project promises a 50 percent decrease in manufacturing costs but will not be implementable until the year 2030, its value is marginal. (See Bruno Augenstein, *When Can Cost-Reducing R&D Be Justified—A Simple Explanatory Model*, The Rand Corporation, P-6372, September 1979.)

[2]For simplicity, we assume that project outcomes are binary. In fact, projects may succeed to greater or lesser extents. We also simplified the model by assuming that R&D ranking is a one-time-only decision. In fact, such decisions are (or should be) stochastic, with the degree of success in one period becoming part of the basis for allocation in the next. As Weitzman notes, R&D decisions have an important stochastic element. The question is not, Should we proceed to fund project X, including the necessary R&D? but, Should we continue funding an effort to reduce uncertainty about the feasibility of project X? The logic of a stochastic formulation is compelling. In practice, however, the politics of budgets often put those who follow sequential strategies at a distinct disadvantage. This is almost as often true in private sector decision contexts as in the public sector. (See Martin L. Weitzman, with Whitney Newey and Michael Rabin, "Sequential R&D Strategy for Synfuels," *The Bell Journal of Economics*, Autumn 1981, pp. 574–590.)

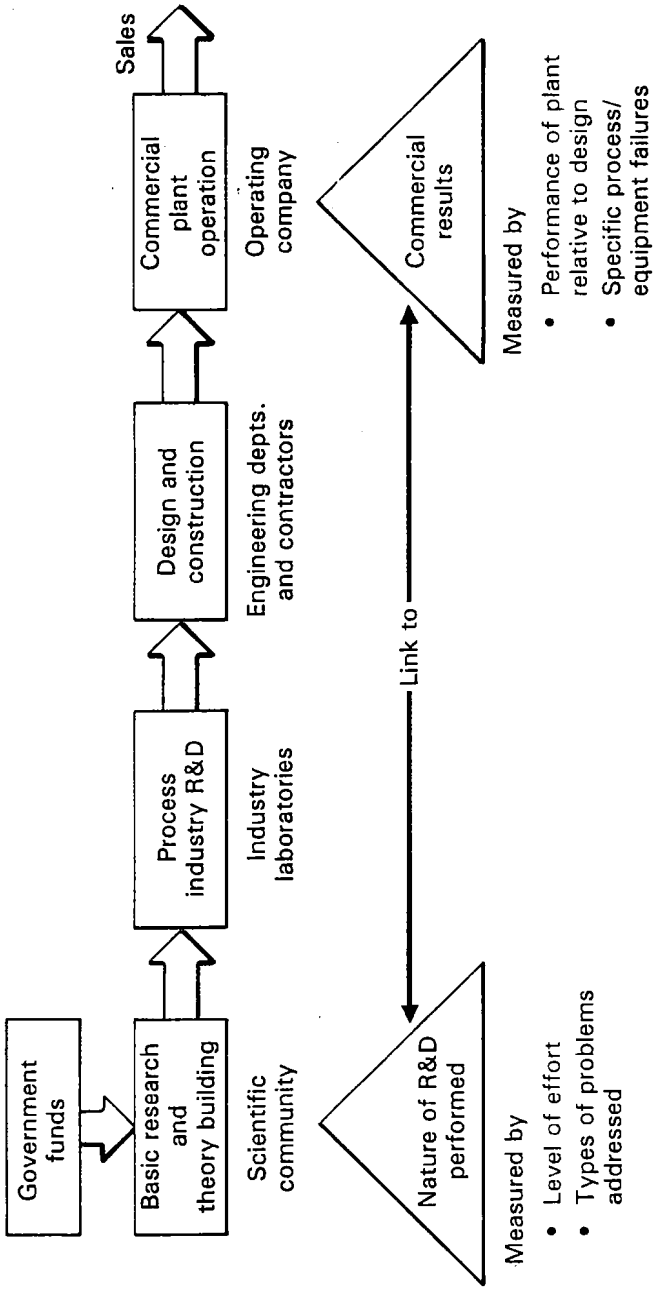

Fig. 2.1 — Approach to the analysis of R&D projects

We therefore chose to examine the extent of a set of basic R&D problems encountered in processing plants and the amount of effort devoted to solving them.

If we were to simply relate performance outcomes to the type of R&D performed for a number of projects, this would involve making the patently false assumption that all of the projects in our database had equally ambitious goals. Therefore, it was necessary to control for the level of difficulty of the R&D projects in our study. We did this by including key measures of the degree of innovativeness in a commercial plant, such as the number of new process steps.[3] In addition, the relationship between R&D and commercial plant performance may be mediated through other aspects of the plant, e.g., knowledge of heat and material balances prior to the beginning of design, and characteristics of the feedstock employed. We therefore examined the relationships between R&D and intervening variables known to be associated with plant performance.

STATISTICAL METHODS

Our analysis relies heavily on correlation and multiple regression,[4] as discussed briefly below.

Correlation

Correlations are handy statistical ways of showing whether or not there is likely to be an association between two variables. They are akin to two-variable plots: If all of the observations fall on an absolutely straight line, the correlation between two variables x and y is perfect, i.e., 1.0. If the relationship is entirely random, the correlation is zero. A correlation is positive if the line formed through the scattered plot points is upward sloping and negative if it is downward-sloping. Thus the range of possible correlation values is -1 to $+1$.

Correlations have a sizable advantage over simple plots, however, because they provide a measure of the likelihood that an association between two variables might be generated randomly. Associated with each correlation coefficient is a calculation of the probability that, given the number of available observations and the arrangement of

[3]The importance of the number of new steps to plant performance was established in Merrow, Phillips, and Myers, *Understanding Cost Growth and Performance Shortfalls*, Sec. V.

[4]For an excellent discussion of the practical use of correlation and regression in parametric cost analysis, see John E. Rolph, *Using Statistical Tools*, The Rand Corporation, N-2121-PSSP, April 1984.

those observations in a plot, the value of the correlation would be obtained randomly. Obviously, if it is likely that a given correlation could be achieved randomly, there is no statistical reason to accept that the two variables under scrutiny are associated. The probability of obtaining a given correlation randomly is called the "significance level."

The relationship between the number of observations one has and the significance of a correlation is shown by the following example. Consider an extreme case in which we might have only three observations that, when plotted, form a straight line. The correlation coefficient between the two variables when the points make a straight line is 1.0, but the probability that such a correlation could occur randomly with only three observations is quite high; therefore, the significance level is very low. In other words, we are not able to conclude anything about a possible association between the variables. As the number of observations rises, the strength of the correlation needed for believability—that is, having less than 5 chances in 100 of occurring randomly—declines.[5] With 38 observations (the number with which we work in most of this analysis), any correlation coefficient above about 0.33 has fewer than 5 chances in 100 of being generated randomly. As the correlation coefficient approaches 0.45, the probability of randomly obtaining such a relationship declines to less than 1 in 100, and as the correlation coefficient approaches 0.55, the probability falls to about 1 in 1000.

Statistics is a "backwards science." When we say that the correlation between two variables is highly significant, we are not trying to calculate the "true" relationship between the two variables. Rather we are testing to see whether we believe that *any* association exists between them and the direction of that association, i.e., whether it is positive or negative.

It is also important to recall that statistics show not causal relationships between variables, but associations. Two variables may be significantly correlated, that is, correlated at a level that we can believe is not random, but not causally related. In some cases, they may both have the same cause. In other cases, the causal relationship may be quite complex: One variable may start a chain that ultimately affects another variable. The belief that causality is or is not present results from theoretical understanding of the phenomenon being examined, not from the statistics. In this context it is wise to remember the classic story of the study in which an undeniable correlation was found between the number of nesting storks in an area and the birth rate in

[5]We have chosen the 5 percent chance level as the threshold for this analysis. While this value is quite conventional, it is, nonetheless, arbitrary. We might as easily have selected a value of 10 percent or 1 percent.

that area, leading to the conclusion that storks really do deliver babies. What the study actually found, of course, was that nesting storks and high birth rates are both attributes of rural areas.

Finally, some relationships between variables may be real and highly significant in a statistical sense, yet completely insignificant and uninteresting in the normal sense of the terms. For example, in our analysis, the various ways by which we measured the degree of technical innovation were shown to be highly correlated with each other. One would expect them to be, and the expectation is fulfilled, but no particular interpretation can be assigned to this correlation. In some cases, relationships between variables may be definitional. For example, whether or not a process is first-of-a-kind is highly correlated with the number of process steps that are new in commercial use. The correlation would happen randomly only about 1 time in 10,000. However, only technologies with at least some new steps are considered first-of-a-kind. Therefore, this correlation is simply an artifact of definition.

Multiple Regression

Multiple regression builds on correlations but enables us to deal with a number of variables simultaneously. A simple, two-variable regression provides almost the same information as a correlation coefficient.[6] The chief virtue of multiple regression, and the reason we used it in this analysis, is that it enables one to see the contribution of a number of factors in describing how something of interest varies. Regression is ideal for describing complex phenomena, such as the factors associated with better or poorer processing plant performance.

In multiple regression, one variable is designated the "dependent" (or predicted) variable, and others are designated "independent" (or predictor) variables. No causality is demonstrated between the dependent and independent variables in a regression. Causality may be imputed from things we know about a phenomenon, but not from the regression itself.

DATABASE DEVELOPMENT

The statistical methods we used permitted us to assess only projects and processes that are a subset of those contained in the database.

[6]The additional element in a simple regression is that the so-called intercept (constant) value is calculated and both variables are expressed in natural, rather than normalized, units.

Therefore, our most difficult task was to develop an appropriate and sufficiently large database to sustain the analysis. The criteria we used to select projects for the database are described below. The projects are described in detail in Section III.

Our original Pioneer Plants database contained data on 15 plants that chemically processed solid materials on the main process train.[7] We did not consider plants that process liquids or gases but handle solids off the main process train, e.g., refineries that reduce hydrogen sulfide to elemental sulfur as part of gas cleanup. We did include processes that use liquid or gas feedstocks but produce a solid material during processing. Some examples of solids processing plants are listed below:

Liquid and gas feedstocks with solids created downstream
- Petroleum coking
- Polyethylene
- Plastics resins

Refined solid feedstocks
- Coke calcining
- Explosive manufacture
- Herbicides

Raw solid feedstocks
- Coal gasification/liquefaction
- Direct reduction of metal ore
- Tar sands

We collected data on 25 additional solids processing plants to create our Solids Processing (SP) database. Thirty-two firms provided data, all under strict secrecy agreements.

To ensure that our results would be applicable to synthetic fuels and other energy process plants, we took special care to develop appropriate criteria for inclusion of plants in the SP database. The reasons for some of the criteria are obvious, but others require some discussion:

1. We preferred pioneer plants that were preceded by an R&D phase.
2. We sought relatively large plants, although we were aware that few very large plants are also pioneer plants. Large plants were sought because relatively large sizes are contemplated for many pioneer energy processing plants.

[7]Although they are usually solids, catalysts are excluded because they are not usually "chemically processed"—that is, they do not undergo a molecular change.

3. We wanted to ensure that all of the basic types of processing typically found in synthetic fuels plants were represented in the database. These include dissolvers, gas-solid reactors, hydrogenation reactors, synthesis gas reactors, and cokers. These five types of reactors represent the key aspects of all current chemically based synthetic fuels processes as well as those of most future systems.

We next selected 30 processes from a list of about 200 chemical and metallurgical processes. These processes, listed in Table 2.1, became our "target" processes for data collection.[8] All of the target processes contained one or more of the five basic processing units listed above and were represented in at least one plant in the database.[9] Although the data collection is slanted toward plants with technical similarities to synthetic fuels plants and other energy processing plants, other types of units are also included, and we believe the results are generally applicable to solids processing R&D requirements.

LIMITATIONS OF THE METHODOLOGY

A statistical approach to assessing R&D requirements has some limitations that should be kept in mind when applying the results of the analysis to particular cases:

[8]The following sources were used to secure process references, technical information, and representative plant information: *Canadian Chemical Registry*, 1978; *Canadian Mines Handbook*, 1982–83; "Construction Alert" series, *Chemical Engineering*; *Directory of Stone Producers and Lime Plants in the U.S. in 1981*, U.S. Bureau of Mines, Department of Labor; *Encyclopedia of Chemical Technology*, 3rd ed., John Wiley & Sons, New York, 1982; *Encyclopedia of Chemical Processing Design*, Marcel Dekker, New York; J. H. Gary and G. E. Handwerk, *Petroleum Refining*, Marcel Dekker, New York, 1975; "HPI Construction Boxscore," *Hydrocarbon Processing*, 1975–1983; F. Lowenheim and M. K. Moran, *Faith, Keyes and Clark's Industrial Chemicals*, 4th ed., 1975; "Metallurgical Works in Canada Nonferrous and Precious Metals," *Energy, Mines and Resources Canada*, January 1977; "Petroleum Refineries in Canada," *Energy, Mines and Resources Canada*, December 1979; "Smelter/Refinery Operations of the Free World," *E&MJ International Directory of Mining 1981*; Refining Process Handbook, *Hydrocarbon Processing*, 1975; *U.S. and Canadian Portland Cement Industry Plant Information Summary 1981*, Portland Cement Association; "U.S. and Canadian Refineries: Location, Capacities, Types of Processing," *Oil and Gas Journal*, March 22, 1982, pp. 132–154; A. L. Waddams, *Chemicals from Petroleum*, Gulf Publishing, Houston, Texas, 1980; 1981–82 World Mines Register, *World Mining*, Miller Freeman Publisher, San Francisco, 1982; and *The 1982 Directory of U.S. Chemical Producers*, SRI International.

[9]We generally excluded processes that had been used only overseas and processes in which a single company that was not a contributor to the database completely controlled the process technology.

Table 2.1

PROCESSES SAMPLED

Dissolver
Zinc (hydrometallurgy)
Nickel (hydrometallurgy)
Iron (hydrometallurgy)
Titanium
Soda ash (trona)
Sodium bicarbonate
Solvent refined crude (decarbonizing)
Upgraded heavy crude (solvent extraction)
Phosphoric acid (wet process)
Gas-solid reactor
Copper (roasting CuS)
Titanium dioxide (chloride)
Activated carbon
Graphite (from coal coke)
Gypsum (slurry)
Cement (dry)
Waste pyrolysis
Calcination (all types)
Hydrogenation reactor
Hydrometallurgy
Reformed liquids (platforming)
Hydrocracking
Upgraded heavy crude (H-oil/L-C fining)
Hydrotreating (severe)
Synthesis gas reactor
Methanol (high pressure)
Higher alcohols (oxo)
Synthesis gas (via steam reforming of natural gas)
Acetic acid by methanol carbonylation
Ammonia (high pressure)
Synthesis gas from heavy crude
Iron ore (direct reduction)
Coker
Residual upgrading (fluid coking)
Residual upgrading (delayed coking)
Residual upgrading (flexicoking)

- There is always some chance that the projects in the database are atypical of R&D projects and commercialization programs generally, or are atypical of such projects in the future. We have no reason to believe that this is the case, but in any statistical analysis, especially one based on a relatively small sample, this is a possibility.[10]
- This analysis is applicable only to R&D for chemical process plants. It is not applicable to R&D for powerplants or facilities that involve only physical processes, nor is it applicable to biological approaches to molecular change.
- Because this analysis is based on an examination of past projects, it cannot anticipate genuinely revolutionary technology.

[10]The solids processing database continues to expand. As additional projects are added, we will periodically update the results.

Fig. 3.2 — Sizes of plants in the database

III. THE SOLIDS PROCESSING DATABASE

In this section we describe our SP database. We begin by describing the general characteristics of the projects in the database. We then discuss the degree to which the plants incorporate innovative technology. We describe the kinds of R&D that were performed for the plants in the sample, the amount of difficulty that each problem posed, and the average effort devoted to R&D activities. We conclude by discussing how we defined plant performance, the figure of merit that we used in our analysis.

GENERAL PROJECT CHARACTERISTICS

All the plants in the SP database were constructed in the United States and Canada between the mid-1960s and 1983. (Thirty-three are in the United States and seven are in Canada.) All of the data were submitted by the plant owners rather than the engineer-constructors, and no company is represented by more than two plants. As shown in Fig. 3.1, chemical companies, minerals companies, and oil and gas companies are well-represented.[1] The "other" category includes companies whose main line of business is outside the process industries. We were able to find no relationship between the type of company and the results of our analysis. This is not surprising, because with very few exceptions, the companies involved have experienced, high-quality engineering staffs.

The basic dimensions that we use to describe the plants in the database are (1) size, (2) complexity, (3) capital cost, (4) project length, and (5) type of feedstock used.

Size

The design output of the commercial plants in the database ranges from just under 1 million lb/year to just under 5 billion lb/year. As shown in Fig. 3.2, most of the plants in the database are relatively large by process industry standards, producing over 100 million lb/year of output. There are, however, several small plants (under 25 million lb/year) and some very large plants (over 1 billion lb/year). The

[1]Several of the oil and gas companies provided data on chemical plants rather than petroleum processing facilities.

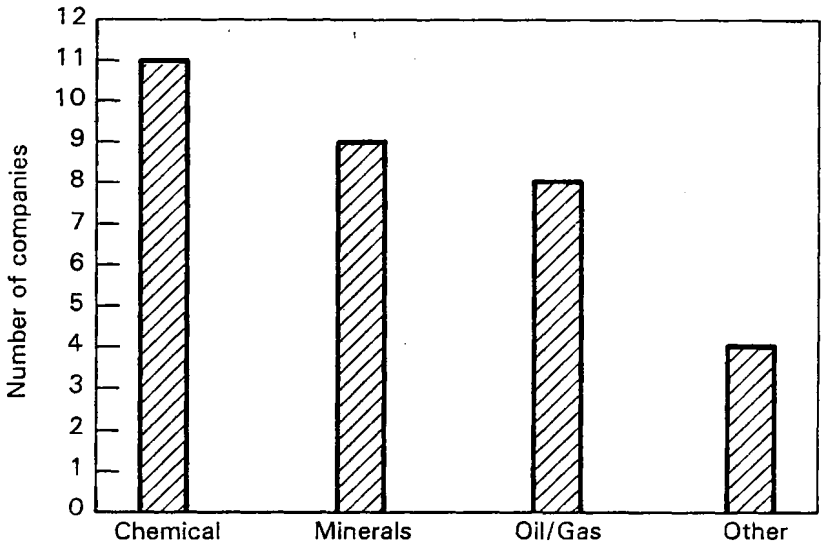

Fig. 3.1 — Types of companies submitting data on solids processing plants

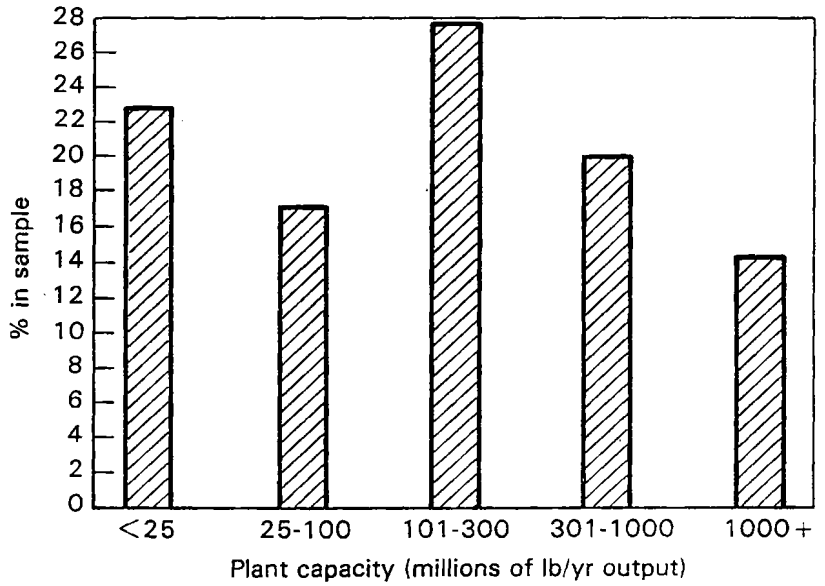

Fig. 3.2 — Sizes of plants in the database

average plant in the database produces about 865 million lb/year when it is operating at the design production rate.

Complexity

Plant complexity is measured by the number of physical and chemical steps in the process from the point at which raw materials enter as feedstocks to the point at which the product emerges.[2] Cleanup steps off the main process train are not counted, nor are parallel, identical steps as in a multiple train plant. Complexity and capacity are not correlated in this database. Some highly complex plants have relatively small throughputs, and some quite simple units have high output rates. Although we did not find this to be true in our earlier research,[3] we must at least consider the possibility that more complex plants will experience higher failure rates because the opportunities for failure increase with complexity.

Figure 3.3 shows the distribution of plant complexity in the database. The average and modal plants in the database have about five major subsystems on the main process train. Over one-quarter of the plants in the sample have seven or more subsystems and are considered complex plants.

Capital Cost

Figure 3.4 shows the distribution of capital costs. The capital costs of the plants in the database range from just over $1 million to over $.5 billion (in mid-1980 dollars), excluding R&D costs and all startup costs, both of which can be major cost elements.[4] We excluded these costs because they are treated in widely differing ways by different companies.

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[2]The principal alternative criterion for complexity is the number of pieces of major equipment. In the past, we collected data for complexity in both ways. Our analysis indicated, however, that the step counts were at least as good for statistical purposes as the major equipment counts and were a good deal easier to obtain. The process step counts are typically obtained from what are called "block" process diagrams.

[3]Merrow, Phillips, and Myers, *Understanding Cost Growth and Performance Shortfalls*, Sec. V. In prior analyses, we found that plant complexity is related to growth in capital cost estimates, but we have found no association with performance when other factors are considered.

[4]For a discussion of the importance of startup costs, see Christopher Myers and Ralph Shangraw, *Understanding Process Plant Schedule Slippage and Startup Costs*, R-3215-PSSP, The Rand Corporation, April 1986.

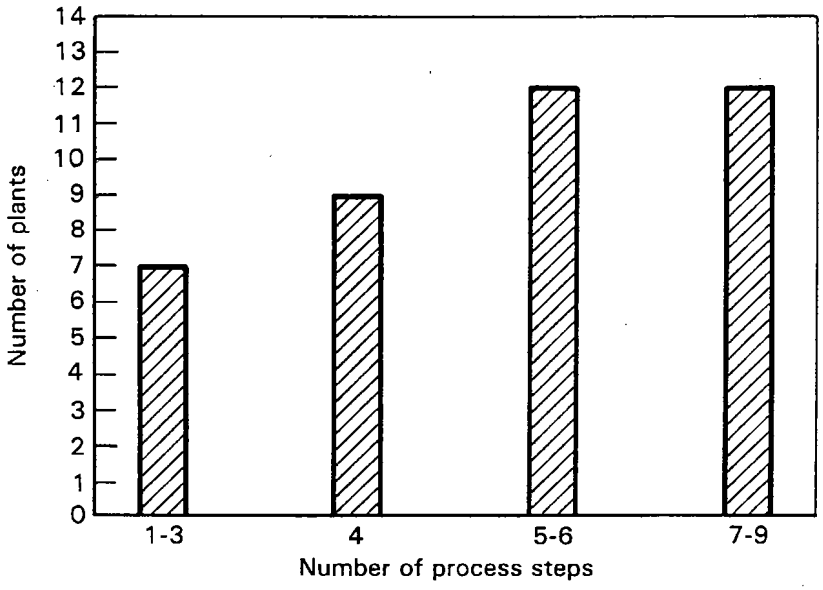

Fig. 3.3 — Complexity of plants in the database

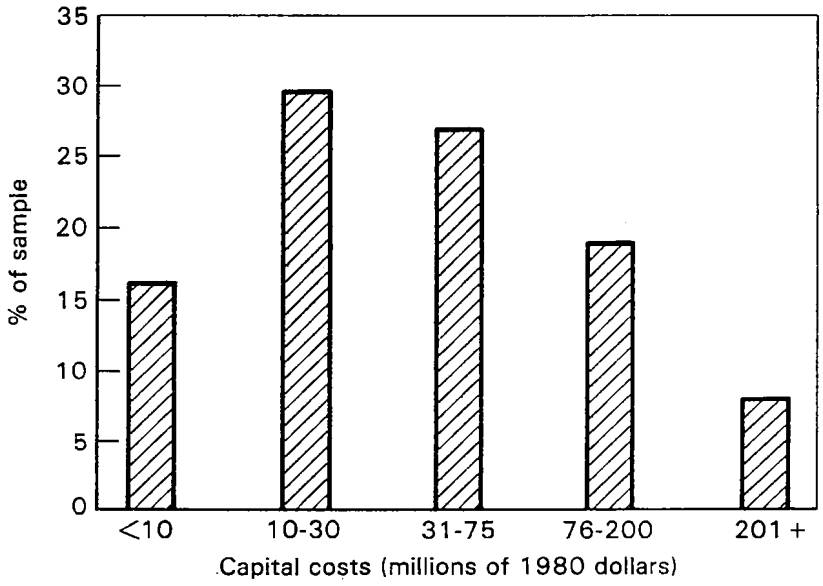

Fig. 3.4 — Capital costs of plants in the database

Project Length

Table 3.1 shows the average elapsed time for the major project phases. The project times are relatively long, totaling well over four years from the beginning of project definition until the end of startup. The wide variability in the median time for plant startup is in itself an indicator of performance problems.[5]

Table 3.1

LENGTH OF PROJECT PHASES IN SP DATABASE

Project Phase	Mean (months)	Median (months)
Engineering	21	20
Construction	23	22
Startup	8	4

Feedstock

As discussed in some detail in Section IV, the characteristics of the materials being processed significantly influence plant performance. Figure 3.5 shows that 14 of the 40 plants in the database convert liquids and gases into solid products or intermediates, while the remaining 26 plants use solid feedstocks. Ten of the plants that use solid feedstocks use "raw solid feeds," that is, solids that have undergone no chemical processing prior to being introduced into the plant. In general, we would expect much greater uncertainty about the characteristics of a raw solid feed than a solid that had been previously processed.

INNOVATION

The projects in the SP database vary enormously in the extent to which they attempt to introduce new and advanced technology. Some

[5]For projects on which the data were available, we also examined the amount of overlap between phases to see whether any of the schedules were clearly "fast-tracked" and whether that, in turn, led to severe performance problems. In a few cases, such problems did appear to be linked to the overlap of R&D with engineering and construction. The result was a constantly changing plant design.

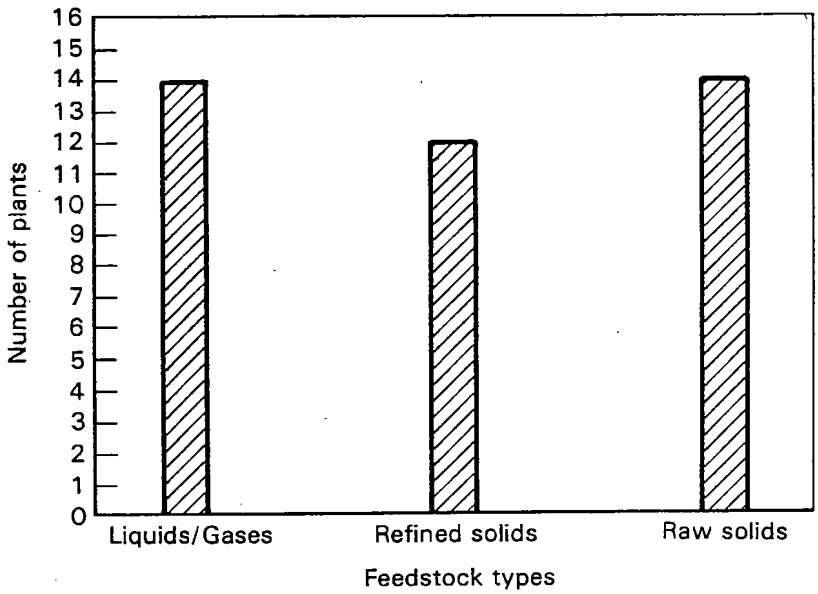

Fig. 3.5 — Types of feedstocks used by plants in the database

are relatively standard plants employing proven technology.[6] Others are the first commercial results of long and arduous R&D phases; these plants frequently introduce major new processes. This variability is potentially very useful to our analysis because it enables us to look for differences as a function of the "technical reach" of the project. Good measures of the extent to which new technology is present enable us to control for the degree of ambitiousness in the project as we examine the relationship between commercial plant performance and the R&D program. Other things being equal, we would always expect a more technically ambitious project to have more performance problems in the pioneer plant.

The most straightforward measure of innovation in a plant is the number of "new steps" in the process. A *step* is defined in this context as a functional subsystem in which a change is made to the material being processed. A step is "new" if it is *commercially unproven*, that is,

[6]Process plants are almost never truly standardized; even plants that, according to our definitions, would incorporate no new technology almost always introduce some new technical "wrinkles." In addition, site and scale differences often preclude repetition of prior designs.

if the chemistry or hardware has not been used before in the same service in a commercial plant. Scale of prior use per se is not an issue. If a step has been used at a smaller scale in a *commercial* facility (i.e., one that is set up to make product for sale rather than to produce information for facility design), then it is not new. We therefore distinguish between scale-up from a commercial facility and innovation as separate problematic dimensions.

Figure 3.6 shows the distribution of new steps in the database. Fourteen of the 40 plants have no new major subsystems on the main process train. The remaining plants have from one to five new steps.[7]

The introduction of a new process step is the exception rather than the rule for process plants. It may be necessary to develop several

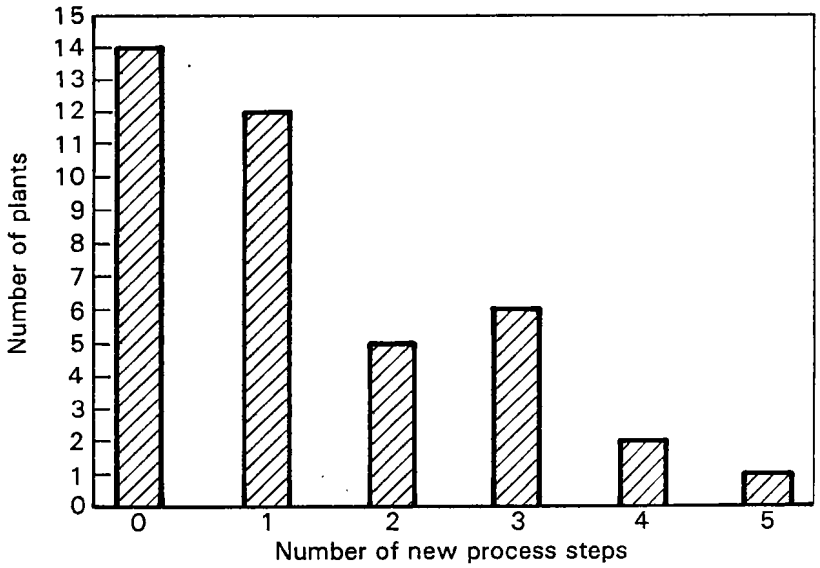

Fig. 3.6 — Distribution of new process steps in plants in the database

[7]The absence of new steps does not necessarily mean that no aspect of the plant is innovative. A plant may introduce new minor equipment such as pumps or valves or may integrate existing steps in new ways. Of the 14 plants in the database that have no new steps, one has some innovative minor equipment and four have one or more first-time integrations of commercially proven steps. Eight of the remaining nine were the largest units of their type constructed to that point. Only one of the 40 plants in the database was a true "replicate" of an earlier plant.

development facilities at increasing scale and then operate them to supply necessary design data. Thus, introducing a new process can be an expensive undertaking.

All of the reasons for introducing a new step involve, in one way or another, increasing the profitability of a plant. *To cut capital costs*, for example, two or more steps may be combined into one or the severity of process conditions may be reduced. A new step may be introduced *to increase the amount of product from a given quantity of feedstock, to improve product quality*, or *to introduce a new product*. Generally, a single new step is introduced to improve an existing process. As the number of new steps introduced increases, it becomes more likely that a substantially new process or product is being introduced.

CHARACTERISTICS OF THE R&D FOR PROCESSES IN THE DATABASE

R&D Difficulties

All of the R&D programs for the projects in our database were highly applied efforts. They did not attempt to break new scientific ground, although in some cases they did attempt to introduce radically new chemical processes. The vast majority of these programs were intended to reduce the cost of the processes involved rather than to introduce a new product. The average cost for professional staff on these programs was about $5 million, but those costs may be as high as $25 million in today's dollars. (These figures do not include the costs of any development facilities associated with the project.)

We asked each company to assess their R&D efforts for a particular plant by rating ten potential areas of R&D work on a scale of 0 to 5, with 0 constituting a non-issue for R&D and 5 indicating the most severe kind of difficulty.[8] In each case, the ratings were provided by someone with intimate knowledge of the project from inception through completion of the commercial plant. That knowledge was augmented with responses from various parts of the owner's organization, e.g., R&D, engineering, and operations.

Table 3.2 lists these areas and the average values assigned to them.[9] We divided the R&D areas into two basic categories, chemistry issues

[8]For full definitions and discussions of the ten areas, see Merrow, Phillips, and Myers, *Understanding Cost Growth and Performance Shortfalls*; and R. E. Horvath, *Pioneer Plants Study Users Manual*, The Rand Corporation, R-2569/1-DOE, June 1983.

[9]Table 3.2 does not include R&D on miscellaneous items such as plant safety and environmental uncertainties. However, these concerns were mentioned in only a small number of cases. It also excludes problems with gas handling, because these issues are not related to any of the phenomena of interest here.

Table 3.2

AVERAGE DIFFICULTY OF R&D PROBLEMS

(On a scale of 0 to 5)

Category	Average	Standard Deviation
Chemistry issues		
Pressure	0.74	0.98
Temperature	1.40	1.62
Corrosion	1.79	1.74
Impurities	1.79	1.80
Physical/mechanical issues		
Abrasion	1.26	1.69
Liquids handling	1.40	1.55
Feed characterization	1.61	1.78
Waste handling	2.0	1.69
Solids handling	2.18	1.94

and physical/mechanical issues, to capture the disciplinary "homes" of the R&D. These categories are the sources of important differences in the success of R&D efforts in improving performance.

The physical and mechanical problems of solids handling and waste handling were clearly the most severe R&D problems for the "average" plant in the database, followed by impurities, corrosion, and feedstock characterization. In virtually all cases, the standard deviation—the statistical measure of variance around the average—is large relative to the average, indicating that the severity of R&D problems represented in the database ranges widely.

The ranking of the R&D issues on the 0 to 5 scale is necessarily highly subjective. However, the ratings obtained with these scales have proven to be very reliable indicators; they correspond well with a variety of objective measures of the degree of innovation in the commercial plants and with the amount of effort (in either staff-years or dollars) going into the R&D program.

R&D Effort

Variations in the level of R&D effort reflect the wide range of innovation in the plants. Unfortunately, data on R&D costs tend to be very poorly kept.[10] Fewer than half of the projects that had R&D costs

[10]For a discussion of information preservation in the process industries, see Christopher W. Myers and R. Yılmaz Argüden, *Capturing Pioneer Plant Experience: Implications for Synfuels Projects*, The Rand Corporation, N-2063-SFC, January 1984.

could trace the amounts. Data on R&D staff-years appear to be kept more carefully. R&D effort on the projects in the SP database ranges from none to more than 70 staff-years; more than one-third of the projects consumed 10 or more staff-years, exclusive of pilot plant efforts.

MEASURING PLANT PERFORMANCE

As stated above, we used plant performance as our figure of merit in assessing the contribution of R&D to the value of a commercial project. We defined performance as the amount of acceptable product that the plant produces over time relative to the amount that it was designed to produce. Because most of the product can be stored, plant availability (the amount of time in which the plant is in an operable condition) is much less important for process plants than it is for powerplants, where storage is generally impractical.

In our calculations of plant performance, we have leaned toward reporting better rather than worse performance. We used the average output as a percent of design for six months, beginning in the seventh month after startup. Month seven was used because, even in relatively standard plants, a few months are usually necessary to repair deficiencies in construction and equipment manufacture. Also, unless operator training has been very thorough and has started well before the end of construction, operator errors can cause substantial lost production in the early months.[11]

There are also other complications that must be recognized and adjusted for, the most important and common of which is deliberate restriction of plant output because markets are soft.[12] We eliminated those periods when plant output was held below the maximum obtainable, along with the month before and the month after such periods, from our counts of six months of performance. We eliminated the adjacent months because there is often a period of gradual turndown in the plant's operation on one side and a period of new startup on the other. Because of these adjustments, the six months that are averaged to provide our measure of performance may have actually extended over the first two years of the plant's operational life.

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[11]Operator error is, not surprisingly, much more common in first-of-a-kind plants. There is also an apparent tendency on the part of designers to cite "operator error" for performance problems even when major design deficiencies were later acknowledged. If a process requires higher-than-average operator skill and technical understanding, the problem is with the process design, not the operator.

[12]In a few cases production was restricted by the lack of available feedstocks. These are treated in the same manner as market limitations on output.

IV. DATA ANALYSIS

In this section, we describe the results of our analysis, including the relationships among R&D, the nature of the projects, and plant performance. The goal of the analysis is to identify empirically the high-payoff areas for R&D in solids processing plants.

Our analysis has four basic steps:

1. Comparison of the performance of solids and liquids/gas processing plants to determine whether solids processing plants constitute a true subset of chemical processing plants and to establish the appropriateness of our choice of plant performance as the figure of merit for the analysis.
2. Exploration of the characteristics of plants that have had performance problems and to explore the possible causal relationships between those characteristics and performance.
3. Examination of the nature and severity of the R&D problems studied for the plants in the database and of the relationships, if any, between those problems and performance. (If the R&D program was successful, there should be no relationship between the problems tackled in R&D and plant performance. To the extent that such relationships exist, the R&D program may have failed to achieve the desired results.)
4. Examination of the actual causes of performance failures among the plants that experienced difficulties, both in areas that were not anticipated in R&D and in areas that were seen as problematic in R&D. We are especially interested in problems that occur widely, whether or not they were anticipated in R&D, because the plants in the database cover a substantial period of time. Problems that occur persistently would suggest that some difficulties experienced by solids processing plants are not being addressed successfully by industry.

COMPARING SOLIDS AND LIQUIDS/GAS PROCESSING PERFORMANCE

To demonstrate that solids processing plants constitute an identifiable subset of chemical processing plants, we compared the plants from

the Pioneer Plants database that process only liquids and gases with those in the SP database.[1]

Figure 4.1 compares the average performance of solids and non-solids processing plants. Of the plants we studied, those that process no solids averaged 84 percent of design performance. The worst plant failed to operate at all, but it was the most innovative plant in the total database, with 7 new process steps. More than 60 percent of the non-solids plants were producing at 90 percent of design performance or better. The average performance of solids processing units was about 63 percent of design. The worst plant produced nothing; the best averaged more than 100 percent.

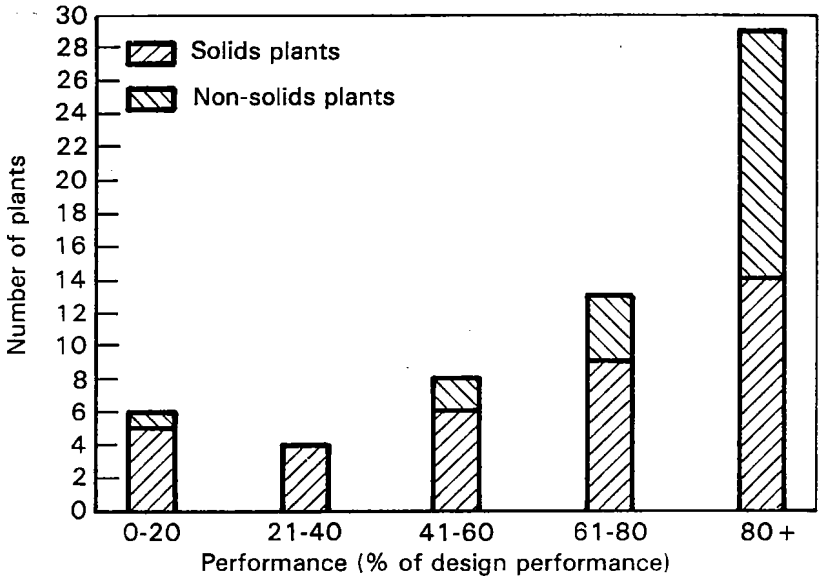

Fig. 4.1 — Performance of solids processing plants vs. non-solids processing plants

[1]The liquid and gas plants include all of those in the database for which the necessary data were available. The liquid and gas plants are slightly more innovative than the solids plants, averaging about 1.6 new steps per plant, as compared with about 1.4 new steps for the solids plants.

In economic terms, the difference between 63 percent of design and 84 percent is very large.[2] It implies a capital cost per unit of output about one-third higher for the solids processing plants, on the basis of poor performance alone. In addition, poor performance is inevitably associated with higher operating and maintenance costs per unit of product. Generally, operating costs per unit output will increase more rapidly than capital costs as performance declines, because higher absolute costs will be incurred for plant maintenance. In addition, poor performance may require additional operating personnel and additional operator training. Other costs tend to be fixed for the plant as a whole and therefore increase uniformly per unit output as performance declines.[3]

The wide range of performance shown in Fig. 4.1 suggests that there are at least two distinct classes of plants in terms of performance: those that process solids and those that do not. This distinction is verified by the following equation:

$$\textit{Performance}\ (\%) = 112 - [9 \times \underset{(.0001)}{\textit{new steps}}] - [44 \times \underset{(.0001)}{\textit{percent of balances unknown}}] - [15 \times \underset{(.0001)}{\textit{if solids plant}}] \quad (4.1)$$

where $R^2 = .83$; the number of plants[4] = 60; the standard error of the estimate (SEE) = ±13 percent of actual performance; and the probability that the coefficient value is indistinguishable from zero, i.e., the "statistical significance" of the coefficients, is .0001. These significance levels are analogous to the significance levels for correlation coefficients discussed in Section II.

[2]For a discussion of the effects of performance on unit product costs for process plants, see R. W. Hess et al., *An Analysis of the Cost, Schedule, and Performance of the Baseline SRC-I Commercial Demonstration Plant,* N-1952-DOE, The Rand Corporation, February 1983.

[3]The only costs that tend to remain stable per unit output are items purchased continuously from outside the plant, i.e., feedstocks and chemical inventories. Of these, only feedstocks may be an important cost item, and feedstock costs may even increase with poor performance, either because the costs are fixed by "take or pay" contracts or because the feedstock is integrated with the plant as in mining operations and it is impractical to lay off workers or sell the feedstock to others.

[4]Unfortunately, two plants were excluded from the analysis because there were no data on the key variable, plant performance. The two plants, both solids processing units, were excluded from all the analyses so that the set of plants examined would be consistent.

We begin with a performance value of 112 percent of a plant's design.[5] (This value is the intercept of the equation. It is an artifact of the statistical model and merely provides a place for the equation to start.) The performance expectations are then reduced by about 9 percent for each process step that is new in commercial use; by 0 to 44 percent of design, depending on the portion of the heat and balance equations for the plant's design that were set without a firm empirical basis (these equations describe the mass and energy flows throughout the process); and by 15 percent if the plant processes solids. Thus, if we had a solids processing plant with 2 new steps, for which 50 percent of the heat and material balances could not be set from data from prior units, we would expect the plant to operate at about about 57 percent of design performance in the second six months after startup:

$$[112 - (2\times9) - (.5\times44) - 15] = 57.$$

As indicated by the R^2 term, these three factors—new steps, percentage of balance equations unknown, and solids processing—account for more than 83 percent of the substantial variability in plant performance.[6] Figure 4.2 illustrates what this means in terms of reducing the uncertainty about plant performance. The top curve (a) shows the "spread" in the actual performance of the plants examined, determined by taking the average plant performance and deriving the standard deviation around the average. A range of ±29 percent of design around the average performance would be necessary to capture 68 percent of the plants in the sample.[7] However, after controlling for the three factors in Eq. (4.1), a range of ±13 percent of design will capture 68 percent of the plants in the sample, as shown in curve (b). As discussed below, inclusion of other factors will generate an even tighter distribution.

Table 4.1 compares the values of the input variables for the SP database with those for the liquids/gas processing units. A key difference is the lack of knowledge about the heat and material balances for

[5]Although it may appear to do violence to the definition of "design," some plants—most of them quite standard, non-solids processing plants—do manage to exceed their design production rate within the first year. The maximum performance among the plants in our database in the six months after startup was 105 percent of design.

[6]This equation and all the other regression models in this report have been subjected to a set of diagnostics that help the analyst understand whether the results may be in part the product of statistical anomalies. The equations were checked for multicollinearity by examining the condition indices, for heteroscedasticity by examining the plots of the independent variables against the residuals, and for influential observations by "Cook's Distance." All diagnostic test results were well within acceptable levels.

[7]That is, 1 standard deviation around the mean.

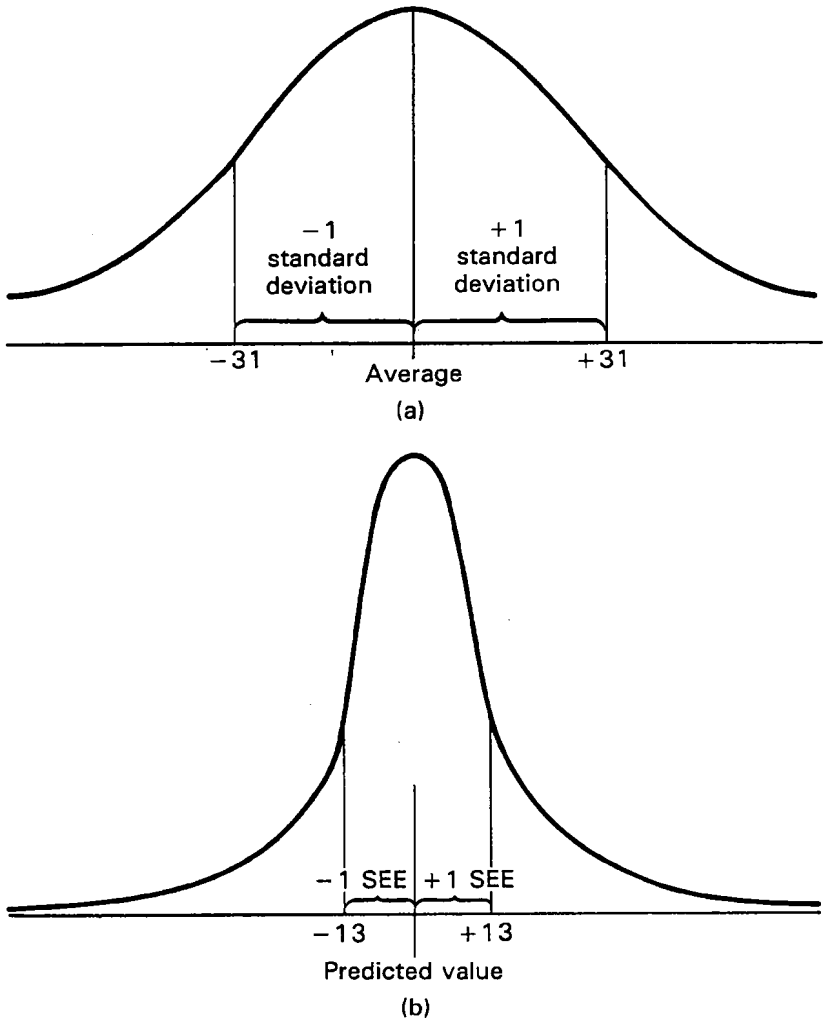

Fig. 4.2 — Reduction in performance variation for all types of plants, using Eq. (4.1)

the solids processing units, relative to the level of knowledge in the liquids/gas processing units. Any explanation of the poor performance of solids units must consider the factors that drive this poor state of knowledge. We will return to this issue below.

The importance of the heat and material balances in the performance of solids processing plants is indicated in Table 4.2, which compares the roles of new steps and the heat and mass balance equations for liquids/gas processing versus solids processing. The correlations between both factors and performance is very high for both types of units. However, the pattern of correlation suggests some differences. The simple relationship between plant performance and the number of new steps is about the same for liquids/gas processing and solids processing units. However, the relationship between plant performance and the knowledge of the balance equations for solids plants is overwhelming. The knowledge variable alone "accounts for" over 70 percent of the variation in the performance of solids processing plants,

Table 4.1

CORRELATES OF PERFORMANCE IN SOLIDS AND LIQUIDS/GAS PROCESSING PLANTS

Item	Type of Plant		Difference
	Liquids/Gas (N = 22)	Solids (N = 38)	
Performance (% of design)	84	63	21
No. of new steps	1.4	1.6	0.2
Percent of heat and mass balances unknown	48	33	15

Table 4.2

CORRELATES OF PERFORMANCE FOR SOLIDS AND NON-SOLIDS PROCESSING PLANTS

Item	Type of Plant	
	Liquids/Gas (N = 22)	Solids (N = 38)
No. of new steps	−0.79	−0.75
Percent of heat and mass balances unknown	+0.68	+0.85

NOTE: All statistically significant at $P < .05$.

but only about 46 percent of the variation in liquids/gas processing units. In other words, if we write two equations of the form

$$Performance = a - b \times [balance\ equations\ unknown]$$

where a is a constant and b is the coefficient of the balance-equations variable, the R^2 for solids processing units is about .72; for the liquids/gas units, it is about .46.

We can summarize our performance comparison as follows:

- Solids plants have substantially poorer performance than liquids/gas processing plants. Solids plants *are different.*
- The difference in performance is very telling for plant economics, since performance drives the cost of other major categories to a significant extent.
- Part of the performance difference is captured by defining solids plants as a separate class. The lack of knowledge of heat and material balance equations among the plants in the SP database also significantly affects performance.

We next examine the characteristics of the 40 plants in the SP database to attempt to identify the factors that are associated with their poorer performance.

DETERMINANTS OF PROCESSING PLANT PERFORMANCE

Based on the performance model (Eq. (4.1)) and theoretical considerations, we would expect the primary factors affecting plant performance to be:

- A project's level of innovation.
- The percentage of the heat and mass balance equations known.
- The characteristics of the materials being processed.

We will consider each of these factors in turn.

Plant Performance and Innovation

As noted in Section III, innovation in process plants can take many forms. It may involve the commercial introduction of new chemistry to produce a new or existing product or to upgrade the commercial quality of an existing one. It may involve all of the process steps or only one.

It may entail new design for all, some, or none of the major equipment items. Novel integrations of proven chemical process steps constitute a type of innovation. Finally, what is conventional for one firm or in one country may be highly innovative in another context.

Because there is no general agreement on the definition of innovation, we have used a number of variables to assess the level of innovation in the plants in our database. Table 4.3 describes the relationship between these measures of innovation and plant performance by showing their correlations.[8] Recall that for 38 observations, correlations larger than ±.33 are significant at $P > .05$, and correlations larger than ±.42 are significant at $P > .01$. The degree of innovation is inversely related to performance, as would be expected. In general, the variables used to assess the degree of innovation without reference to the firm's experience with the process are better predictors of performance.

Table 4.3

CORRELATIONS BETWEEN MEASURES OF INNOVATION AND PERFORMANCE

Variable	Correlation with Performance
First-of-a-kind facility	−.53
First time built in the U.S. or Canada	−.48
First time built in the U.S. or Canada by this firm	−.36
Facility largest of its kind	−.37
Number of new steps in process	−.75
Number of first-time integrations of commercially proven steps	−.42
Plant required design of new process equipment	−.46

Of the various measures, the number of new process steps has the highest degree of correlation. Indeed, modeling plant performance using this variable alone produces reasonably good results. Figure 4.3 shows the relationship between performance and the number of new steps for the 38 plants in the SP database. Equation (4.2) formally states the relationship.

$$\underset{(.0001)}{Performance = 88 - 18 \times [new\ steps]} \qquad (4.2)$$

[8]A brief discussion of the statistical interpretation of the correlations is provided in Section II. For a more complete discussion, see Rolph, *Using Statistical Tools.*

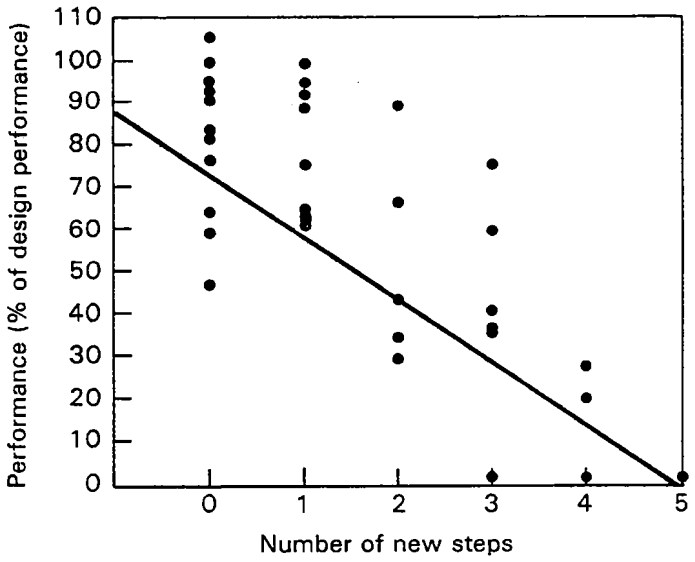

Fig. 4.3 — Performance as a function of new steps

for the case where R^2 = .60; N = 38; the standard deviation of performance = 31 percent; SEE = 20 percent; and P > F = .0001.

Equation (4.2) indicates that starting at a level of 88 percent of design, performance will be reduced by 18 percentage points for each new process step. Thus, expected performance would be within 20 percentage points of actual performance about two-thirds of the time. This is a modest improvement over simply taking the average performance value as the expected value, which would be accurate within ±31 percentage points about two-thirds of the time. As we will see below, far better and more complete models of solids plant performance are possible.

Plant Performance and the Heat and Material Balances

The degree of technical uncertainty involved in designing, constructing, and starting up a plant depends on more than just whether the process steps have been commercially proven or the other measures of innovation shown in Table 4.3. Technical uncertainty also depends on the basis or source of the process information used in designing the

plant. Among the most critical data for plant design are the heat and mass balance equations. As Fig. 4.4 suggests, these equations model all of the energy and material flows in and out of every step in the plant. Correct balances are essential for sizing all the equipment in the plant, and they are also essential to some of the chemical process involved.

The best source of data on heat and material balances is usually experience from commercial plants of the same or nearly the same scale. When the balances are not available from prior operating experience, however, they can be calculated from a number of other sources, including:

- Data from a full-scale pilot or demonstration facility
- Data from process development units
- Laboratory data
- Computer simulation models
- Theoretical information (such as equilibrium data, heat and mass transfer correlations, published kinetics data, or design correlations)

The variable that we use to describe the state of knowledge of the heat and material balances is the percentage of all heat and material balances around each process step that are based on prior commercial experience. For example, a 10-step process will have at least 20 equations to describe its energy and mass flows. If 16 are based on data

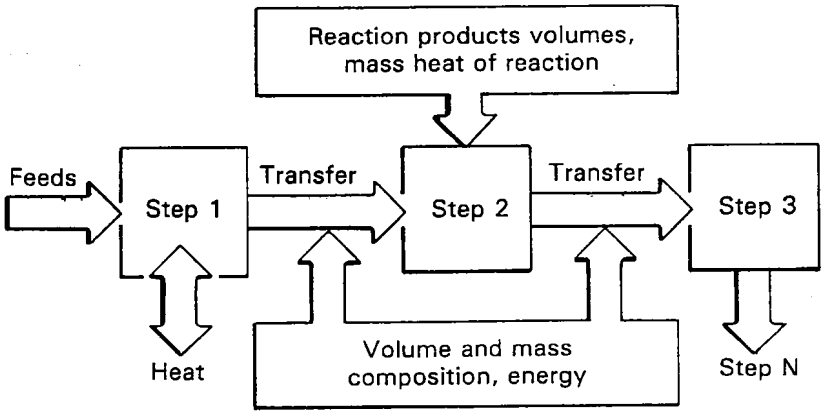

Fig. 4.4 — Heat and mass balance

from prior commercial units, the portion "known" would be 80 percent.

Recall from Table 4.1 that knowledge of the heat and material balances for the solids processing plants was substantially less than for liquids/gas processing plants. Figure 4.5 shows how knowledge of the heat and mass balances is distributed among the 38 plants in the SP database. The distribution is somewhat bimodal, suggesting a tendency to know either virtually all of the balances or almost none.

Knowledge of the balance equations is not strictly a function of the number of commercially unproven blocks in a plant or of any other measure of innovation, as illustrated by the ranges in Tables 4.4 and 4.5.

Table 4.4 shows a clear relationship between the number of new process steps and knowledge of the heat and material balances: The average percentage of the equations known declines from about 75 when there are no new steps to 0 when there are 4 or more new steps. As indicated by the range, however, the heat and mass balances do not depend strictly on the number of new steps. *Some plants with no new steps had none of the balances based on data from prior commercial*

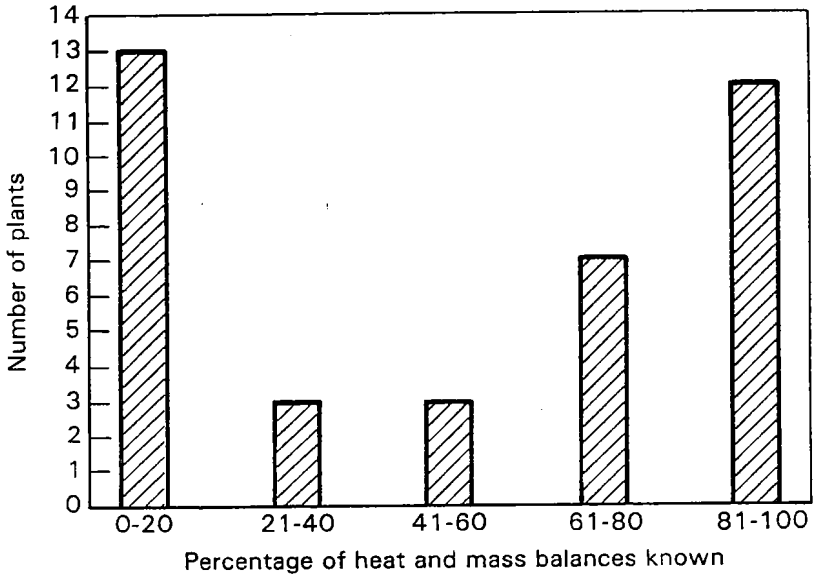

Fig. 4.5 — Distribution of heat and mass equations knowledge

units, and some plants with several new steps had substantial portions of the balances derived from commercial experience.

The same pattern is evident in Table 4.5, which shows the relationship between the balance equations and several measures of innovation.

In general, the greater the resemblance of a facility to a pioneer plant, the less the firm is able to use commercial experience to calculate the balance equations. For pioneer plants, the existence of a similar facility in the United States or Canada makes a substantial difference, as does, to a lesser extent, the firm's prior involvement in such units. In each category, however, considerable range in knowledge is evident. In pioneer plants built by companies that had built plants of a related type before, there was apparently better understanding of the heat and material balances at an early stage.

Table 4.4

RELATIONSHIP OF NEW STEPS TO KNOWLEDGE OF BALANCE EQUATIONS

Number of New Steps	Percent of Balance Equations Based on Prior Commercial Units	
	Average	Range
0	75	0–100
1	58	0–100
2 or 3	31	0– 80
4 or more	0	—

Table 4.5

RELATIONSHIP OF INNOVATION TO KNOWLEDGE OF BALANCE EQUATIONS

Measure of Innovation	Percent of Balance Equations Based on Prior Commercial Units	
	Average	Range
First-of-a-kind facility	35	0–100
First time built in North America by *any* firm	40	0–100
First time built in North America by *this* firm	46	0–100

The extent to which the heat and material balances are not based on commercial experience is strongly associated with the performance of solids processing plants, as shown in Fig. 4.6. The relationship is formally stated in Eq. (4.3), which attempts to predict solids plant performance on the basis of the knowledge of the heat and mass balances alone:

$$\textit{Performance} = 95 - \underset{(.0001)}{65} \times [\textit{percent of balances unknown}] \quad (4.3)$$

for the case where $R^2 = .70$; N = 38; the standard deviation of performance = 31 percent; SEE = 17 percent; and P > F = .0001.

Beginning with an intercept value of 95 percent of design, expectations of performance decrease by about 6.5 percent for each 10 percent of the heat and mass equations not based on data from prior commercial units. This model explains more of the variation in plant performance than did Eq. (4.2)—70 percent versus 60 percent—and it has a slightly smaller standard error—±17 versus 20 percent of design.

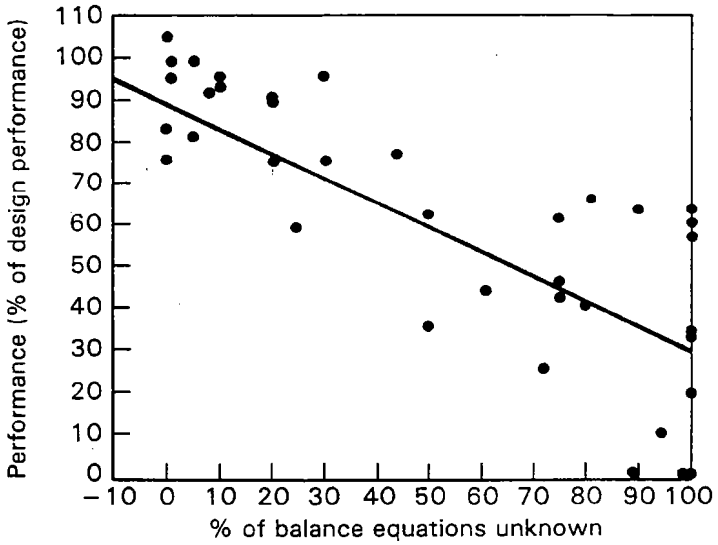

Fig. 4.6 — Effect of knowledge of heat and mass balances on performance

It is possible that knowledge of the heat and material balances and the number of new steps explain the same kind of variation in plant performance. However, Eq. (4.4) suggests that they tap significantly different dimensions:[9]

$$\underset{}{\textit{Performance}} = 100 - \underset{(.0001)}{10} \times [\textit{new steps}] - 45 \times \underset{(.0001)}{[\textit{percent of balances unknown}]} \tag{4.4}$$

for the case where $R^2 = .84$; N = 38; the standard deviation of performance = 31 percent; SEE = 12 percent; and P > F = .0001.

The model produced by including both the number of new steps and the balance equations measure is substantially better than that produced by either variable alone. Equation (4.4) explains about 84 percent of performance variation in plants in the SP database, and the standard error is only ±12 percent of design—a substantial improvement over Eqs. (4.2) and (4.3).

Plant Performance and Feedstock

Because a wide variety of feedstocks are represented in the SP database, it is not possible to isolate differences that might be attributable to particular feedstocks. However, we can characterize some basic differences according to whether the feedstock is a gas, liquid, or solid. Figure 4.7 shows the average performance and range of performance for these three types of primary feedstock.

Liquid and gas processing plants perform almost identically. We therefore treat them together in this analysis. However, an enormous gap exists between the performance of the solid feedstock plants and all others. We can test to see if this gap is an artifact of new steps and the lack of knowledge of balance equations by adding a categorical variable for solid feedstock plants to Eq. (4.4). If the difference is merely an artifact, the regression coefficient will not be significant:

$$\underset{}{\textit{Performance}} = 104 - \underset{(.0001)}{9} \times [\textit{new steps}] - 39 \times \underset{(.0001)}{[\textit{percent of balances unknown}]} - \underset{(.006)}{14}\,[\textit{if solid feedstock}] \tag{4.5}$$

for the case where $R^2 = .87$; N = 38; SEE = ±12 percent; and P > F = .0001.

[9]As noted before, the independent variables do not display multicollinearity or heteroscedasticity problems.

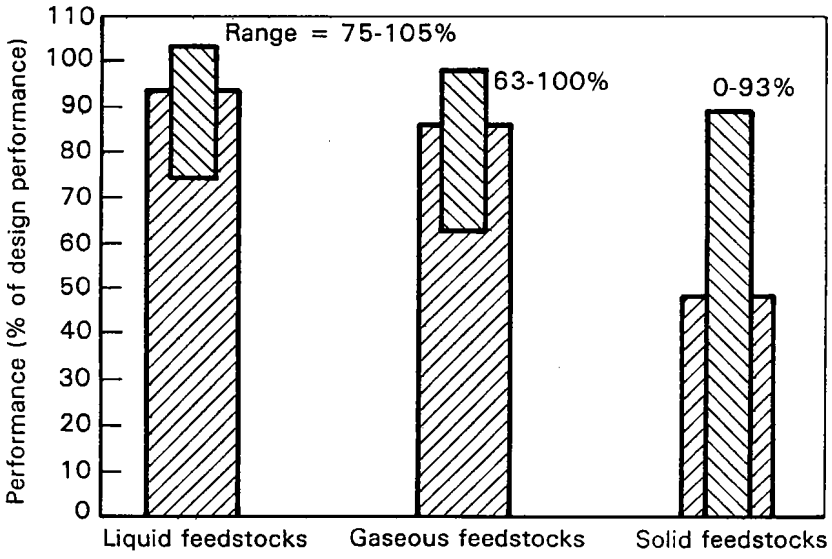

Fig. 4.7 — Effect of feedstocks on performance

Although the solid feedstock coefficient is significant (.006) and the addition of the solid feedstock distinction improves the model, solid feedstocks account for only 14 of the 40+ percentage point difference between performance of liquids/gas feed plants and that of solid feed plants. Most of the remaining difference is accounted for by the lack of knowledge of the heat and material balances at the solid feedstock plants.

It is not surprising that differentiating solid feedstock processes helps explain performance. Plants with solid feedstocks generally engage in much more solids processing than do those that start with liquids and gases and then produce solids somewhere downstream, often at the last or the penultimate step in the process.

To complete the performance model for plants in the SP database, we substitute a dummy variable for unrefined ("raw") solid feedstocks for the more general category of solid feedstocks. A refined solid feedstock has undergone chemical processing prior to being introduced into the plant, whereas a raw solid feedstock is generally a mined mineral, such as coal, phosphate rock, or metal ore. Raw solid feedstocks are associated with a host of operational difficulties. Plants using raw feedstocks must do more solids processing, the feedstock is

more variable, and it is much more difficult to accurately characterize[10] the feedstock.

The final performance model is shown in Eq. (4.6):

$$\begin{aligned} \textit{Performance} = 102 &- \underset{(.0001)}{8} \times [\textit{newsteps}] - 44 \\ &\times [\textit{percent of balances unknown}] - \underset{(.0001)}{} 21\ [\textit{if raw solid feedstock}] \\ & \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (.001) \end{aligned} \tag{4.6}$$

for the case where $R^2 = .91$; N = 38; the standard deviation of performance = 32 percent; SEE = 9 percent; and $P > F = .0001$.

The interpretation of Eq. (4.6) is summarized in Fig. 4.8. Beginning with an intercept value of 102 percent of design, expectations about performance should be reduced by an average of 8 percent for each new step incorporated in the commercial plant, minus 44 percent of design times the fraction of the heat and material balances not based on empirical data from prior plants, minus 21 percent of design if the plant employs a raw solid feedstock.[11]

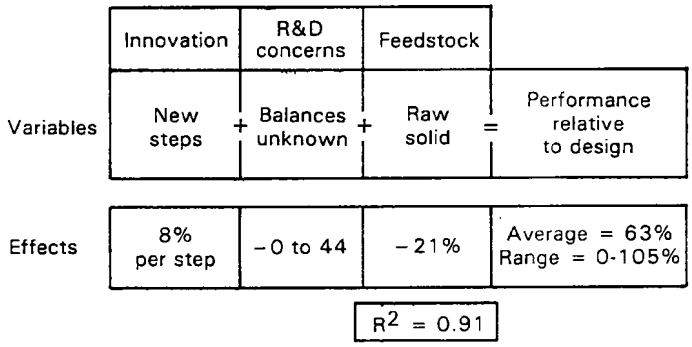

Fig. 4.8 — Plant performance as described by Eq. (4.6)

[10]That is, to delineate the precise chemical mixture and chemical compounds in a solid material, as well as certain properties of the material such as friability, grindability, etc.

[11]One other variable almost meets our .05 test of statistical significance: use of refined solid feedstocks. When a dummy variable for refined solid feedstocks was included in the model, plants operated on average about 6 percent of design worse than liquid and gas feed plants. The difference, however, is not quite consistent enough to be included in the final model.

These three variables account for more than 91 percent of the variation in plant performance (R^2 = .91), and they reduce the standard error around performance of solids plants to a little over ±9 percent of design. The magnitude of improvement that this represents is illustrated in Fig. 4.9. The first distribution represents the performance of plants in the database before adjustments for new steps, balance equations knowledge, and solid feedstocks. The second distribution shows the remaining variation after these factors are accounted for.

R&D PROGRAMS FOR PROJECTS IN THE SP DATABASE

The model described above satisfactorily explains the characteristics of projects that are associated with poor plant performance. Now we shall investigate whether the problems worked on in R&D affect performance through the variables in the performance model.

We begin by describing the R&D programs that presaged the commercial plants in our database (using data we were given on 29 explicit R&D programs).[12] We will then explore the nature of the R&D problems addressed. Finally, we will examine the relationships between the kinds of R&D problems addressed and the two major factors that determine plant performance: the knowledge basis for the balance equations and feedstock type.[13]

Description of the R&D Programs

As would be expected, the variability in the R&D programs in the SP database mirrors the variability in the innovativeness of the ultimate commercial plants. Table 4.6 shows the distribution of R&D program lengths. The median program was 27 months.[14] The levels of effort, not including the time associated with building pilot plants and similar facilities, ranged from about one staff-year to more than 70 staff-years.

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[12]Some of the nine projects that had no R&D phase were the standard plants in the database; others had R&D performed by a third-party process developer from whom little or no information was available. In general, data on the nature of the R&D programs are less complete than other types of data; R&D information is often poorly kept. See Myers and Argüden, *Capturing Pioneer Plant Experience*, for a full discussion of this problem.

[13]The number of new process steps is also included in the analysis as a control on the difficulty of the R&D effort involved. As we will see, however, this control is unnecessary.

[14]The median is more meaningful than the mean in this case because a few programs were extremely long, raising the mean to over four years.

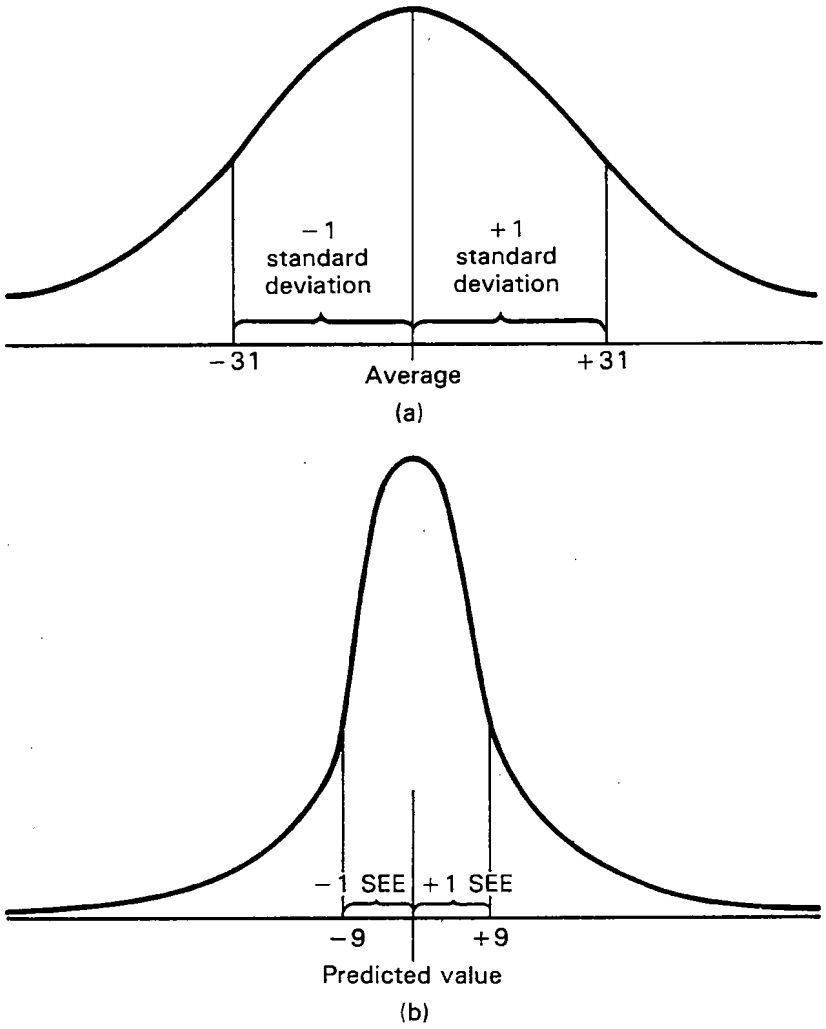

Fig. 4.9 — Improvement in the predictability of performance of solids processing plants, from Eq. (4.6)

Table 4.6

R&D PROGRAM LENGTH

Year(s)	Percent of Firms (N = 26)
1 or less	32
1+ to 2	5
2+ to 3	18
3+ to 4	8
4+	37

The R&D efforts for plants in the database are, like most industrial R&D, highly applied programs. They are intended to meet specific commercial goals, rather than to enhance basic R&D knowledge. The programs are intended to reduce the uncertainties associated with a process (or some portion or aspect of a process) so that preliminary design work can proceed for a commercial plant. In 18 cases, the R&D programs per se were augmented with process development units or integrated pilot plants.[15] The R&D programs focus on those aspects of the process that are innovative or have been shown to be problematic in prior units of the same general type.

The Nature of the R&D Problems Addressed

We requested information about problems that were worked on in R&D preceding commercial projects and about the degree of difficulty of those problems. Each of ten potential R&D areas was rated for degree of difficulty on a subjective scale of 0 (no difficulty) to 5 (major problem). The average values assigned to the categories are shown in Table 4.7 (repeated from Table 3.2). We discuss each of the R&D areas below.

Problems of temperature and pressure control are the "heart" of much chemical process R&D, especially for complex-molecule organic chemicals processing. Temperature and pressure uncertainties generally receive more R&D attention than any other items, if only because they must be resolved, or there is no process.

Corrosion problems typically result from impurities in feedstocks or impurities created during processing. Corrosion can result in serious cost problems. There are modern materials that will withstand

[15]There were also 17 bench scale process units. These units were very small and are generally considered part of the R&D program. Industry generally views pilot plants (including process development units, fully integrated pilot plants, and demonstration-type units) as part of engineering.

Table 4.7

ASSIGNED VALUES OF AVERAGE DIFFICULTY OF R&D PROBLEMS

(On a scale of 0 to 5)

Category	Average	Standard Deviation
Chemistry issues		
Pressure	0.74	0.98
Temperature	1.40	1.62
Corrosion	1.79	1.74
Impurities	1.79	1.80
Physical/mechanical issues		
Abrasion	1.26	1.69
Liquids handling	1.40	1.55
Feed characterization	1.61	1.78
Waste handling	2.0	1.69
Solids handling	2.18	1.94

corrosive attack from even highly concentrated corrosive agents, but such materials are expensive and may pose equipment fabrication problems.

Problems associated with *chemical impurities* in intermediate process streams often arise when new chemistry is being introduced, especially when organic chemicals are involved. Because of the complex reactions associated with some organic chemicals production, process-damaging impurities are frequently produced. The problem tends to be exacerbated when processes require extensive recycling of materials to reactors. In such cases the recycle stream can act as a concentrator of impurities, and this may in turn cause corrosion of reactor internals or the "poisoning" of a catalyst.[16]

We would expect serious R&D problems with temperature, pressure control, corrosion, and impurities to be associated with large technical advances (almost as a matter of definition), and resultant attempts to advance the state of the art rapidly to be associated with performance difficulties. However, as Table 4.8 shows, the relationships are quite unclear for solids processing plants. With the exception of corrosion, none of these chemistry-related areas is sufficiently strong to have less than a 5 percent chance of occurring randomly. Also, there is no relationship between the average level of difficulty in a problem area and performance problems. Of the four areas, impurity buildup

[16]Of course, a number of advanced fossil energy conversion processes share the characteristics of impurity problems.

problems are, on average, judged to be the most serious in R&D. However, the correlation with performance is also very weak. Thus, although a significant number of the solids processing units had problematic R&D in chemistry-related areas, there is no simple relationship between those problems and performance.

In the absence of other information, we would be unable to interpret this negative finding. It might reflect other plant characteristics dominating and "washing out" any relationship with the chemistry-related R&D problems, or it may indicate that chemistry-related problems outside the corrosion area are being resolved. Evidence presented later (in Table 4.12) strongly suggests the latter: temperature, pressure control, and impurity-buildup problems were only occasionally mentioned as sources of actual plant production loss. Corrosion, on the other hand, was cited in 30 percent of the solids processing plants as a cause of significant performance losses.

Distinct from problems of chemistry are the so-called "unit operations" of a process plant, i.e., the physical (as opposed to chemical/molecular) change in materials, plus material transport and related handling. We collected data on the following handling-related problems that might arise in process R&D.

Abrasion problems[17] limit equipment life, thereby decreasing plant performance and increasing operating and maintenance costs.

Uncertainty in the precise composition of the feedstocks that will be used for a process often results when minerals (including coal) or other "raw" feedstocks are employed. R&D is needed to either better characterize the feeds, e.g., through research on the properties and reactivities

Table 4.8

CHEMISTRY-RELATED R&D AREAS AND PLANT PERFORMANCE

R&D Area	Average Difficulty of Problem	Correlation with Plant Performance
Pressure control	0.7	−0.18
Temperature control	1.4	−0.17
Corrosion	1.8	−0.37[a]
Impurity buildup	1.8	−0.27

[a]Significant at $P < .05$.

[17]When abrasion and corrosion occur interactively, the result is called "erosion." In this analysis, erosion problems are grouped with abrasion problems.

of various coals, or design the process to be indifferent to swings in feedstock composition.

Materials handling problems can occur in any kind of process plant. Solids handling problems are, of course, most common in plants that process solid materials. However, solid catalysts in liquids/gas processing units can also be a source of serious solids handling problems. A failure in the processing and disposal of waste streams will generally result in plant shutdown or decreased capacity utilization. Waste handling problems tend to be more severe when wastes are toxic or constitute a threat to worker or public health. Table 4.9 shows the relationship between materials handling issues and plant performance.

Ideally, there would be no relationship between the R&D problem scales and plant performance; problematic R&D issues would not continue to cause difficulties when the plant reached the point of commercial operation. In fact, however, there are apparent associations between performance and corrosion, abrasion, solids handling, and waste handling problems. The negative correlation with plant performance indicates that the more severe the problems in R&D, the poorer the plant performance. Furthermore, correlations for other materials handling and mechanical R&D problems such as feedstock characterization and liquids handling also approach significance.

Since none of these R&D issues appear as variables in our "best fit" performance model (Eq. (4.6)), we next explore the relationships between R&D problems and performance by examining how the R&D issues relate to the major predictor variables in the performance model.

Table 4.9

PHYSICS-RELATED R&D AREAS AND PLANT PERFORMANCE

R&D Area	Average Difficulty of Problem	Correlation with Plant Performance
Abrasion	1.3	−0.46[a]
Liquids handling	1.4	−0.30
Feed characterization	1.6	−0.21
Waste handling	2.0	−0.50[a]
Solids handling	2.2	−0.54[a]

[a]Significant at $P < .05$.

Relationship Between R&D Problems and the Balance Equations

As indicated in the basic performance model, knowledge of the heat and material balances is the most important predictor of plant performance. Therefore, it is logical to ask whether R&D problems are associated with performance through the balance equations variable. In other words, we will be testing a model of the following form:

$$\textit{Balances known} = f(\textit{new steps}, \textit{R\&D problem scales}, \textit{other factors}) + \textit{error}.$$

We include the number of new steps as a measure of innovation to control for the direct relationship between severity of R&D problems and new technology. We begin by examining the correlations between knowledge of the balance equations and the R&D problem scales. Table 4.10 shows these relationships, along with performance correlations from Tables 4.8 and 4.9. Two additional variables are included that represent the sum of the chemistry-related and physics-related problems.

Table 4.10

R&D ISSUES, BALANCE EQUATIONS, AND PLANT PERFORMANCE

R&D Area	Average Difficulty of Problem	Correlation with H&M Balances	Correlation with Plant Performance
Chemistry issues			
Pressure control	0.7	−0.16	−0.18
Temperature control	1.4	−0.19	−0.17
Corrosion	1.6	−0.39[a]	−0.37[a]
Impurity buildup	1.8	−0.34[a]	−0.27
Sum of chemistry problems		−0.39[a]	−0.34[a]
Physical/mechanical issues			
Abrasion	1.3	−0.52[a]	−0.46[a]
Liquids handling	1.7	−0.35[a]	−0.33[a]
Feed characterization	1.7	−0.36[a]	−0.21
Waste handling	1.8	−0.49[a]	−0.50[a]
Solids handling	2.2	−0.70[a]	−0.54[a]
Sum of physics problems		−0.76[a]	−0.65[a]

[a]Significant at $P < .05$.

Table 4.10 shows that

- There is a clear pattern of association between the difficulty of R&D problems and the level of knowledge about the heat and material balances. The lack of experience with processes is manifest in poor knowledge of these balances.
- The relationships are clearly stronger and more systematic for the physics-related issues than for the chemistry-related issues. Not only are all of the physics-related problem coefficients statistically significant, but they are higher than those for the chemistry-related issues.
- In general terms, the pattern of relationships between R&D problem scales and heat and materials balances is similar to the pattern with performance: For the chemistry-related issues, only corrosion is strongly related; for the physics-related issues, all scales are related to the knowledge of balances and all but feedstock characterization are related to ultimate commercial plant performance.

We can model the exact extent to which performance difficulties are reflected in R&D problem areas and manifest in the level of knowledge of the heat and mass balance equations. The best model is shown below:

$$\begin{aligned} \textit{Balances known} = {} & 106 \\ & - \underset{(.0001)}{11} \times \textit{R\&D solids handling problems scale value} \\ & - \underset{(.02)}{6} \times \textit{R\&D waste handling problems scale value} \\ & - \underset{(.0001)}{30}\ \textit{if plant processes solid feedstocks} \end{aligned} \tag{4.7}$$

for the case where $R^2 = .65$; N = 38; and SEE = ± 25.

Figure 4.10 summarizes the interpretation of the equation. The model does not imply a direction of causality; rather, causality probably flows from poor knowledge of the balance equations to more serious problems identified with the solids handling and waste handling. Finally, there is no doubt that the presence of solid feeds is responsible for poorer knowledge of the heat and material balances.

Above all else, poor knowledge of the balance equations is associated with solids handling problems. Other things equal, the failure to know 55 percent of the balance equations (5 on the 0-to-5 problem severity

R&D problems		Type of feedstock	
Degree of solids handling problems +	Degree of waste handling problems +	Use of solid feed =	% heat and mass balances known
Effects			
−0 to −55%	−0 to −30%	−30%	Average 52% 0-100%

(Number of new steps has no effect)

$R^2 = 0.65$

Fig. 4.10 — Performance difficulties as expressed by heat and mass balance equations

scale times the coefficient, 11) is associated with the most pressing solids handling R&D and design problems. From Eq. (4.6), being unable to base 50 percent of the heat and material balances on hard data is associated with a loss in plant production of 22 percent of design performance.[18]

There is no relationship between the use of solid feedstocks and other solids handling problems in R&D, however, nor is there any relationship between the type of solid feed—refined or raw—and the degree of handling difficulty. Plants that process liquids and gases into solid materials are just as likely to have solids handling R&D problems.

The relationship between poor knowledge of the heat and material balances and R&D waste handling problems is not surprising. In the past 15 years, new regulations have necessitated constant redesign to meet more stringent waste handling standards. However, unlike other processing plants, where waste handling difficulties in R&D are directly associated with poorer plant performance, that is not the case for solids processing plants.[19] In solids processing plants, waste handling problems are associated with inadequate knowledge of the heat and material balances.

[18]The coefficient for percent of balances unknown is 44; thus, (44 times .5) = 22.

[19]See Merrow, Phillips, and Myers, *Understanding Cost Growth and Performance Shortfalls*, Sec. V, for the model in which waste handling is included. When we model the *full* Pioneer Plants database, waste handling is a significant predictor of poor plant performance.

Finally, the model does not include any measure of innovation, because none of our measures will fit in the equation. For example, if we try to force the number of new steps into the model, the results do not even come close to statistical significance. Also, none of the chemistry-related R&D issues are associated with the balance equations.

Factors Associated with Solid Feedstocks

Equation (4.6) showed that the type of feedstock employed by a plant had a clear and important effect on plant performance. In modeling the balance equations, we again find that in solid feedstock plants, a far smaller portion of the balances are known than in solids-processing liquid and gas plants. The critical distinction is simply between solids and non-solids. Why are solid feedstocks associated with problems, both in knowing the balance equations and with performance directly?

We start by examining the relationships between solid feedstocks and other characteristics of the projects and plants in our database. Table 4.11 shows the correlations that are statistically significant, as well as a few of interest that are not correlated. Despite the strong relationship between solid feedstocks and both poorer plant performance and less knowledge of the heat and material balances, the solids plants are not more complex than the liquids/gas plants. In most respects, they are also not much more innovative. They do have more first-time integrations of proven process steps than liquid- and gas-fed plants as a group, however, which suggests that the plants that process solids are less standardized, an issue we will come back to in Section V.

Only three of the plant characteristics we examined are associated with solid feed plants: temperature problems, abrasion, and erosion (that is, the combination of abrasion and erosion). The use of solid feedstocks does not, by itself, tip off industry to take solids-related problems more seriously in the R&D phases of projects. This is particularly interesting in light of the strong association that exists between solid feedstocks and startup problems related to solids, as well as the longer slips in startup schedules. This is an example of a mismatch between R&D and sources of problems in plant performance.

THE PROXIMATE CAUSES OF PLANT FAILURE

We now turn to pieces of equipment that failed at the plants in the SP database that displayed performance problems. We were able to

Table 4.11

RELATIONSHIP OF SOLID FEEDSTOCKS TO OTHER PROJECT CHARACTERISTICS

Variable	Correlation with Solid Feedstocks	Definition
Performance	−0.62	Plant performance
Balances unknown	+0.50	Portion of heat and material balances not based on actual data from prior plants
Complexity	+0.25[a]	Number of major subsystems in plant
New steps	+0.39	Number of new steps incorporated in design
First of kind	+0.39	Plant is first-of-its-kind
First in NA	+0.47	First use of technology in North America
New int	+0.43	Number of new integrations of old equipment
Temp problems	+0.36	Higher levels of difficulty with temperature control issues in R&D
Abrasion	+0.35	R&D difficulty with abrasion of equipment
Erosion	+0.33	Presence of erosion problems in R&D
Solid problems	+0.24[a]	Higher levels of difficulty with solids issues in R&D
Start problems (S)	+0.49	Startup problems related to solids
Startup time	+0.51	Time required for startup
Startup slip	+0.46	Actual startup time as a portion of planned startup time

[a]Not statistically significant at $P > .05$.

obtain information on the sources of major plant failures for 34 of those plants. Table 4.12 lists the major problems.

There are a number of important points to be made about the causes of major performance problems:

- First is the simple ubiquity of serious operational difficulties for these plants. The 34 plants experienced a total of 244 major operational problems—an average of 7, with a mode of 5 and a range of 0 to 15.[20]
- Second, the problems are overwhelmingly related to solids processing. Of the 89 problems cited, only a few corrosion problems do not result directly from the processing of solids. This would not be surprising if all the plants in the database processed solids throughout the process train, but many of them

[20]Table 4.12 shows only 89 problems rather than 244, because if a problem occurred two or more times in a given plant, it was counted only once, and problems that were mentioned only once or twice and operator-created problems were not included.

Table 4.12

CAUSES OF MAJOR PERFORMANCE PROBLEMS

Nature of Problem	No. of Plants Affected
Failure of rotating mechanical equipment	18
Plugging of reactor inlets, outlets, or internals by solids	15
Slurry and pneumatic solids transfer failures	14
Missized major equipment/process steps[a]	12
Waste treatment steps (6)	
Other (6)	
Corrosion problems	9
Valve performance (especially tight shutoff)	8
Fines and dust problems	7
Instrumentation failures (excludes pumps, valves, etc.)	7
Chronic conveyor failures	6
Plants with no major problems	2
Total	98

[a]Replacement of those steps was necessary.

process solids in only a limited number of units. Several (including the two plants that reported no problems) have liquid and gas feeds.

- The problems are overwhelmingly mechanical rather than chemical in origin. Only corrosion, a few of the reactor plugging problems, and a few line plugging difficulties have their genesis in the chemistry of the process rather than the inability of the mechanical equipment to do what was intended by the designers.
- In light of our findings about specific causes of failure, the relationship between knowledge of the heat and material balances and plant performance becomes obvious: Many of the performance problems stem from undersized or oversized equipment.[21] (Sizing is, of course, governed by the heat and material balance assumptions.) Contrary to much conventional wisdom in the industry, the heat and material calculations by which equipment needs are calculated are more than occasionally faulty.

[21]In some circumstances, oversized equipment will not function efficiently, and in extreme cases it will not function at all. Therefore, one cannot avoid problems simply by systematically oversizing mechanical equipment. Of course, oversized equipment will also fail if it is misdesigned.

Most startling of all are the 12 plants in which one or more steps had to be rebuilt because of incorrect sizing. In addition, there are numerous instances of incorrect sizing of minor equipment, especially pumps and valves. These cases too reflect a poor empirical basis for the heat and material balances.

- The correlation between knowledge of the heat and material balances and difficulty in the design of waste treatment steps is also reinforced by the failure data. In six cases, the waste treatment steps had to be completely revamped because they were undersized for the job. In each case, solid wastes were the culprit.

The actual problems encountered by the plants support our statistical analysis as well as our basic thesis: Problems related to physical and mechanical difficulties are not being effectively tackled in R&D. In the next section we discuss the implications of these findings for R&D priorities for solids processing technologies.

V. IMPLICATIONS FOR R&D PRIORITIES

We selected plant performance as the measure of merit for this analysis because poor performance usually dominates profitability. When non-feedstock costs predominate, plant performance is almost always the key element in product costs. Although there are important exceptions, the plants in our database generally did not perform well, averaging only about 63 percent of design.

Only about 12 percent of the average performance loss in these plants can be attributed to innovation, as measured by new steps. Roughly 20 percent of the reduction in performance is attributable directly to processing raw solid feedstocks; poor knowledge of the heat and material balances, which can reduce performance by as much as 44 percent, accounts for the remainder. Poor knowledge of the heat and material balances does not depend primarily on the level of innovation in the process.[1] We know that there is an association between solid feedstocks and poor knowledge of the heat and material balances, and we also know that only two of the 38 plants in our SP database had no major operating problems.

Solids processing plants do not perform well, and we know the R&D areas most cited as sources of difficulties. What does our analysis imply for setting an R&D agenda to improve performance?

CHEMISTRY-RELATED R&D

In general, chemistry-related R&D issues (i.e., temperature problems, pressure problems, impurities, and corrosion) are not related to the performance of plants in the database. Process chemistry, of course, concerns the behavior of materials in reactors, with temperature requirements and control, and with reactor pressures. But even though these factors are at the heart of new processes, they show no correlation with plant performance. The buildup of impurities in intermediate process streams is also unrelated to plant performance.

Temperature and pressure problems were cited as causes of major operational problems in only one process. It thus appears that chemistry-related problems are being identified in R&D and are being

[1]The number of new steps is the measure of innovation most closely associated with the heat and material balances measure. New steps, however, account for *less than 30 percent of the variance* in the heat and material balances.

resolved effectively. This may account for increased capital costs of systems being developed, but it is generally a small price to pay for improved performance.[2]

There is an exception to this rosy picture in the chemistry area: Corrosion was identified as a serious R&D problem for a number of plants,[3] and plants that had serious R&D problems also show poorer than normal commercial performance. Corrosion of equipment was cited in nine plants—almost one-quarter of the plants in the SP database—as a cause of major performance difficulties. In six of those cases, the corrosion problems had been identified as a very serious problem in R&D, but they were not adequately resolved. In three cases, the corrosion problems came as an unwelcome surprise. Therefore, there is some mismatch between the identification of corrosion as an R&D problem and corrosion-caused performance problems. If the plants' designers realized the extent to which corrosion would cause performance difficulties later on, they would not have let them "slide by."

Corrosion problems and buildup of impurities in recycle streams are causally related. Frequently, it is the recycle buildup that brings an impurity up to the concentration required to begin an attack on equipment. This relationship is reflected in the very strong (+.74) correlation between the two R&D problem scales. Despite this causal and statistical connection, however, corrosion is related to poor performance, while impurity problems are not. The sources of corrosion problems are related to poor plant performance, while those related to impurity buildup are not.

Corrosion problems can be viewed as either chemical-process design issues or materials issues. That is, they can be dealt with either by modifying a process to reduce or eliminate the chemical sources of corrosion or by adopting construction materials that are impervious to attack.[4] Corrosion is also sometimes caused by unexpected materials in the feedstock. In these cases, a raw solid feedstock is almost always to blame. Viewed in this way, corrosion is more akin to physical/mechanical problems such as abrasion.

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[2]See Merrow, Phillips, and Myers, *Understanding Cost Growth and Performance Shortfalls*, Sec. IV. These chemistry-related R&D issues are associated with cost growth between cost estimates made during R&D and the actual costs of the first commercial plant.

[3]Corrosion was viewed as the sixth most serious R&D problem at the plants in the database.

[4]The choice of approach may be dictated either by the situation or by economics. E.g., a materials approach would have to be taken if the source and concentration of the corrosive was inherent in the process; on the other hand, if only one reactor and associated piping had to be clad with alloy, cladding most of the equipment would render the process uneconomical.

PHYSICS-RELATED R&D

We deliberately use the term "physics-related R&D" to refer to research into the variety of mechanical problems experienced by the plants in our database, since physics should be the theoretical underpinning of most of these problems. The physics-related areas of R&D difficulty are feedstock characterization, abrasion, solids handling, liquids handling, and waste handling.

It is the inescapable conclusion of our analysis that the physicist and the mechanical engineer must play a larger R&D role if the performance difficulties of solids processing plants are to be solved systematically. More than three-quarters of the serious performance problems of plants in the SP database were physical and mechanical, rather than chemical in origin.[5] We divide these problems into the following categories for purposes of discussion:

- Heat and material balances
- Solids processing
- Solids transfer

Heat and Material Balances

At a number of points in the data analysis we noted the strong relationship between plant performance and the level of knowledge about heat and material balances based on hard data. Of the hundreds of variables in the database, "heat and material balances known" has the strongest correlation with plant performance. By itself, this one factor accounts for 70 percent of the variation in plant performance.

The data on actual plant failures lead us to believe that there is a causal relationship between plant performance and knowledge of the balance equations. Twelve of the commercial plants in the database suffered failure of one or more steps (subsystems) due to missizing of major equipment, the literal manifestation of not setting the heat and material balances correctly.

If poor knowledge of the heat and material balances were simply a reflection of new technology, it would be much less important. For solids processing systems, however, this knowledge is not even primarily a matter of innovation.[6] It appears to be extremely difficult to

[5]Many of the problems that were related to the process chemistry could have almost as easily been assigned to the physical/mechanical category. For example, erosion was included in the process chemistry category, although it combines corrosion and abrasion.

[6]This is an area of significant difference between solids and non-solids processing. The relationship between the heat and material balances and measures of innovation is stronger for liquid and gas processing plants. When the balances are not known for

translate the heat and material balances from one plant to the next, even if the process is identical. Any kind of change—slightly different feed, modest scaleup, even a different owner—appears to reduce the applicability of the equations for an existing plant to a new one.

All of the measures of physical/mechanical problems in R&D are associated with inadequate knowledge of the heat and material balances (see Table 4.10). We concluded that three attributes in particular are associated with poor knowledge of the H&M balances: (1) solids handling problems, (2) waste handling problems, and (3) the use of solid feedstocks. Inclusion of chemistry-related R&D problems did not even remotely improve the heat and material balances regression model.

We believe that the magnitude and persistence of the heat and material balances problem for solids processing reflects the poverty of the theoretical understanding of solids. Not only does the relatively poor performance of solids processing plants reflect this, so does industry practice. Much more evidence is necessary to proceed with a solids process than with a liquid or a gas process. Unlike the liquid and gas areas, there are no examples of successful solids processing scaleups of two and three orders of magnitude. Conventional wisdom in the process industries is that designing and obtaining good performance from a solids processing unit is an art; it is more empirical, more "seat-of-the-pants," and more dependent on long experience than the design and operation of liquid and gas processing systems. In this case, the conventional wisdom appears to be exactly right.

Processing Solid Materials

Well over half of the plants in the database reported one or more major problems with solids processing, i.e., with making physical and molecular changes to solids.[7] Eighteen plants reported failures of major rotating equipment; 13 of the failures were in conjunction with solids processing. Another 15 plants had reactor problems that resulted from plugging by solids.[8] Seven plants had serious problems

liquid and gas processing plants, it is because commercial experience has not yet established what they should be. For solids processing, lack of commercial experience is only one contributor to poor knowledge of the heat and material balances; the other main source is the inability to transfer experience from one setting to another due to poor theoretical understanding of solids behavior.

[7]We treat solid/liquid slurries as solids throughout this report. Strictly speaking, all solids processing entails multiphase processing.

[8]Plugging in reactors is by no means a minor problem: One of the plants in the database failed completely because of plugging. While reactor plugging may be considered mundane (and perhaps that is part of the problem), it is a serious problem.

with fine dust or other manifestations of inability to generate the proper consistency for solids.

These problems were more common among the solid feedstock plants than among those that produced solids from liquid and/or gas feedstocks. The problems were most common among plants that processed raw solid feeds.

Solids processing problems frequently involve an inability to translate process requirements into mechanical equipment that can meet the required service needs. Valves, pumps, and instruments are the most common minor items to fail. It is true, of course, that minor equipment items are easily replaced. However, repeated failures of these items can cause significant losses of performance, increased maintenance costs, and higher chances of operator error that could cause more serious failures or accidents.

Solids Transfer

Moving liquids and gases is usually a very predictable process; moving solid materials is often problematic. Over one-third of the plants in the database experienced failures in slurry or pneumatic transfer lines. The failures ranged from occasional plugging problems, which resulted in temporary shutdown, to complete failure of the solids transfer approach. In several cases, plant managers fell back on batch or even manual transfer after the system that was designed and built failed completely. Another four plants had such chronic failures in conveyors that they were cited as serious operational problems. More than half of the plants in the database experienced important failures in solids transfer.

Once again, all of these failures are manifestations of mechanical problems. These problems are also not confined to plants that process solid feedstocks. They can occur in any plant that processes or produces a solid, even when the solid is as common as polyethylene beads or petroleum coke.

The problems with solids transfer illustrate a more general problem: the inability to standardize many types of equipment for a general type of service. This difficulty results from the sensitivity of solids equipment design to even very small changes in the characteristics of the material being processed.

RANKING NEGLECTED R&D AREAS

In Section I, we argued that a desirable approach to R&D allocation would have the following characteristics:

- It would *include both basic and applied R&D*, thereby permitting the relationship between basic and applied requirements to be examined.
- It would maximize the use of *objective measures and procedures* and minimize the use of measures that could be idiosyncratic to individuals.
- It would, in principle at least, *include all fruitful research avenues* within a particular technical area—that is, it would contain no inherent biases or blind spots.
- Its results should be *reproducible* and therefore correctable as uncertainties are reduced.
- It would *tie research priorities to some figure of merit.*
- It would produce *clear R&D priorities,* preferably with a meaningful interval scale for ranking alternatives.

Our statistical analysis has these characteristics. Although we were unable in this study to examine the likelihood of research being successful in any particular area, we can rank the areas in such a way that if a project *is* successful, it can be assured of reducing product costs. Research and development areas are listed below in order of their relationship to the performance of solids processing units:

1. *Research aimed at improving the ability of engineers to transfer knowledge of heat and material balances from one plant and context to another.* The research should be both theoretical and applied, with interaction between the two. The theoretical research should focus on minimizing the parameters necessary to accurately characterize solids flow and processing. The research might take the form of experimental, mathematical paper studies, or even statistical analyses that fit observed data. Applied R&D should focus on improving the empirical basis for the heat and materials equations by developing improved instrumentation and diagnostics for solids processing and flow. Such improvements would translate directly into better plant performance throughout the process industries for both pioneer and subsequent plants.
2. *Solids handling.* Experimental and testing work in the general area of handling solid materials—especially powders, which are associated with both reactor and transfer line plugging—

would be relatively inexpensive and would have a high payoff. Solids handling is important both as it relates to performance directly and as it relates to the heat and material balances.

3. *Waste handling.* R&D problems in handling wastes from solids processing facilities have tended not to be resolved. In at least three plants, the waste treatment step failed, resulting in serious loss of production and the need to completely redesign the subsystem.
4. *Corrosion, abrasion, and erosion* are clearly related to plant performance. These materials-related areas do not appear to be neglected so much as unsuccessfully researched. They were widely recognized as serious R&D issues, but they remained problems in many plants. It appears that plant designers may be making overly optimistic assumptions about materials performance in the face of evidence to the contrary in order to keep costs from rising. This suggests that before new initiatives are taken in the materials area for solids processing, the precise reasons that current R&D programs do not appear to be successful at the plant level needs to be studied.

Special attention is warranted in three of the four R&D areas listed above. Figure 5.1 summarizes the potential payoff from R&D in terms of product costs. The horizontal axis shows increasing performance as a percent of design. We take as our base case performance at 90 percent of design being equated with a product cost of 100 percent. The most dramatic improvements in product cost are associated with better understanding of the processing of solid feedstocks and improvement in fundamental knowledge of the heat and material balances. We conclude that significant advances in these areas would achieve the most dramatic reductions in the costs of solids processing.

Why Has There Been No Improvement in Solids Plant Performance?

We are left with the basic question of why the chronically poor performance of solids processing plants has persisted over the last several decades.[9] Why haven't additional resources been allocated to fundamental research on the processing of solids material—that is, to

[9]There is not even a glimmer of an improvement in the data. The correlation between the residuals of the solids plant performance equation (Eq. (4.6)) and the year of mechanical completion for the plants is −.19, with a probability of being random of .26. The minus sign indicates that if the correlation were significant, *things would be getting worse rather than better.*

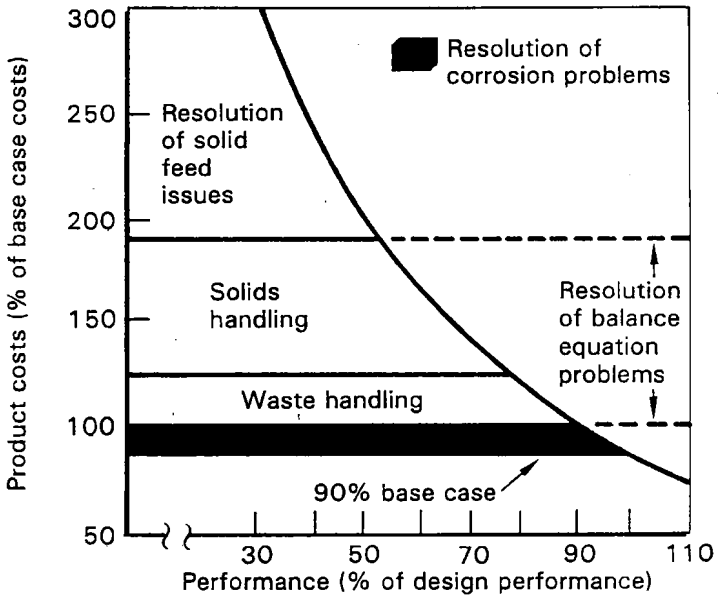


Fig. 5.1 — Effect of R&D priorities on product costs

achieving a better understanding of how to set heat and material balances for solids—as well as on specific items such as solids handling?

We believe that the situation has not improved because of basic communication problems in the solids processing industries. Figure 5.2 illustrates these problems:

- Academic science does not appear to be pursuing the basic research that is needed because there is no clear demand (i.e., funding) for that research. Expert panels drawn from the scientific community to help establish priorities for R&D allocations have failed to identify problem areas outside their chemistry-related realms of expertise.
- Within the industry itself, the problems that are most germane to plant performance are not solved but are passed along the chain from industrial R&D to engineering and from engineering to operations. Industrial R&D departments in the oil and chemical industries gave us the impression that such research is not in the mainstream—indeed, is not worthy of serious concern. R&D managers in the oil and chemical industry appear to feel that mechanical problems should be the province of the

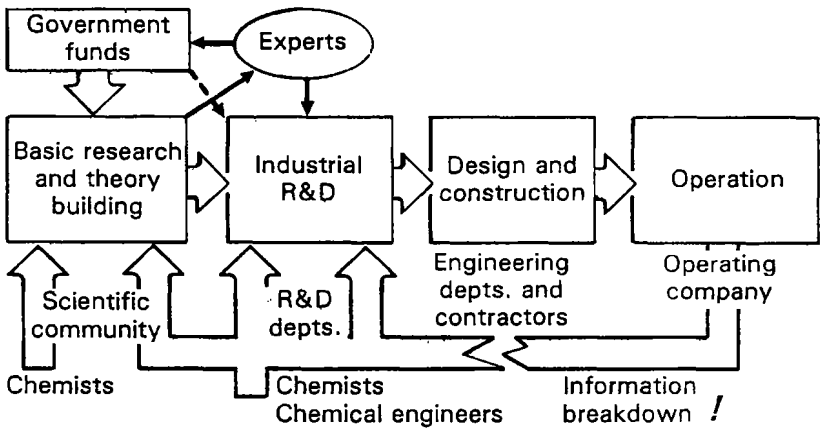


Fig. 5.2 — Basic problems in solids processing industries

design engineering departments, and perhaps even plant managers, not an area for industrial R&D.

- Engineering departments, and particularly the design teams for process plants, tend to be dominated by chemical engineers who also see physics and mechanics-related issues as outside their area of expertise. They tend to believe that mechanical problems can be fixed in startup—that is, by the operators.
- In operations, the problems are not being solved but only patched. No solutions are forthcoming, because there is no effective feedback from plant operators back to the industrial R&D departments and to the research community. If the information is in fact getting through—and we believe that it is not—it is not being heeded. Despite the predominance of mechanical and physical failures, emphasis continues to be placed on chemistry-related rather than physics-related R&D.

Based on this research and our view of the past decade, the process industries appear to be extremely effective in translating advances in chemistry into commercial technology and products. However, the system that works so well in chemistry-related areas appears to break down in all areas where the problems are outside the chemistry paradigm.

IMPLICATIONS FOR SYNTHETIC FUELS DEVELOPMENT

Since this research was started, the nation's interest in developing synthetic fuels from coal, shale, and oil sands has waned considerably. Nonetheless, an eventual transition to synthetics to meet much of our transportation fuel requirements is still likely. This research has several implications for synthetic fuels development.

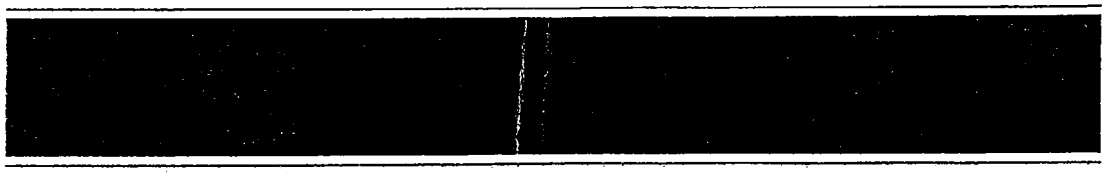
The initial commercialization of synthetic fuels is likely to prove even more costly than is currently anticipated if the problems outlined in this report are not dealt with effectively by R&D. Because synthetic fuels technologies—at least those developed to date—are very capital-intensive, product costs will be especially affected by poor plant performance. Although performance can be expected to improve as commercialization progresses, the need to tailor synthetic fuels processes to particular sites and raw materials will require the effective transfer of knowledge to enable smooth startups and operation. Poor transfer of knowledge in solids plants is particularly problematic in the area of heat and material balances.

The areas that should be stressed in R&D generally apply with full force to synthetic fuels. Our analysis suggests that R&D on solids processing behavior, better understanding of nonuniformities in feedstocks, waste processing, and corrosion should be among the top priorities for synthetic fuels research. In addition, R&D support for synthetic fuels is clearly needed if we are to have any hope of making a smooth transition away from petroleum in the next century. The results also suggest that current DOE efforts to find substantially new processing routes to synthetic fuels should be encouraged.

THE GENERAL APPLICABILITY OF THE APPROACH

We believe that the parametric approach to setting R&D priorities has been successful in this application to solids processing. But is it generally applicable? We see no bar to using the approach wherever the potential for the requisite database exists. This means that the approach is best suited for setting R&D priorities in areas that have some commercial experience. A parametric approach is usually expensive because of its data requirements. But where an appropriate database already exists, the approach would be quite inexpensive. And assembling groups of distinguished experts and taking them on tours of R&D facilities is also costly.

Whether or not a statistical approach is used, this should not obscure the central message of this report: The use of expert opinion to set R&D priorities can discourage the identification of the real areas

of need. Expert opinion must be augmented with some form of reality-testing—for example, a systematic linking of R&D efforts with commercial results, or the use of plant operators, consumers, and others downstream from R&D to establish what the real problems are. The relevant experts can then draw up the R&D agenda within the bounds provided. Simply bringing in a strong R&D manager whose disciplinary background is different from those he supervises may serve to leaven the loaf. Few experts would disagree that creative science requires breaking disciplinary blind spots. The same sort of "countercultural thinking" needs to be applied to setting R&D priorities.

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