A RAND NOTE

SELECTED PAPERS FROM THE ENERGY WORKSHOP:
INDUSTRY PERSPECTIVES ON PIONEER
PROCESS PLANTS

R. E. Horvath, Editor

July 1981

N-1709-DOE

Prepared For

The U.S. Department of Energy

Rand
SANTA MONICA, CA. 90406

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PREFACE

During the past two years, The Rand Corporation has been investigating the accuracy and reliability of initial project estimates for first-of-a-kind process plants. The investigation sought to determine the causes of cost growth and poor plant performance in innovative projects similar to those with which the Department of Energy will be concerned. That effort led to further study of the management, technology, and cost estimation of pioneer process plants.

This Note documents the results of a workshop, "Industry Perspectives on Pioneer Process Plants," held in the Rand Washington Office, September 17, 1980, to discuss process plant management, technology, and cost issues that would be of interest to the Department of Energy. Representatives of Rand and of the chemical and petrochemical industries participated in the workshop. The work was performed for the Office of Resource Applications, DOE, under Contract DE-AC01-79PE70078.

Because this Note simply documents selected workshop presentations, it has not been subjected to the usual Rand review process.

ACKNOWLEDGMENTS

I would like to acknowledge the presenters who gave their time and effort to contribute to the success of the workshop. From the chemical and petrochemical industries, I would like to thank John Hackney, John Fisher, Allen Norman, Dick Summers, and Larry Nault. Finally, I would like to thank my Rand colleagues who generously reported on their recently completed and current research: Susan Bodilly, Ron Hess, Marc Lieber, Ed Merrow, Dick Nelson, and Ken Phillips.

R. E. Horvath, Editor

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INTRODUCTION

Cost overruns and poor plant performance often accompany first-of-a-kind process plants in the chemical, petrochemical, and mining industries. These problems can be traced to both the extent to which a plant is defined in the early stages as well as the extent to which the technology is unproven at commercial scale.[1]

While industry has been building such plants for decades, few inroads have been made in understanding the complex difficulties involved with designing and constructing pioneer process plants. This lack of analysis is largely explained by the fact that assembling a data base that cuts across the interested industries is virtually impossible for a single industry member to do, and no single member is large enough to pull together the data base itself. Beginning with the Pioneer Plants Study, Rand has undertaken an effort aimed at assembling just such a data base. While the research is continuing and the results still forthcoming, it has become clear that much needs to be learned in the areas of cost growth, schedule slippage, and plant performance.

To initiate a spirit of cooperation within the process plant industries and between industry and the federal government, we conducted an energy workshop on 17 September 1980 in the Rand Washington Office. The intent of the workshop was (1) to demonstrate that much useful analysis could be done with a data base supplied by many corporations

[1]See E. W. Merrow, K. E. Phillips, and Christopher W. Myers, Understanding Cost Growth and Performance Problems in Pioneer Process Plants, The Rand Corporation, R-2569-DOE, June 1981. See also R. E. Horvath and J. R. Nelson, A Technology Scale for Pioneer Process Plants, The Rand Corporation, R-2570-DOE, forthcoming.

spanning several industries, and (2) to allow the government to see that industry has been thinking about many of the same problems that have plagued government-sponsored projects. In short, we hoped to provide a forum for industry and Rand speakers to present recent thinking on a wide range of pioneer plant issues important to the Department of Energy.

The audience at the workshop was made up of DOE personnel interested in the general area of pioneer process plants. The speakers were from Rand and private industry. We asked the speakers to address issues in the three areas of plant economics, cost and performance, and management. Six of those papers are reproduced here, chosen so that each of these areas is represented.

John Fisher addresses the question of economy of scale in electrical generating plants, and concludes that when performance is included in the analysis, a case can be made that the very large electrical generating stations do not show evidence of economy of scale. John Hackney examines the effects of a number of well known incentive plans for spurring industry into the construction and operation of energy plants.

Richard Summers discusses his own experience with certain management techniques and their effects on the successful construction and operation of pioneer process plants. Summers concludes that early project definition and an integrated project team with a strong project manager are two important keys to successful projects.

J. R. Nelson presents the results of an effort to construct a technology scale for pioneer process plants, and links the scale to a

project's cost growth, plant performance, and start-up schedule slippage. Addressing more specifically the area of capital cost, Ron Hess provides a tutorial on the use of cost estimating ratios in energy plants. Finally, Ken Phillips suggests an approach for analyzing the problem of forced production outages that tend to occur with technologies that are unproven at commercial scale.

During the course of the day, it became clear that industry and government are about to face a fundamental dilemma. The energy plants under construction by industry are by current standards quite large and expensive, so expensive that it may be impossible for any single corporation but the largest two or three to build one of these plants by itself. A consortium will be necessary to put together the required financial package for a typical energy plant. The design and construction of that plant will be performed under the management of that consortium. Unfortunately, a consortium is likely to use tiered management, otherwise known as management by committee. Opposite of what is known to be good project management, this style of management will likely lead to cost overruns, schedule slippages, and poor plant performance. If such problems are to be avoided for the large energy process plants under consideration, we must either turn our attention to alternate methods of financing these large projects that will allow good management techniques, or find a way to permit well-known management procedures to be used in conjunction with a tiered management structure.

ECONOMIES OF SCALE IN ELECTRICAL GENERATING PLANTS

John Fisher

The program says I am from General Electric, and I was at the time I agreed to participate in this seminar. I am now an independent consultant and entrepreneur. But the work I am going to talk about was done when I was a GE employee, and it was done mostly on their premises--some when I was visiting EPRI, The Electric Power Research Institute, and some when I was visiting IIASA, The International Institute for Applied Systems Analysis. I used no GE data in this analysis. My feeling was that I wanted to be objective, so I used mostly government data and some public data from industry associations.

I want to talk about economies of scale, an often observed decline in unit costs of a product or a service as the scale of related equipment or activity increases. When you apply the scale economy concept to the cost of electricity, you can talk about the economy of scale for a whole utility system or a piece of equipment. I am going to talk about a piece of equipment, the generating unit. A generating unit is a building that makes electricity; it contains facilities for burning some kind of fuel, a boiler, a steam turbine, a generator, and transformers. It is an electricity-producing factory that comes in all sizes, and it is commonly believed that there is a scale economy for it.

Since I don't believe what people say--I decided to go to the outside data and see if there really is a scale economy, and if so how big it is. And I want to take you through my search in that regard.

First, I want to point out that it is also possible to have diseconomies of scale. Sometimes when you make things bigger, they become economically unattractive on one ground or another. The first example I want to talk about is the cost of nuclear plants. Chart 1 is a plot of all nuclear plants with construction permits granted 1964 through 1970 that went into operation in the United States, with the exception of about four or five very small prototypes. In a sense, these are all pioneer plants. They range from about 400 megawatts for the smallest ones up to 1100 megawatts or so for the largest ones. In general, as we go along year after year the average rating gets larger and larger.

Chart 2. Now let's look at how long it took to build these plants. This chart shows the year of construction permit, 1964 through 1970, versus the number of months from construction permit to the operating license. The construction permit is granted about the time construction begins and the operating license about the time it is completed. Bechtel and others agree that the bound of these two documents is a good measure of the length of construction. We find that the duration of the construction job varies from about 35 months to 100 months. And we find that there is a general upward trend: construction took from 35 to 50 months back in 1964, but about 60 months for plants that got their permit in 1970.

The conventional wisdom in the industry is that the lengthening of construction time results from increasing regulation and environmental intervention, which are lengthening the construction cycle for plants in the later era. However, I want to draw your attention to the ratings

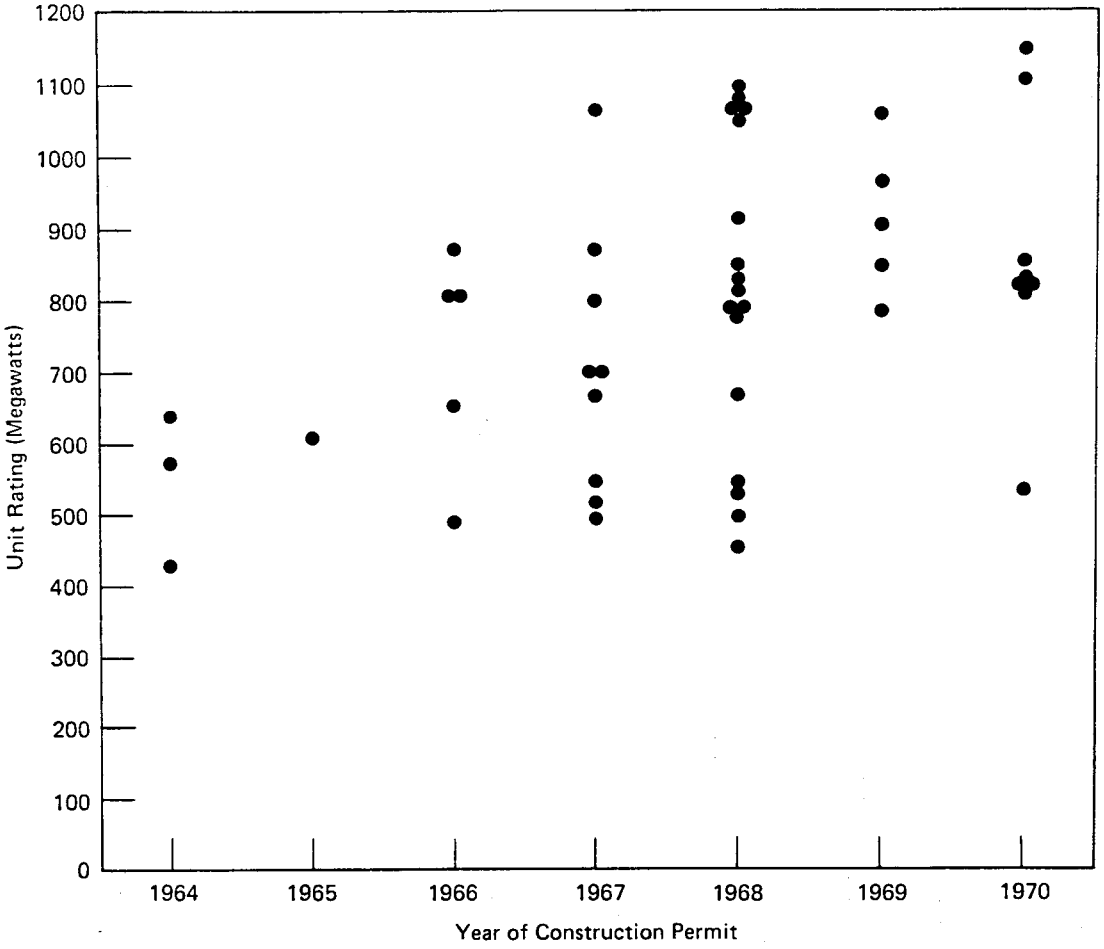

Chart 1--Nuclear unit design rating in megawatts, versus year of construction permit

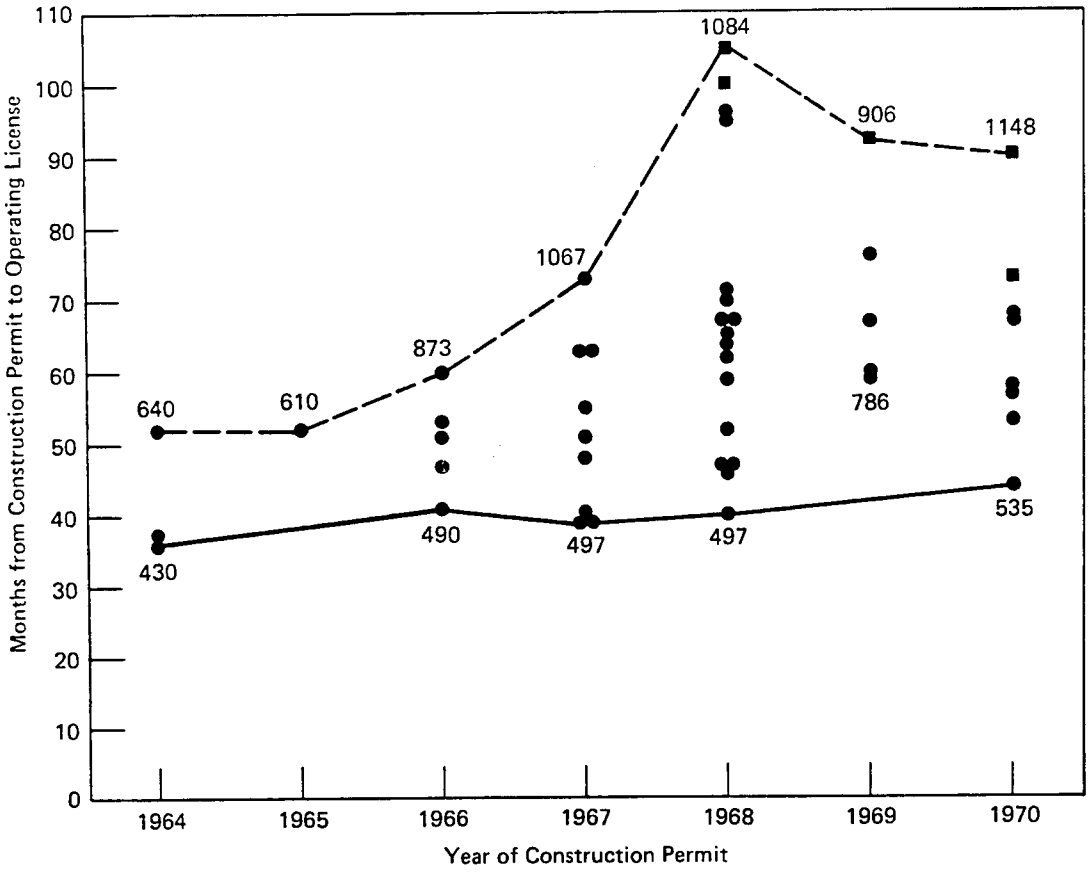

Chart 2--Time required for nuclear plant construction, measured by months from construction permit to operating license, versus year of construction permit. Data points marked by squares are estimates. For each construction permit date, the design rating for the fastest-built unit is written below the data point for that unit; and the design rating for the slowest-built unit is written above the data point for that unit.

for the plants that were built in the shortest time--430, 490, 497, 497, and 535 MW. They are all about the same size--fairly small plants. The ratings of the plants that took the longest are 640, 610, 873, 1067, 1084, 906, 1148 MW. They are all bigger plants. That suggests that perhaps these plants took longer to construct because they were bigger.

Chart 3. It is easy to check this hypothesis by making the plot in a different way: to plot the time it took to build them as a function of their rating in megawatts--400 to 1200 megawatts. Chart 3 shows the number of months from construction permit to operating license. You can see that the general trend is upwards. The bigger the plants are, the longer it takes to build them. There are two lines in Chart 3, denoted by two kinds of dots. The darkened circles represent turnkey units which Westinghouse and General Electric agreed to put up for a fixed price. The white circles designate non-turnkey plants. Because of the many contract changes for the non-turnkey plants, the non-turnkey units generally took about 10 months less time to construct. Westinghouse and General Electric wanted to get the construction job done quickly so they would lose less money. But the slope is the same for turnkey and non-turnkey plants.

It takes about 52 months per thousand megawatts longer to build larger units, or about 5 months per 100 MW. That is clearly a diseconomy of scale. For example, when a utility builds a generating unit, it buys an enormous amount of reinforcing rod, concrete, equipment, and what-not, and piles it around in a field, a muddy field as a matter of fact, and borrows money from the banks to pay for it. The utility owns that stuff--owns it all the time that the unit is under

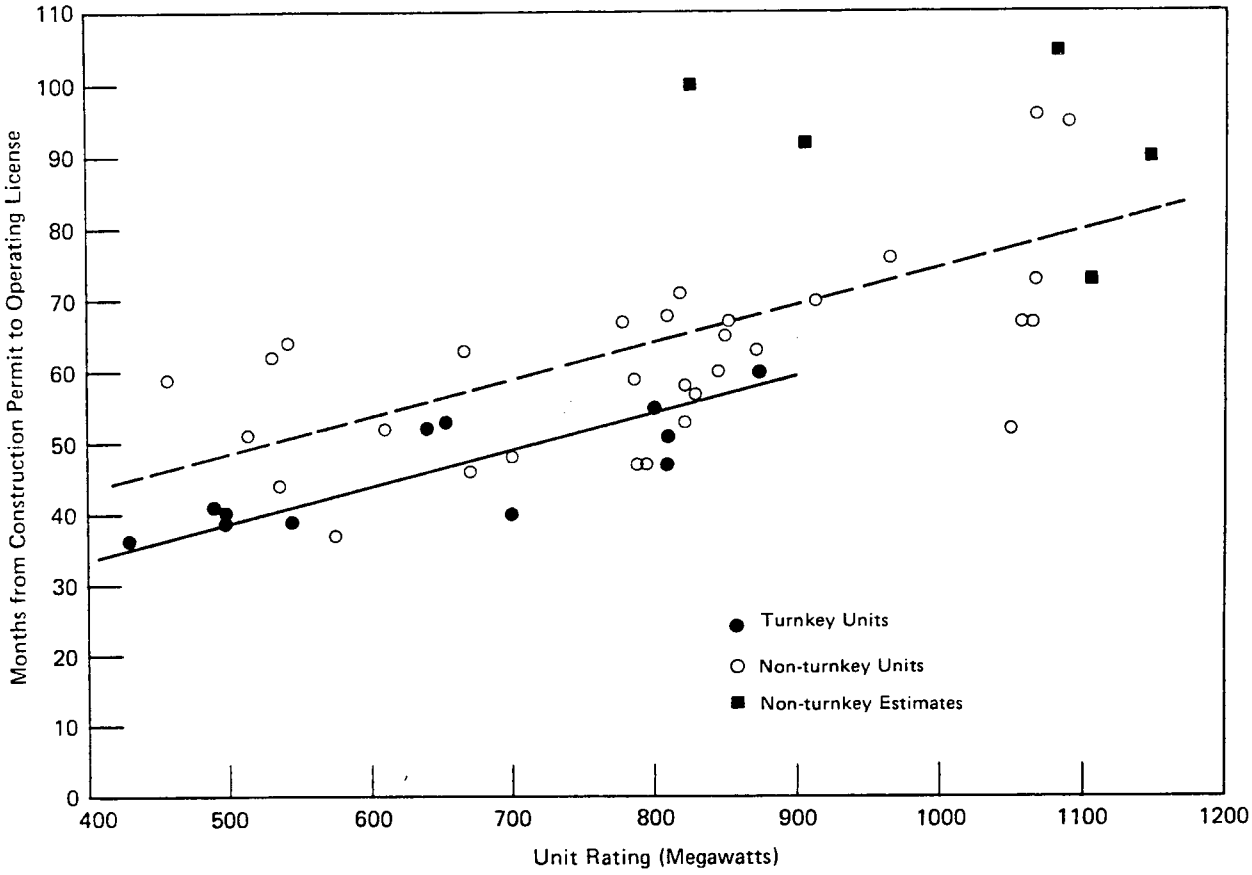

Chart 3--Time required for nuclear plant construction versus unit rating in megawatts. Separate trend lines are shown for turnkey units (solid line) and for non-turnkey units (dashed line). The trend lines rise 52 months per 1000 megawatts.

construction. The utility pays interest on the money, so there is a time-dependent cost. The larger the unit, the higher the interest cost.

There are other scale diseconomies in construction. The way cost estimating was done when I studied it, and probably still is, is that the cost estimators estimate what it costs to buy all that stuff that is sitting in the field. Then they assume that it doesn't make any difference what size the plant is; it costs the same time to pile it up into a structure. That isn't true. If you are building a big plant, people have to walk farther through the muddy field, and it is harder to find material and bring it back to where they want it. Since they are building a three-dimensional structure, they have to lift it higher off the ground. That takes longer and costs more money. So there are real costs, extra costs, for building big plants. That is one diseconomy of scale which, as far as I know, holds for any three-dimensional structure, including fossil generating units as well as nuclear.

Now I want to talk about another diseconomy of scale. It is not enough to know the cost of building a plant. You have to know how well it will run after it is built. If you have a plant that costs $1000 per KW but runs only half the time, it is equivalent to a $2000 per KW plant that runs all the time. So the fraction of time that the plant is operating is crucial. The fraction of time that a generating unit is actually generating electricity, if it is in baseload, is called the capacity factor.

Chart 4. This chart summarizes industry-wide capacity factor data for different size ranges--60 to 89 MW, 90 to 129, 130 to 199, 200 to 389, 390 to 599, 600 MW and above. Any plant has teething problems when

Rating (MW range)	Year of Commercial Operation						
	1	2	3	4	5	6	4-6
60-89	0.886	0.898	0.947	0.936	0.940	0.924	0.933 ± 0.017
90-129	0.865	0.948	0.791	0.896	0.918	0.874	0.896 ± 0.045
130-199	0.858	0.905	0.900	0.909	0.913	0.880	0.901 ± 0.037
200-389	0.781	0.822	0.840	0.854	0.835	0.835	0.841 ± 0.023
390-599	0.752	0.794	0.778	0.796	0.790	0.819	0.802 ± 0.032
600 and over	0.646	0.663	0.722	0.707	0.728	0.684	0.706 ± 0.045

Chart 4--Dependence of capacity factor on design rating and year of commercial operation

Note: Rectangle encloses mature plants.

it just starts; it takes several years before it operates well. You will notice that the capacity factor in year one of operation is poorer than year two, which is generally poorer than year three, but after that it settles down. Let's consider what it settles down to. In order to reveal the influence of scale on capacity factor as clearly as possible, I wanted to focus on plants with mature designs, so I threw out everything over 600 megawatts. All the units over 600 were of relatively new design. They were having worse problems for this reason, and it wasn't really fair to compare them with the others. I averaged performance for operating years four through six, and found that for the smallest plants the capacity factor is 93 percent. For the next ones in order of size it is 90 percent, 84 percent, 80 percent. The units in the range 400 to 600 MW only produced about 80 percent of the electricity that they would have produced if they could have operated at their design rating. That is another diseconomy of scale: the bigger the plants are, the more they are broken down with unscheduled outages.

Having illustrated two kinds of scale diseconomy--that larger things take longer to build, and that larger things tend to break down more often--let me show you my first search for scale economy. General Electric was in nuclear power, and I wanted to find out what the scale economy was for nuclear power. Since we didn't have much of a record of nuclear plant history, I thought first to look at scale economy for fossil plants where the record is perfectly clear. So I obtained the old Federal Power Commission records for all fossil units rated over 200 MW that went into commercial service in the United States for the last 20 years. Charts 5 and 6 display my raw data. The first plot in Chart

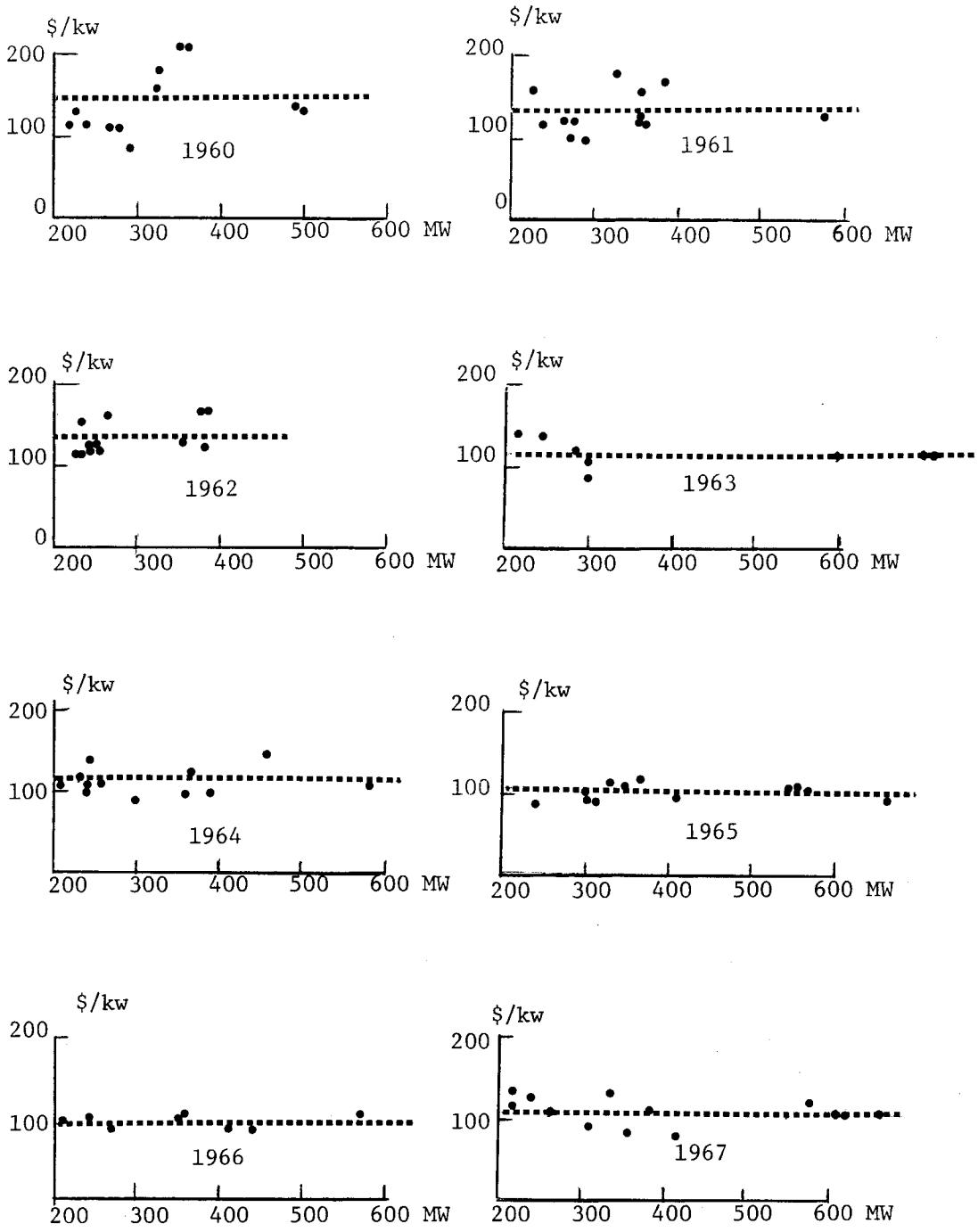

Chart 5--Megawatt ratings versus $/kw for fossil plants, 1960-1967

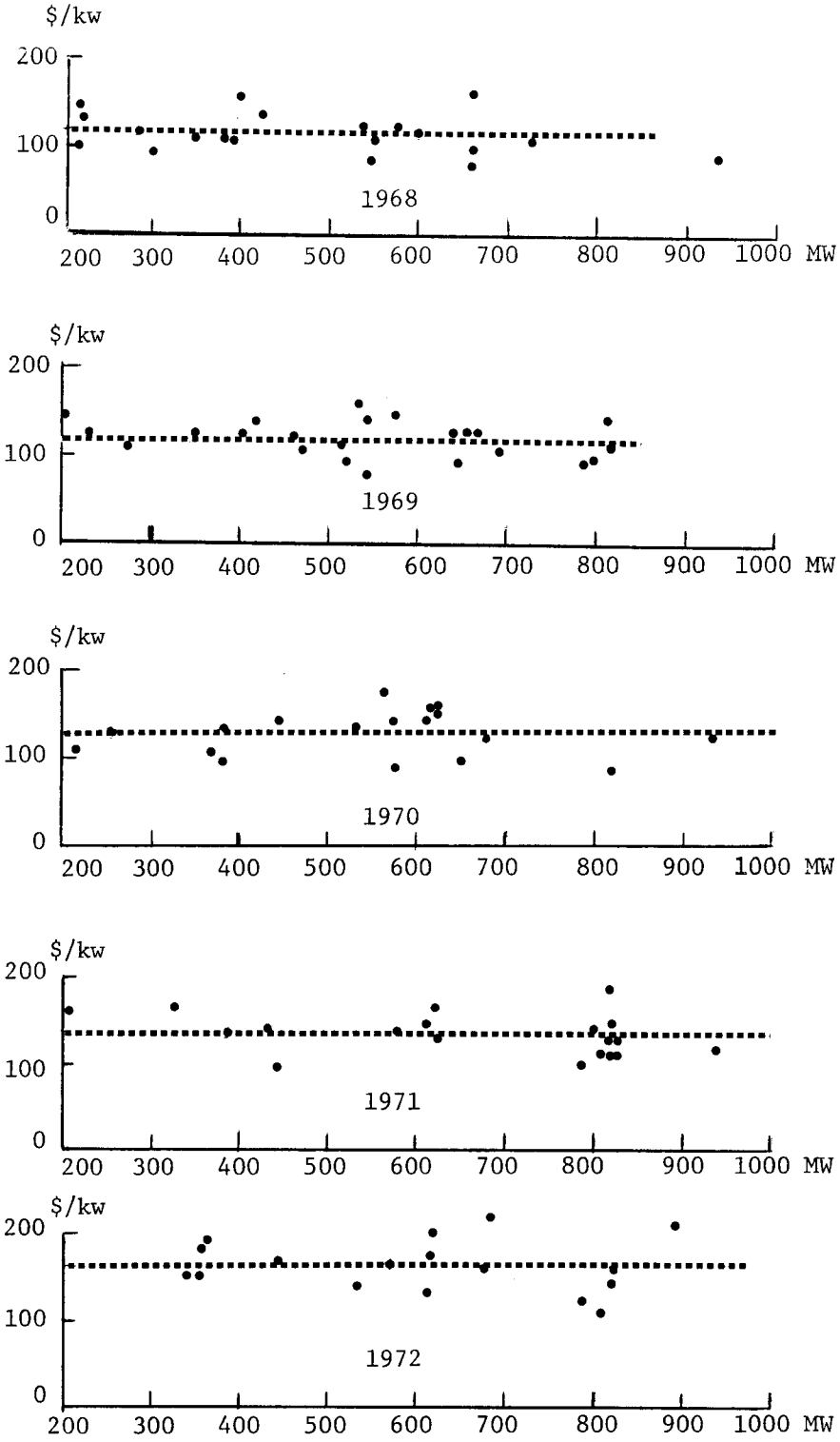

Chart 6--Megawatt ratings versus $/kw for fossil plants, 1968-1972

5 is dollars per kw versus rating for units that went into commercial operation in 1960. There is a lot of scatter and the horizontal line shows that there isn't much trend. The following figures are similar: In 1961, 1962, 1963, 1964, and 1965, there is scatter, but no trend. In 1966 there is less scatter, but still no trend. I was getting nervous. Rating doesn't seem to make any difference. Scatter, but no trend in 1967, 68, 69, 70, 71, 72. Where is this scale economy? The bigger ones are supposed to be cheaper in dollars per kilowatt.

However, there is a trend that some of you may have spotted. Chart 7 shows the unit cost in period dollars per kilowatt as a function of the year of commercial operation. In 1960 it was $140 per kilowatt, which is just the average of all the units within that year. In 1961 it was $130 or $135. In 1966, the unit cost fell all the way to $95 per kilowatt in period dollars. Inflation was going up, dollars per kilowatt was going down. Then, after 1966, unit cost went back up. It rose to $155 by 1972. In the early days, people looked at these figures and thought "This is the economy of scale working. We are building them bigger and they are getting cheaper." But it wasn't scale economy, as we have seen, because the cost went down for units of every rating. And in 1966 when they were building the plants still bigger, the cost rose again for units of every rating.

Chart 8. The decline and subsequent increase haven't anything to do with scale, but they create a problem for comparing one year to another. In order to compare different years, I normalized units for each year. I divided the cost of units of all different sizes by the average cost of units in 1964 for 1964 units, and so on. Chart 8 is the

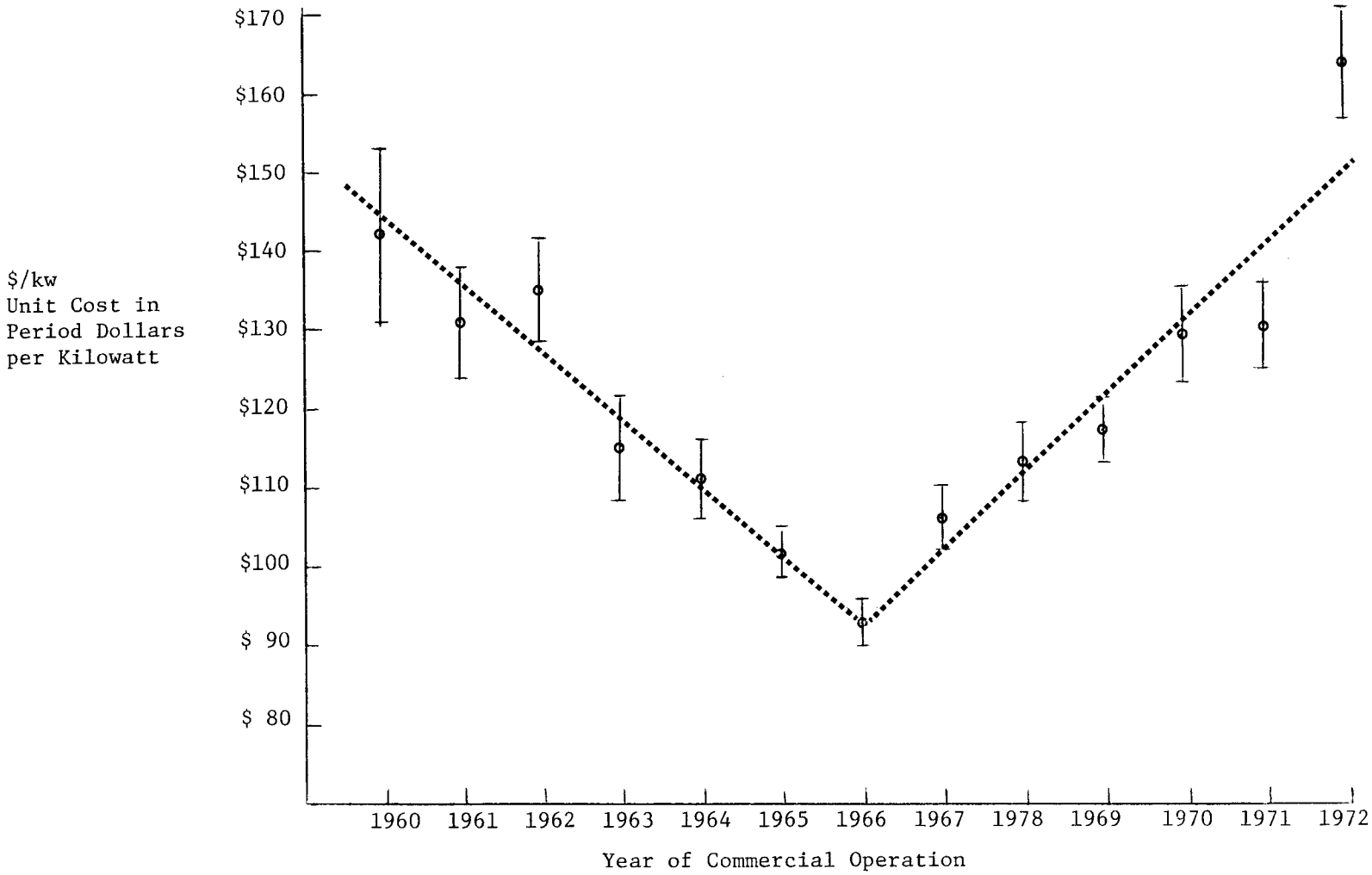

Chart 7--Unit cost per kilowatt of nameplate capacity versus calendar year (in period dollars, adjusted for type of construction and for special first-unit and second-unit costs)

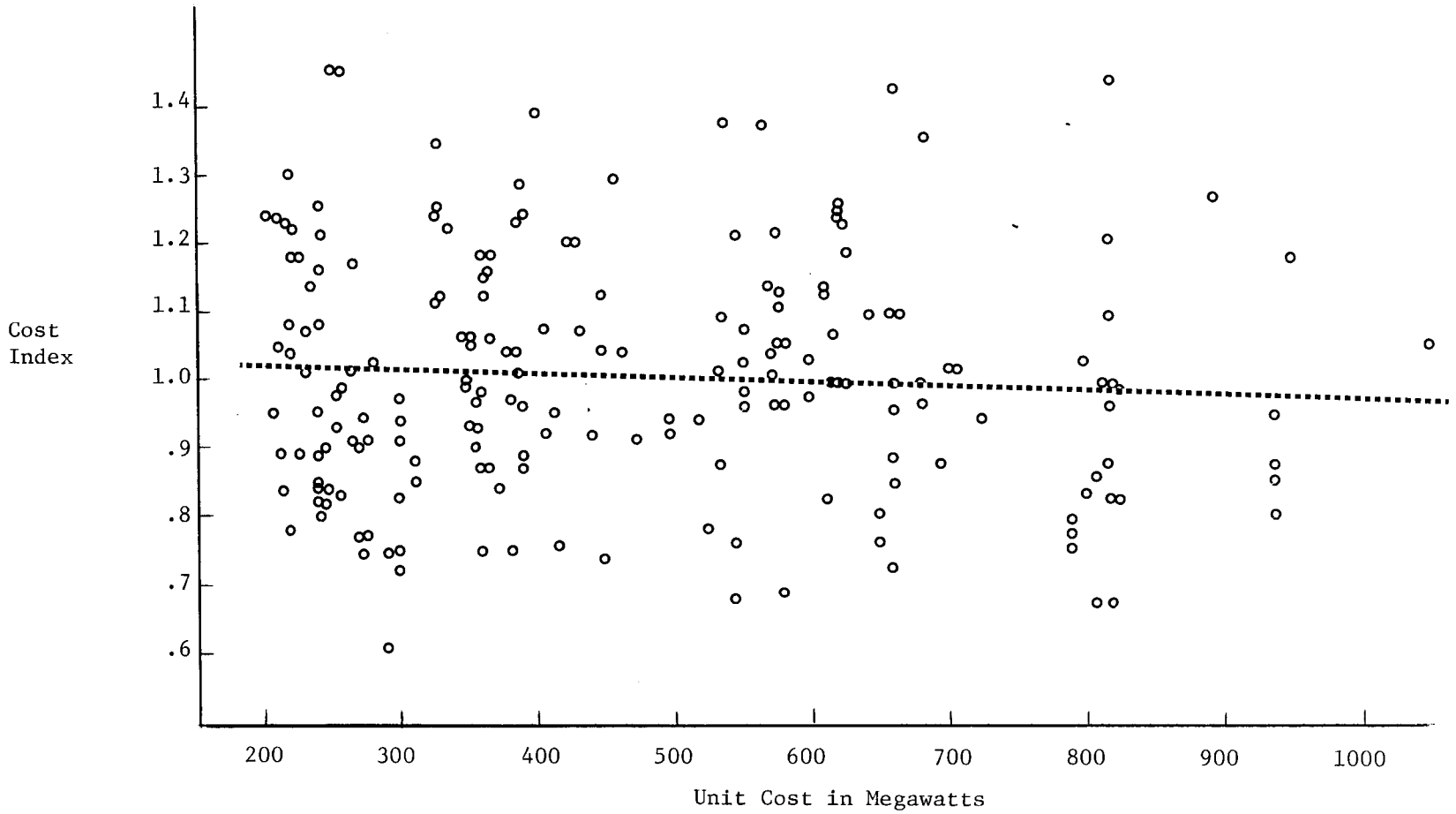

Chart 8--Normalized unit costs for fossil plants versus nameplate capacity

result of these calculations. And yes, there is a slight decline in cost as a function of unit rating.

Chart 8 only tells part of the story. It turns out that there is a mixture of technologies in the data base I was using. Large units tend to use a different turbine technology. I was somewhat baffled at finding so small a scale economy. When I talked to knowledgeable GE engineers about it, they mentioned the technology mix. I resisted the idea for awhile, but my later analysis corroborated their statement. There is a mixture of technologies: cross compound units in which the steam enters in different ways to high pressure turbines, as well as a mixture of low-speed and high-speed generators all in one unit.

To pare the data base down to a single technology, I picked a standard technology that has been around a long time, one with a single 3600 RPM turbine and subcritical steam. I put together a smaller data base for units that had steam at 2400 pounds per square inch at 1000 degrees F, single reheat at 1000 degrees F, driving a generator at 3600 RPM; there were 130 or so units like that of different sizes built in the United States over a 10 or 15 year period. Then by multiple regression, I analyzed all the various factors that people had told me were important, and I found that they were indeed important (see Chart 9).

One important factor is whether or not a unit is the first one built on a particular site. The first unit on a site costs 1.21 times the average of all units on the site, because the land is charged off to that one, as is the cost of putting in the road, the office building, and so on. The 95 percent confidence limit puts the cost at 11 percent

Variable Name	Coefficient	95 Percent Confidence Limits
unit 1 cost factor	1.21	(1.11-1.31)
unit 2 cost factor	0.87	(0.80-0.94)
oil or gas only cost factor	0.74	(0.67-0.82)
public or cooperative cost factor	0.85	(0.75-0.96)
region 1 cost factor	1.51	(1.33-1.71)
region 2 cost factor	1.08	(0.96-1.21)
region 4 cost factor	1.15	(1.03-1.29)
region 5 cost factor	0.80	(0.72-0.90)
region 6 cost factor	1.21	(1.04-1.41)
region 7 cost factor	1.33	(1.11-1.59)
percent annual inflation	12.7	(11.4-14.2)
scale economy exponent	0.16	(0.02-0.29)

Chart 9--Regression coefficients for construction costs of generating units

to 31 percent higher, so we are pretty sure that the first unit costs more. The second plant costs less than average. That is because the same office building is used. The third plant requires another office building, and that is significant. Building a unit so that it burns just oil or gas, not coal, knocks 26 percent off the cost. If it is built by a public or cooperative utility, that knocks 15 percent off. If it is built in Region 1 it costs 51 percent more. (I am comparing these with Region 3.) Region 2 costs 8 percent more; Region 4, 15 percent more, Region 5, 20 percent less, Region 6, 21 percent more, Region 7, 33 percent more. There is a highly significant annual cost inflation of 12.7 percent, with confidence limits at 11 to 14 percent. And finally, there is a scale economy exponent, which is what I have been looking for. The value is 0.16, with 95 percent confidence limits of 0.02 to 0.29. The uncertainty is fairly large, but that is the best one can do.

So I found 0.16 for the scale economy exponent. There is a scale economy, but it is not very large. Doubling the size of a unit reduces its cost per kilowatt by the factor $2^{-0.16} = 0.90$, a 10 percent saving in construction cost.

If you were interested only in construction cost, you would build as large a plant as possible because the dollars per kilowatt to construct it would slowly decline with size. But that is not exactly what you want to do. Consider this formula:

$$\text{Actual \$/kw} = \frac{\text{Construction \$/kw}}{\text{Capacity Factor}}$$

The dollars per kilowatt of actual electricity is given by the ratio of

(1) the dollars per kilowatt that it cost to construct the plant to (2) the capacity factor. If the plant has a capacity factor of 50 percent (only runs half the time), then the dollars per actual kilowatt are twice as big as the dollars per design kilowatt. If it doesn't run at all, the capacity factor is zero and the cost is infinite.

To summarize in an equation, I want to determine the realized capital cost, which is construction cost adjusted for capacity factor:

$$\underset{\substack{\text{realized}\\\text{capital}\\\text{cost}}}{(\$/kw)} = \underset{\substack{\text{construction}\\\text{cost}}}{(R/1000)^{-a}} \times \underset{\substack{\text{capacity}\\\text{factor}\\\text{reliability}\\\text{adjustment}}}{b^{-R/1000}}$$

The construction cost $(R/1000)^{a}$ is the construction scale economy. R is rating in megawatts and "a" is the 0.16. The term $(b)^{-R/1000}$ adjusts for the capacity factor falling off with size. The result is that the realized capital cost per kilowatt of actual average capacity is a minimum at a certain size. When the value of "a" is 0.16 and "b" is .70 (as determined from the statistics of the data), that size is about 450 MW, which is about where utilities are building fossil units these days. They experimented, they built much larger, and now they have returned to about 450. The 95 percent confidence limits on the optimum size are very wide, lying between 100 and 800 MW. A British study suggests that the optimal size is smaller than 450 MW.

In one sense everything I have talked about so far bears on pioneer plants because pioneer plants are likely to take longer to build the bigger they are, and they are likely to be less reliable the bigger they are. Probably the optimum size for the first-of-a-kind is close to the optimum size for the second- or third-of-a-kind, unless you settle on

one design for a plant and build a lot of them. And that opens up the possibility of a new avenue of cost reduction, which I would like to mention. If you build something repetitively such as aircraft or automobiles or tanks, the cost per unit declines as the number of units increases. Generally, every time you build twice as many, your costs drop by 10, 20, 30 percent. Suppose that we built power plants the same way: we have a standard design and we replicate one after another. Then what would happen? So far, I have talked about actual data that I have analyzed. Now I have a hypothetical projection, one that has not yet been made, and I am suggesting that it be considered.

Chart 10. Suppose you want to add 1000 MW to a utility system. If you do this the usual way, you hire an architect-engineer; you make a special design for a 1000 MW unit; you build one. It costs you $500 per kilowatt. Suppose you build two that are 500 MW each. Because of the scale economy for construction, the first 500 is going to be more expensive per kilowatt than the 1000. The first unit will cost $556/kw, but since the second unit is a carbon copy it will cost $472/kw--an average of $514/kw. If you build 4 units--250 MW each--the first one will cost $617 per kilowatt, but then the carbon copies drop off to an average of $518. If you build 8, the first one costs $686 per kilowatt, but the carbon copies go all the way down to $421--average $512. As Chart 10 shows, it doesn't really matter for construction costs how you do it. Construction cost comes out $500 per kilowatt, or a little over, for every alternative. You might well ask why bother to build a lot of little ones if the construction cost doesn't change much. The answer is that because they are little, they are reliable. When I adjust these

Construction cost in $/kw

Alternative for 1000 Mw	1 1000MW unit	2 500MW units	4 250MW units	8 125MW units
Unit 1	500	556	617	686
Unit 2	-	472	525	583
Unit 3	-	-	484	537
Unit 4	-	-	446	496
Unit 5	-	-	-	476
Unit 6	-	-	--	457
Unit 7	-	-	-	439
Unit 8	-	-	-	421
Average $/kw	500	514	518	512
$/kw adjusted for CF	714	614	566	536

$/kw for first unit increases because its size decreases

$/kw for subsequent units decreases because of accumulating experience

average construction $/kw stays roughly constant

adjusted for capacity factor, average capital cost per kw of available capacity declines as unit size decreases

Chart 10--Hypothetical example of the effects of scale and reliability on construction cost

construction costs for the capacity factor that I expect for each size, the dollars per kilowatt of actual capacity achieved range from $714 for the single unit through $614, $566, down to $536. A multiplicity of identical small units gives the lowest cost.

That has bearing, I think, on pioneer units, too. You may be tempted to build a big one because the cost per unit of output will be only $500. If the unit is small, the cost will be $686. The point is, if you build a little one and replicate it, it is going to cost about the same to construct and, it is going to be cheaper in terms of overall performance because of its higher reliability.

Q. How do you validate the learning curve reduction with cost for electric power plants?

A. I cannot validate it for this kind of power plant, because repetitive construction generally hasn't been done for them. They are mostly one or two of a kind with separate designs for each. The only kind of power plants I can do it for are jet engines where the Air Force has looked into it, and that particular kind of power plant does follow the learning curve.

Q. You've got production learning there, where the same workers are working, but in the construction industry I am not so sure you have the same company or the same workers.

A. If I were a utility, I would. I would say, look fellas, I am going to put up 10 of these plants in this particular area here; why don't you get your families out of those trailers and into some houses here and send your kids to school, and we'll build these things one at a time, and spread them over 10

years, or whatever, and I think that I would get those cost reductions. If you didn't do that, then you wouldn't be able to take advantage of that degree of learning.

Q. So far your analysis has implied that there is no difference in environment and safety regulations between small plants and large plants, and also that there has been no change in safety and environmental requirements from year to year as you went through your analysis. Did you look at these variables and decide they didn't have any bearing on this, or were they just left out for some other reason?

A. When I analyzed the construction time for nuclear plants, I put the year of construction permit into the multiple regression as one of the parameters, the theory being that units that had their construction permit at a later date would cost more on account of the additional regulatory problems associated with getting a permit later on in the calender history. And the multiple regression showed that that variable had no significance. It is a little hard to accept, but there was no significance to the year of the construction permit. There was significance to whether the plant was a turnkey or not, and there was significance as to the rating of the plant. I have thought about that, and it is my personal opinion, but I cannot substantiate it, that there was a dead heat going on between the designers of plants and the regulators of plants. The regulators were putting out new regulations and the designers were learning how to design plants better, so those things

compensated for each other, and the only variable left over was plant rating. That is speculation. But the regression didn't show any effect of regulation.

Q. Can you find any explanation as to the lowered capacity factor of the larger plants versus the higher capacity factor for the smaller plants?

A. Yes, certainly. There are many. I will give you some. Let's compare a 1000 MW unit and a 200 MW unit. In a 1000 MW unit, the turbine has about five times as many buckets and blades. In the condenser there are five times as many tubes. The boilers have five times as much tubing. For a lot of the equipment you have five times as much in the 1000 MW plant as in the 200 MW plant. So if there is any probability of failure of a turbine blade or bucket, or of a condenser tube or a boiler tube, that probability will be about five times higher in the large plant, so the large plant will break down more often on that account. I know that the quality of the components that are put into units of different sizes is about the same. The assembly line workers making the turbine buckets don't know whether the turbine bucket is going into a 500 MW or a 1000 MW plant. It is the same machinist, the same machines, so you have about the same probability of failure per unit part, but you've got more parts in big plants.

There are other equipment items where that is not true. Examples are the turbine casing, or the generator casing, and the valves. If you have a big plant, you have a big valve and

a big pipe. In a little plant you've got a little valve and a little pipe. If you make a big valve, you make it out of a big casting. But you can only make castings and forgings so big, so a big part is a part that has not had the same degree of mechanical work, forging, and refining of metal properties as a small part. And for this reason its mechanical properties are worse. Mechanical properties are improved by progressive hot work and cold work. So generally speaking, larger parts are made of poorer material, or if not poorer, you had to go to more expensive material, which you don't like to do because the reason for going larger is to get cheaper. So you tend to make it out of the same material, but it is poorer quality, and the part tends to fail more often.

Another thing that happens in a 1000 MW plant is that because the owners know it will be expensive, they are more careful in the engineering design. That means that they build the plant closer to the limits. More engineering design means that you can design to get away with a smaller factor of safety, because you know better what the limits are, so that large plants are designed closer to the limits. For that reason, they tend to fail more often.

And there are other reasons why large plants are out of commission so much. Every plant needs maintenance--scheduled maintenance as well as remedial maintenance. Let's talk about scheduled maintenance. If you open up a steam turbine for maintenance as soon as you shut the plant down, the turbine is

wrecked because the turbine runs red hot and it will thermally distort. So after you shut down you have to wait for the turbine to cool down so it won't distort; also so it won't cook the workmen. And a big turbine takes longer to cool down so that your scheduled outages for routine maintenance are longer and will take you out of operation longer for a big plant than for a small plant.

All of those things combine to make large plants be out of commission more than small plants for perfectly understandable, sensible, economic reasons. I talk to GE engineers about this and it infuriates them. They say, "John, you say that large units are going to have a smaller capacity factor than small units, but that isn't going to be so. We can design them so they will have just as high a capacity factor as small units." I get tired of telling them, but I keep telling them, "Yes that is true, but they won't give you the money. It will cost so much to achieve that level of reliability that the dollars per kilowatt for a big unit would turn out to be more than the dollars per kilowatt for a small unit, and the reason they make it big is to try to save money. So they won't give you the money. It doesn't make any economic sense to pay more for increased capacity through increased reliability instead of simply through building another plant."

Q. In your example, are you essentially assuming that the plant is one site with multiples of the units on it, or are you assuming multiple units on a number of different sites?

A. I assumed that they were all at the same physical site, all built by the same crew of workmen, serially, one after the other. By "serially" I mean that each task was done repetitively with the same crew of workmen. When guys finish their task at one of these plants they move on to the next one. It would be similar to a builder putting up a batch of houses. The houses are in various stages of construction and he is moving his work crew from one to the other; that is the mode that I had in mind. Chart 10 is a hypothetical possibility which was meant to stir the thinking of my then company and the other organizations that I was working with to try to get them out of what I judged to be a rut.

Q. John, if the smaller plants were not built any cheaper--say you didn't get any learning at all even though they were built the same--would they still get cheaper per kilowatt?

A. In that case, if there was no learning, then my judgment is that there is then an optimum rating around 450 megawatts. This is a fairly broad minimum so that you couldn't go wrong by say a factor 1.5 one way or the other from that.

Q. One of the things that seems to be a problem is operating costs after you get the plant built. Have you considered that factor?

A. I looked at two kinds of operating costs, one carefully and the other casually. The one I looked at carefully was the question of efficiency, which is important for power plant operation. It might be that big plants would be more efficient for some

reason. I took a look at it and the data did not support that. There was no variation of efficiency with rating that was of any significance. So that wasn't a factor. The reason is that these are heat engines, and the main thing that determines efficiency in heat engines is the steam temperature and pressure. I also tried to understand labor costs, but it was not easy. I assumed that every plant would require operators, so there would be more operators per kilowatt for a small unit. And I assumed that all the maintenance that was required would require personnel and there would be less maintenance for the smaller ones because they're not broken down as much. I expect that the operating costs will be larger per kilowatt for the larger units because of their lower reliability and the fact that they are out of commission being fixed up a bigger fraction of the time. But that I have not proven. I have that on my list of things to do.

Q. John, you used a learning curve rather glibly there. Do you have any real basis for that?

A. Do I have any real basis for using the learning curve for this type of power plant? The answer is no. I wish somebody would study it.

EFFECTS OF INCENTIVE PLANS ON PROCESS INDUSTRY ECONOMICS

John Hackney

Title Chart. I'm going to talk a bit about how incentive plans affect process plant economics. But before we can talk about incentive plan effects, we need to briefly review process plant economics.

OUTLINE

- Present Business Environment for Pioneer Process Plants
- Profit Sensitivities for a Typical SNG-from-Coal Plant
- Spectrum of Incentive Plans
- Incentive Plan Effects

Chart 1. Here is the general outline of our discussion: (1) the present business environment for pioneer process plants; (2) the profit sensitivities of this particular type of plant (what makes their profits go up, and what makes them go down); (3) the spectrum of incentive plans that are available; and (4) the effects of each type of incentive plan.

- Business Environment for Pioneer Process Plants

Variable Inflation Rates, affecting -

Construction costs

Operating costs

Product prices

Chart 2. Let's look at the present business environment for process plants, and especially pioneer process plants. As shown in Chart 2, we're faced with variable inflation rates, which affect construction costs. They also affect operating costs, and the operating costs involved are not those of today. They are costs as they will be five to eight years from now. So the impact of inflation on operating costs is even more difficult to predict than the impact on construction costs. Inflation rates also affect product prices. If you could tell me what product prices will be for oil five months from now, I think you and I could become millionaires!

• BUSINESS ENVIRONMENT FOR PIONEER PROCESS PLANTS - CONT'D

FLUCTUATING INTEREST RATES, AFFECTING -

COST OF BORROWED MONEY

FINANCING ARRANGEMENTS

THRESHOLDS FOR INVESTMENT RETURN

Chart 3. Another key aspect of the business environment we're facing is the fluctuation of interest rates. We had a strong peak in interest rates in April 1980. They went down again--and not a little bit. They're going back up now. Please tell me what they are going to be a month from now, and you and I will be friends forever. Interest rates affect the cost of the borrowed money that you need for these projects, and they affect the financing arrangements you can make. They especially affect return thresholds: the go/no-go percentages for acceptable investment return. It used to be that a board of directors could look at a project and say, "We're reasonably sure this thing is going to give us a 15 percent rate of return, we can borrow money at 8 percent; so, let's go." Now they aren't so certain where that threshold should be. We'll be looking a little later at this matter of thresholds, and how they are influenced by other economic conditions.

- BUSINESS ENVIRONMENT FOR PIONEER PROCESS PLANTS - CONT'D

  PIONEERING NATURE OF PROJECTS, ENTAILING SIGNIFICANT -

  INVESTMENT GROWTH RATIOS, WITH CONSEQUENT OPERATING COST INCREASES

  PERFORMANCE RATIOS

  START-UP DELAYS

Chart 4. A third aspect to be considered is the pioneering nature of these plants. Investment growth ratios, which were discussed earlier today, are strongly related to the degree of pioneering involved in a project. Degree of pioneering also affects performance ratios (how much actual production you will get compared to the plant's nameplate capability), and the startup delays (whether you will actually be able to start it up as planned).

- BUSINESS ENVIRONMENT FOR PIONEER PROCESS PLANTS - CONT'D

  GOVERNMENTAL INVOLVEMENT, ENTAILING -

  ENVIRONMENTAL RESTRICTIONS

  PERFORMANCE DELAYS

  ENERGY PRICE CONTROLS

  INVESTMENT INCENTIVES

Chart 5. A final, key aspect of the business environment for energy projects is governmental involvement. For all energy projects this entails environmental restrictions. If these restrictions were fixed they wouldn't be nearly so much a problem as they are now, when they present a constantly moving target. Furthermore, anytime you bring another powerful organization into a project, you create delays. This is particularly true of governments and governmental agencies. And, I'm not just speaking of the United States. It could be the government of Norway, the government of England, the government of Indonesia, or the government of South Africa. When governments participate in a project you have to count on performance delays because there is a political process involved. Furthermore, we must consider governments energy price controls, present and prospective. The government has a strong influence on what energy prices are, and what they are going to be. Finally, and the subject of the rest of this particular talk, there are incentives government can provide to encourage pioneer energy projects, and return the country to energy self-sufficiency.

- Business Environment for Pioneer Process Plants

  Variable Inflation Rates, affecting -

  - Construction costs
  - Operating costs
  - Product prices

  Fluctuating Interest Rates, affecting -

  - Cost of borrowed money
  - Financing arrangements
  - Thresholds for investment return

  Pioneering Nature of Projects, with significant -

  - Investment growth ratios, with consequent operating cost increases
  - Performance ratios
  - Start-up delays

  Governmental Involvement, entailing -

  - Environmental restrictions
  - Performance delays
  - Energy price controls
  - Investment incentives

Chart 6. In summary, let's list all these issues on one sheet. These are the main uncertain features of the business environment about which people are being asked to make reasonable judgments, and then to commit themselves to spending very large amounts of money. Pioneering energy projects are being developed in a truly complex and uncertain business environment.

It seems appropriate to tell a little story right now. Back when I started in this business I worked for the Aluminum Company of America,

which was and is a very conservative organization. I worked in the engineering department, which was a conservative part of the Aluminum Company. Because of the Depression, I was the only engineer they had hired in seven years. I was lucky enough to be thrown in with a select group of experienced professional engineers--some terrific personalities. We'd meet in the evenings and we'd play poker. These fellows were very good poker players. They taught me how to play poker (and I paid to learn). They played a very conservative game (it was nickle ante). We'd play five-card stud, five card draw, and if you felt real bold, seven-card stud. I got pretty good at this conservative game. When the war came along, I went out to Modesto as a construction manager. Every noon we'd sit in the office, eat our lunches, and play poker. We didn't play for money, because it was a governmental project and we didn't want things to look bad, so we played for paper clips. But I assure you we played for those paper clips just as hard as if they'd been dollar bills. Again I learned. These fellows didn't play five-card stud; they played "baseball," they played high-low seven-card draw, aces-sevens-and-deuces wild, the damnedest games you ever saw. And for the first week or so, I held back. I thought, "What kind of a poker game this? It's pure luck!" Then I began to find out that the same fellows were lucky most of the time. There had to be something here I didn't understand. Over the next 8 months I learned how to play wild-card poker. There is a technique to it--you must be sensitive to the odds, instantly reassessing them as they change from one game to the next. The sequel was interesting. At the end of the 8 months I was

1495 paper clips ahead. There had been many fluctuations, but I'd been able to keep my total climbing. They paid me off at a penny per paper clip. Then we all went out and drank up the winnings!

If you think about it a bit, this is exactly the sequence we've experienced with respect to economic studies. We went to school, we learned economic analysis "straight up and down." The interest rate is so much (the inflation rate we didn't even consider, because it wasn't enough to be considered); the cost of labor is so many dollars per hour; the product price is so and so. All this was fixed within a fixed framework of time. We were playing a straight poker game. Now we've graduated; we're in a new economic era. We're playing in a volatile set of economic conditions. But there still is skill involved, there still are ways to beat the game. The trick is to keep your head and dig away at these problems. Find out what makes them problems. Learn how to solve them, so that we can win this terribly difficult game of building a synthetic fuels system within the present unstable economic environment. It <u>is</u> a wild game, but we can learn how to play.

One helpful technique is to think in terms of a base case, a fixed location from which to start exploring project economics. The early explorers who came to this country were exploring a vast unknown area, but they were exploring it in only two dimensions. Even then they had a hell of a time keeping track of where they were. Here we're exploring a multidimensional space--not a three-dimensional space, not a four-dimensional space, but something like a ten-dimensional space. We're exploring this economic space to find where the core of profitability is, the core of feasibility for the synfuels industry.

- PROFIT SENSITIVITIES FOR A TYPICAL SNG-FROM-COAL PLANT

BASE CASE IS SNG-FROM-COAL DATA PROVIDED BY
JOSEPH P. LEONARD, CHEMICAL ENGINEERING, P. 183-6,
MARCH 26, 1979 -

PLUS ADDED "REASONABLE ASSUMPTIONS" AS REQUIRED.

Chart 7. What I have done here is to take as a base case some data Joe Leonard published in Chemical Engineering. (Incidentally, I have his approval to do this. I've added some assumptions, as necessary, for this study.) It doesn't really matter though what base case you choose. What you need is one fixed set of economic conditions from which you can explore the economic space, but still know where you are in that space with reference to your base.

BASE CASE

(IN 1980 BASEDOLS)

CAPITAL INVESTMENT, INV (EST. COST $1500, GR = 1.33)	$2000MM
SALES AT 100% OF CAPACITY	82.5 TR. BTU/YR.
PERFORMANCE RATIO	0.8
NET SELLING PRICE	$6/MM BTU
FIXED PRODUCTION COSTS AT GR = 1.00 (PROPORTIONAL TO INVESTMENT, INCLUDES ALL COSTS EXCEPT COAL)	$95MM/YR.
VARIABLE PRODUCTION COST (COAL)	$60MM/YR.
BY-PRODUCT CREDIT, AT 100% OF CAPACITY (SULPHUR AND AMMONIA; VARIABLE)	$15MM/YR.
ECONOMIC LIFE, LY	19 YR.
DEPRECIATION LIFE, DY	12 YR.
DEPRECIATION METHOD	SYD
DEPRECIABLE PORTION OF INVESTMENT	100%
DEBT/EQUITY RATIO	0.00
INCOME TAX RATE, T%	40%
INVESTMENT CREDIT	0%
INFLATION RATE	10%

NOTE: Approximated from SNG-from-Coal 1980 Plant; J. P. Leonard, Chem. Eng. p. 183-6, Mar. 26, 1979. All in 1980 basedols.

Chart 8. These are the details of the base case. The actual capital investment is $2 billion, which results when the expected capital investment of $1.5 billion experiences a 33 percent overrun; sales volume at nameplate capacity is 82.5 trillion BTUs per year; performance ratio is 8/10; net selling price is a fixed amount in constant dollars; production costs are fixed in constant dollars; economic life is assumed to be 19 years; and depreciation life is 12 years, with sum-of-the-digits depreciation. The debt/equity ratio is

0--quite different from the projects talked about this morning. Income tax is an arbitrary amount (40 percent). Investment credit is zero for this base case. That is one of the incentive types we want to explore. We assume an inflation rate of 10 percent, but other possibilities need to be explored. We need to "cut cross-sections" through this economic space.

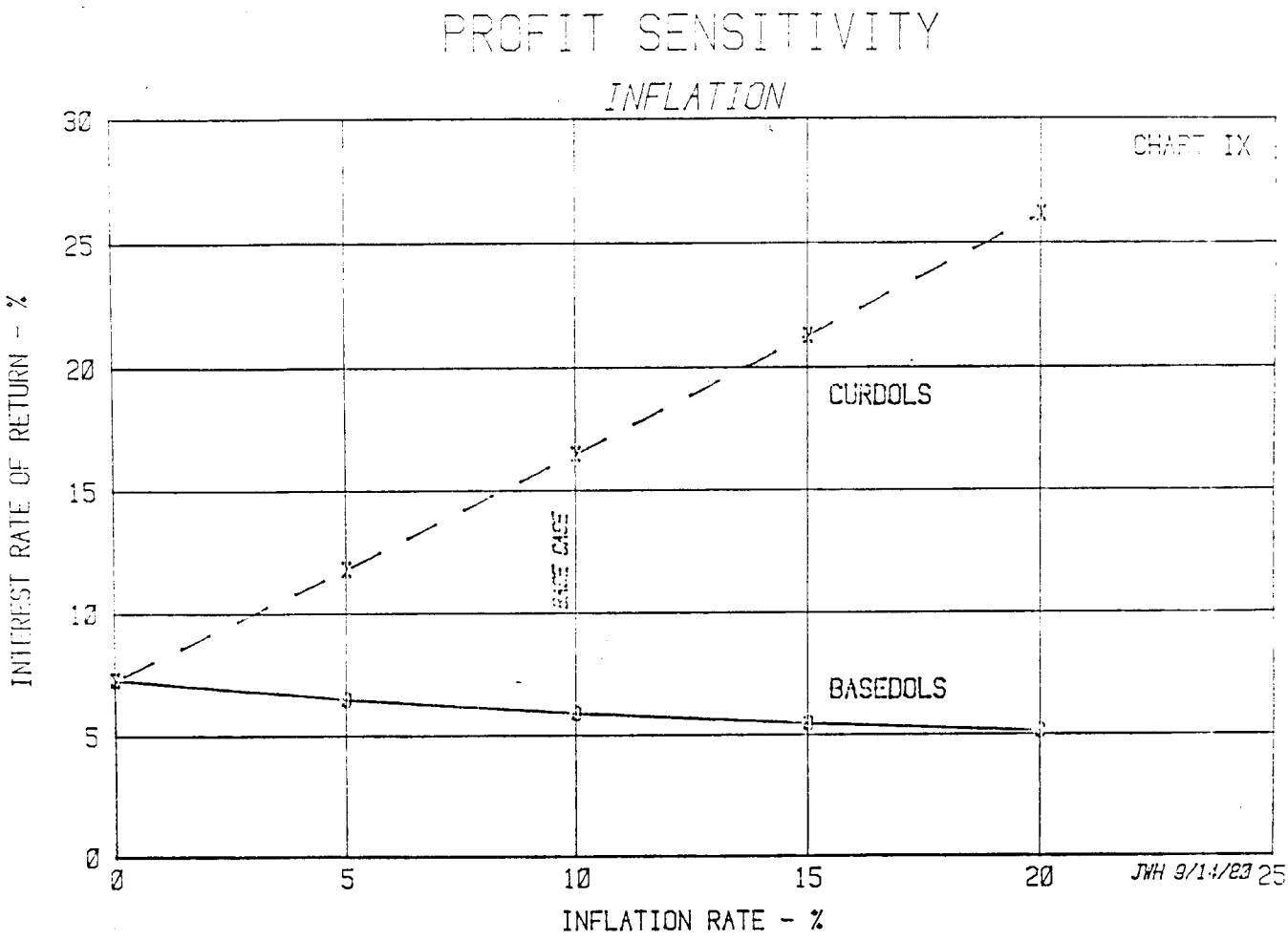

Chart 9. Let's look first at the sensitivity to inflation of this project's interest rate of return. This set of computations assumes that the costs of operating the plant are going up at the same rate as the general rate of inflation in the country, and that the price of the product is going up at exactly the same rate. As you can see, the project will give you about a 7 percent rate of return with a zero inflation rate. With a 10 percent inflation rate, the current-dollar return is going to appear to be about 17 percent. Happy days! But the

fact of the matter is that taking into account the base value of your net income dollars, and what you can buy with them, you will actually be getting about a 6 percent return. Ladies and gentlemen, that's where we are in industry at the present time. We've got a lot of corporations reporting a 15 percent or 17 percent rate of return, but their actual return is much less. It depends on the company's situation, but in many cases it is down around 6 percent, and even lower. Yes?

Q. Your base dollar return seems to be dropping as the inflation rate increases. If product prices are increasing with the rate of inflation, I mean if everything is just sort of moving up together, shouldn't the return be constant?

A. What's happening is that you are paying your taxes in current, inflated dollars. That is where you are losing out; it's distinctly a tax effect.

This whole subject of inflation accounting is a very serious matter, and being widely discussed in accounting circles. The Securities Exchange Commission is requiring that some inflation-corrected information be presented in annual reports, but so far it's been way back there in the footnotes. A lot of apparently profitable corporations are paying dividends out of corporate assets, and their corporate assets are wasting away.

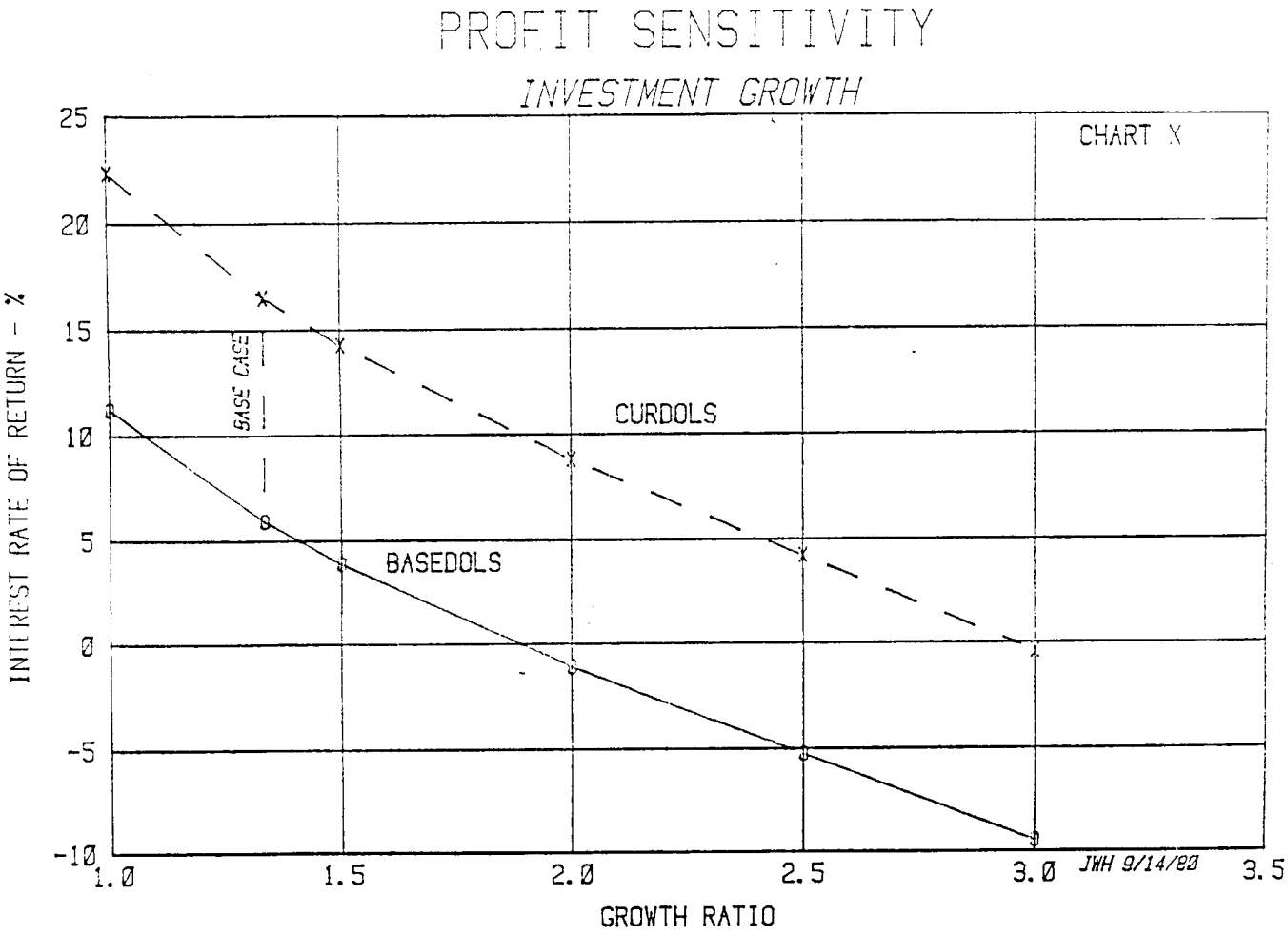

Chart 10. Let's take another excursion into this multidimensional space to see what changes cost growth can produce. Our base case shows up here with an investment growth ratio of 1-1/3, producing the same 6 percent return in base dollars and 16-1/2 percent on a current dollar basis. If the growth ratio actually is 1.00 (in other words the project goes forward in such a way that no increase in the estimated cost of the plant is required to produce the specified amount of gas), then the base-dollar return is going to be much

improved, about 11 percent. On the other hand, if the cost growth ratio goes to 3.0, you have what appears to be a break-even situation in current dollars; but you're actually in a loss situation in terms of base dollars.

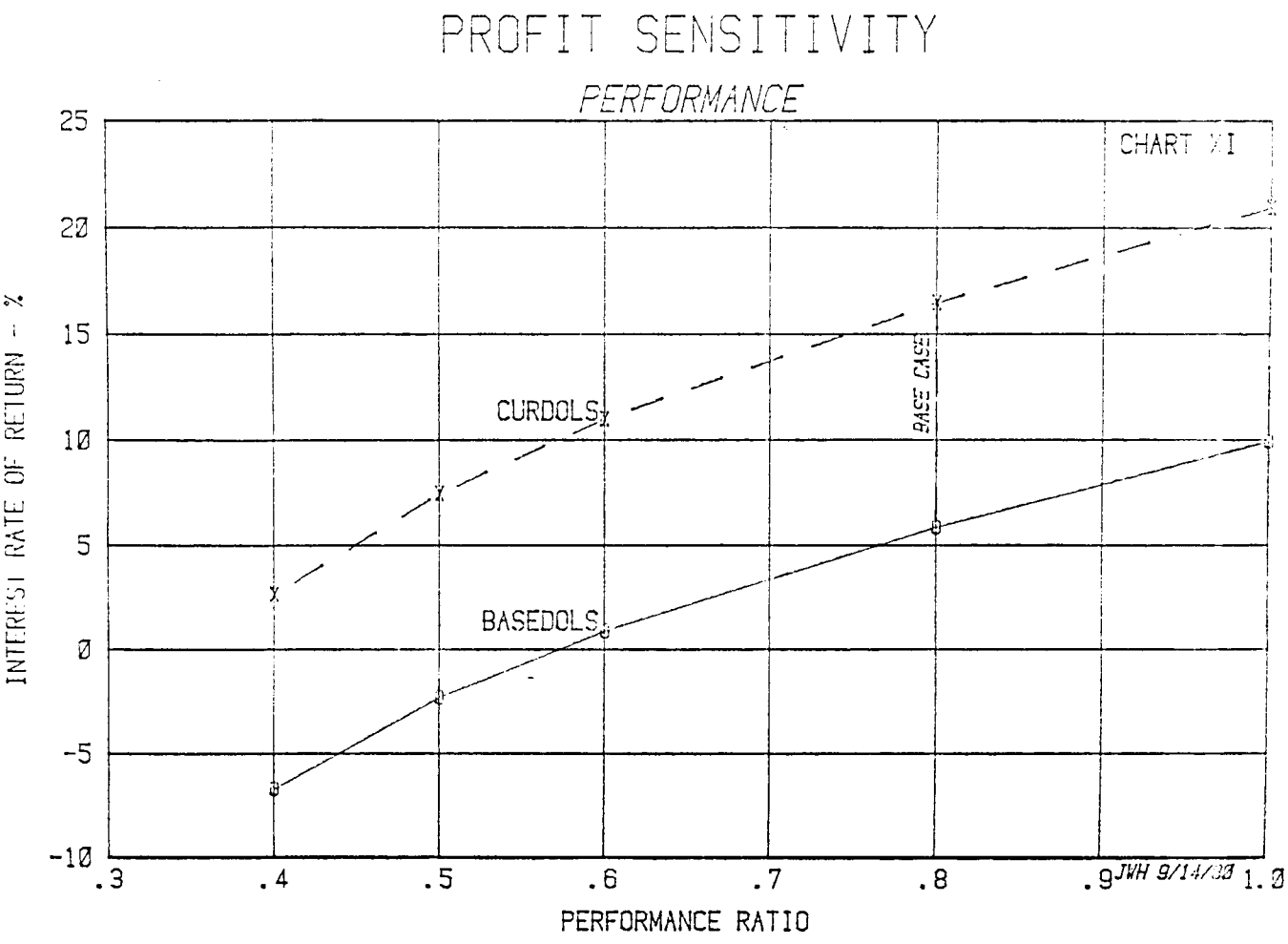

Chart 11. Here is what happens when we move from the base case to different performance ratios. If instead of an 80 percent performance ratio, the plant performs at full nameplate capacity, we have a 10 percent rate of return in base dollars. On the other hand, if the performance ratio goes down to 0.40, we're in a loss situation in base dollars, although on a current-dollar basis it looks as though we're making some money (remember we're being taxed on a current-dollar basis).

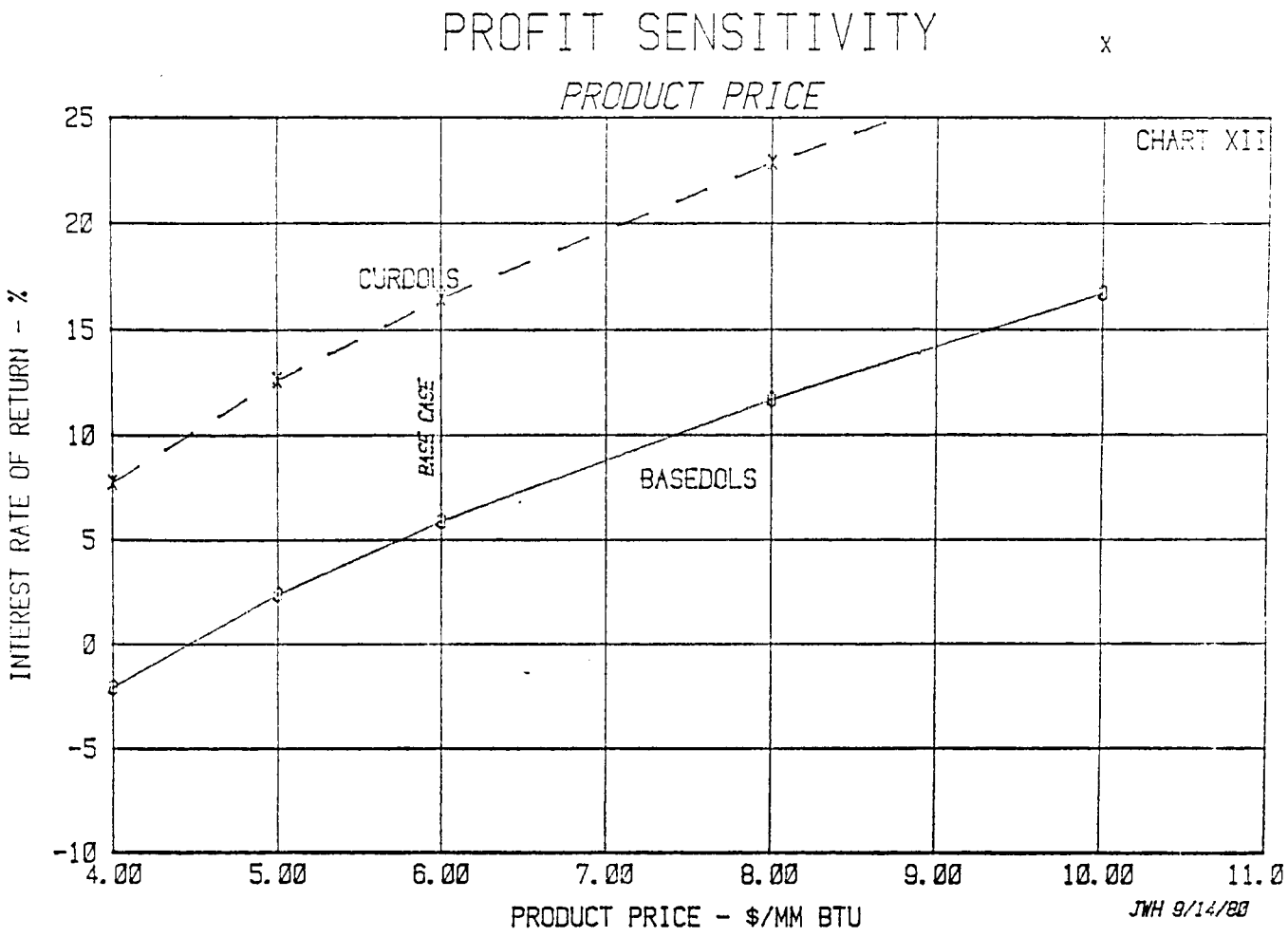

Chart 12. This chart shows the effects of product price changes. Base-case returns are as before. If the product price improves to around $10/MM BTU in base dollars, we can get a return of 16 to 17 percent. If it goes down to $4 we'll be in a base-dollar loss position.

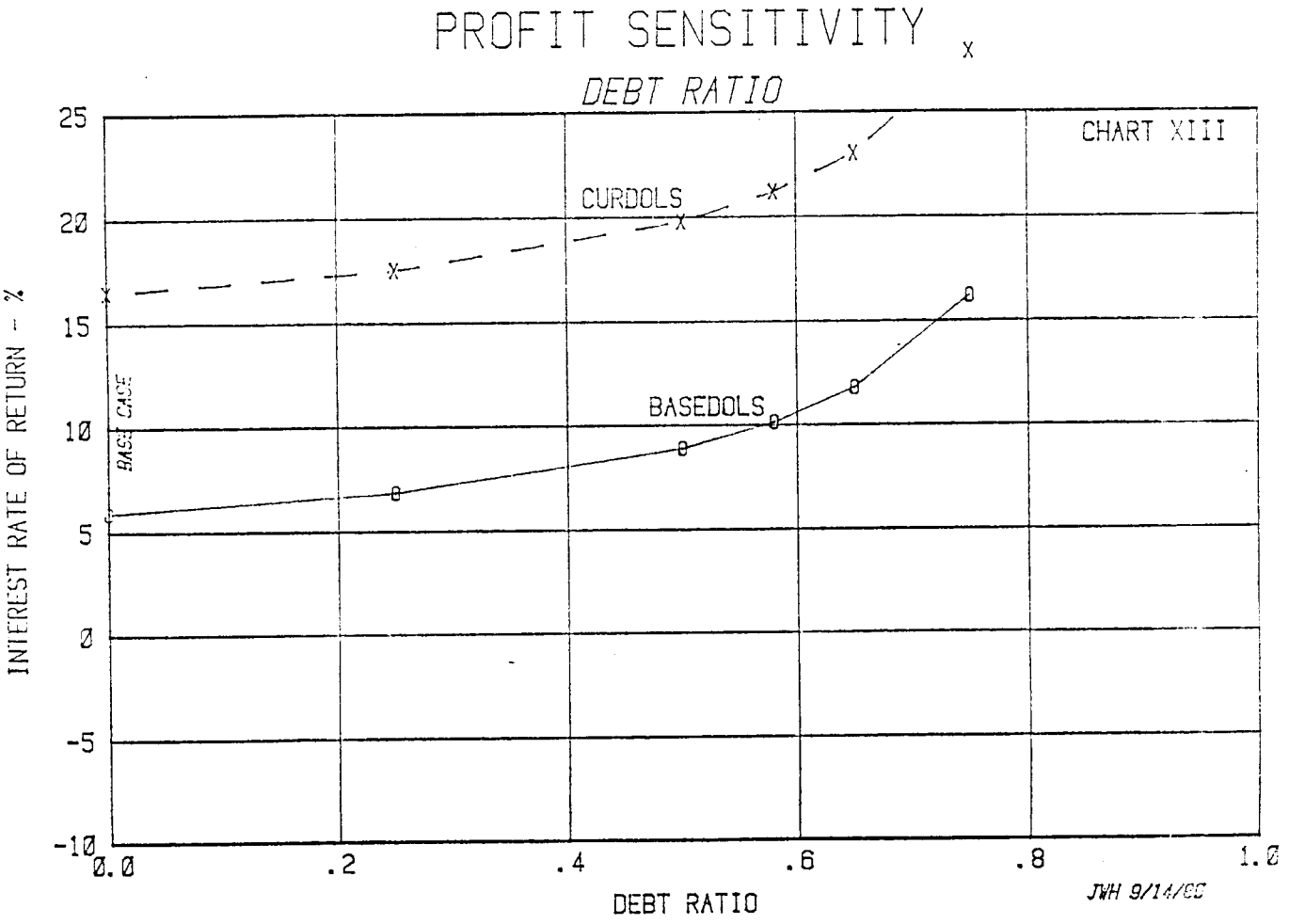

Chart 13. Debt ratio is another dimension of sensitivity, one which was discussed this morning. I've made the assumption that this project can borrow money at 12 percent. Return increases steadily as the debt ratio increases from 0 (which we used for the base case) to a 0.20 ratio (which is where the major oil companies operate), to 0.25 (where the average oil company operates), to 0.45 (which is where the gas companies operate). Then we move into the area of higher debt ratios that was discussed this morning. For a consortium operating with

0.80 debt and 0.20 equity, you can see the profit curve is turning sharply upward. This is the "leverage" effect. If a leverage project is profitable, it can be very profitable indeed for the equity holders. The inverse is that if some of the adverse things we're talking about develop, you get a "reverse leverage" effect, and your equity profit goes to hell--quick. A highly leveraged project's return is extremely sensitive to favorable or unfavorable economic developments.

Q. How do you plot those points or cases? In other words when you have a debt/equity ratio of 0.70 or 0.80, how do you get the profit of roughly 16 percent?

A. What you do is to change the cash flows of the base case to represent what is going to happen in the new circumstance. Debt-financed projects have to pay interest on the borrowed money. With a debt ratio of 0.50, the project will be paying interest on $1 billion at, say, 12 percent; and that becomes a regular cash out-flow. You recompute the interest rate of return based on the revised cash flow. That gives you a base dollar return of about 9 percent as shown on the diagram.

Q. What it amounts to is that returns will become very high as equity approaches zero. But that does not happen in reality. There is a tradeoff; there is an optimum debt/equity ratio.

A. Exactly, and that's the reason why different organizations operate at different points on this curve.

They are led to an optimum position determined by their financial situation, by the maturity of their industry, by a number of things that bring the companies of an industry to a general consensus of opinion on debt ratios. It's astonishing, for example, how close the debt ratios of the gas companies in this country are. There are some differences along oil companies: the largest have slightly lower debt ratios than the balance of the industry. Each operates in a zone which they have found works best for them.

- SPECTRUM OF INCENTIVE PLANS

  - PRICE GUARANTEE,
    W/ OR W/O INFLATION CLAUSES
  - ACCELERATED WRITE-OFF
  - LOAN GUARANTEES
  - DIRECT LOANS
  - INVESTMENT TAX CREDIT
  - GRANTS,
    FIXED OR PERCENTAGE

Chart 14. Getting back to the general subject of profit sensitivity, we could go on to other dimensions of sensitivity, but I think we've covered the principal ones. So let's take a look at the available spectrum of incentive plans. The first is a price guarantee, with or without inflation clauses; that is, the government could guarantee that you'll be paid so much for gas. Accelerated write-off: The British go the full route on this one; they'll let you write off the whole plant the first year. Loan guarantees: this is the sort of thing being done for Chrysler and others. Direct loans, investment tax credits, and grants (either fixed or percentage) round out the spectrum.

- PRICE GUARANTEE W/INFLATION CLAUSE

  REMOVES MAJOR ITEM OF UNCERTAINTY

  RETAINS INCENTIVES TO CONTROL CONSTRUCTION AND OPERATING COSTS

- PRICE GUARANTEE W/O INFLATION CLAUSE

  FAILS TO REMOVE PRICE UNCERTAINTY, BECAUSE OF INFLATION POSSIBILITIES

  DIFFICULT TO ESTABLISH EQUITABLE PRICE LEVELS IN INFLATIONARY ENVIRONMENT

Chart 15. A price guarantee with an inflation clause (in other words, indexing the price of synfuel to some general index of inflation) removes a major item of uncertainty from the decisionmaking process. It doesn't necessarily have to be a very high price. It can be a valuable aid to the decisionmaking if it is a reliable price, adjusted to compensate for inflation.

Price guarantees with inflation clauses retain the incentives to control construction and operating costs, because with such guarantees you're getting a constant dollar price for your product. The cheaper you can build the plant, and the lower your operating costs are, the more money you're going to make. So you've got a strong incentive to do things well in such a framework.

Q. Is there within the petroleum community a serious concern about price performance? I'm talking about negative price performance of petroleum products relative to projected inflation. Of the variables you've mentioned, is the question of price of equal magnitude to the others?

A. I would say it is equal to or greater than the others, especially when you consider present and possible future price control problems.

Q. For example, Canada slapped price controls on crude oil from tarsands projects, and immediately three projects died?

A. Yes, in that case there was just no way those boards of directors could say "let's spend some more money" when they were faced with a price ceiling that was apparently unpiercable.

Q. These product price guarantees you're talking about seem to be a lot like agricultural parities.

A. You're right. They may be nearly the same thing. Is a parity price for oil like a parity price for wheat?

Q. The difference is the farmers are the good guys, the oil companies are the bad guys.

A. Quite true, unfortunately. But there can be a lot of parallels that need to be thought through. Maybe we can learn from the experiences with agricultural parity prices.

Price guarantees without inflation clauses don't help at all, because you're completely at the mercy of a runaway inflation. The possibility of runaway inflation in this country is not all that remote. It also is difficult to establish current price levels which will be an incentive to build in an inflationary environment. You have the political problem of setting an adequate future price level. If people are now selling gas for four dollars per MM/BTU, and you set a 1985 price level of seven dollars somebody is going to holler "ripoff." Yet a $7 level might not be enough to make the project viable. That price could be dirt-cheap by 1985.

- ACCELERATED WRITE-OFF

EFFECT DEPENDENT ON AVAILABILITY
OF UNRELATED PROFITS FROM OTHER
COMPANY ENTERPRISES

MAXIMUM EFFECT (100% FIRST YEAR)
INCREASES BASE CASE RETURN
FROM 5.9% TO 8.1%

LITTLE EFFECT ON UNCERTAINTIES
OF PROJECT ECONOMICS

Chart 16. Accelerated write-off: the magnitude of this effect is dependent on the availability of unrelated profits from other company-owned enterprises. A company with a lot of other things going may have profits against which it can write off this investment just as rapidly as the provisions of the law permit. The maximum effect on the base case is to increase the rate of return from about 6 percent to about 8 percent if you go from a base case 12 year depreciation period to an immediate write-off. Accelerated write-offs have a significant, but not a dominating, effect on the project economics.

- Loan Guarantees

  Reduce interest rates modestly
  for prime borrowers
  (11% vs. 12% improves IRR 1/2% @ 0.25)

  Enable non-prime borrowers to
  operate competitively

- Direct Loans

  Similar, but effects stronger
  if interest rate is below
  government's cost of borrowing

Chart 17. Loan guarantees: these reduce interest rates modestly for prime borrowers. Unfortunately, Uncle Sam isn't able to borrow money much more cheaply these days than prime borrowers can. A prime borrower may get a 1 or 2 percent rate improvement if the government guarantees a loan. Guarantees do enable non-prime borrowers (such as the leveraged consortia we were talking about) to enter this arena and compete, because with the government's backing they can borrow money at the same or better levels than prime borrowers can.

Direct loans: these have similar effects, but the effects are stronger if interest rates are set below the government's cost of borrowing. If the government loans money at 4 percent for one of these energy projects, it is going to help one hell of a lot in improving the project economics.

- Investment Tax Credit

Augments return vis-a-vis threshold level

Ameliorates pioneering growth problems and construction cost inflation

Retains most of the incentive to control construction costs

Retains all of the incentive to control operating costs

Chart 18. Investment tax credits: these improve the interest rate of return as compared to the threshold level. They also reduce pioneering growth problems somewhat, because they usually are credited as a percent of actual cost, not as a percent of the estimated cost. They retain most of the incentive to control construction costs, and they retain all of the incentives to control operating costs.

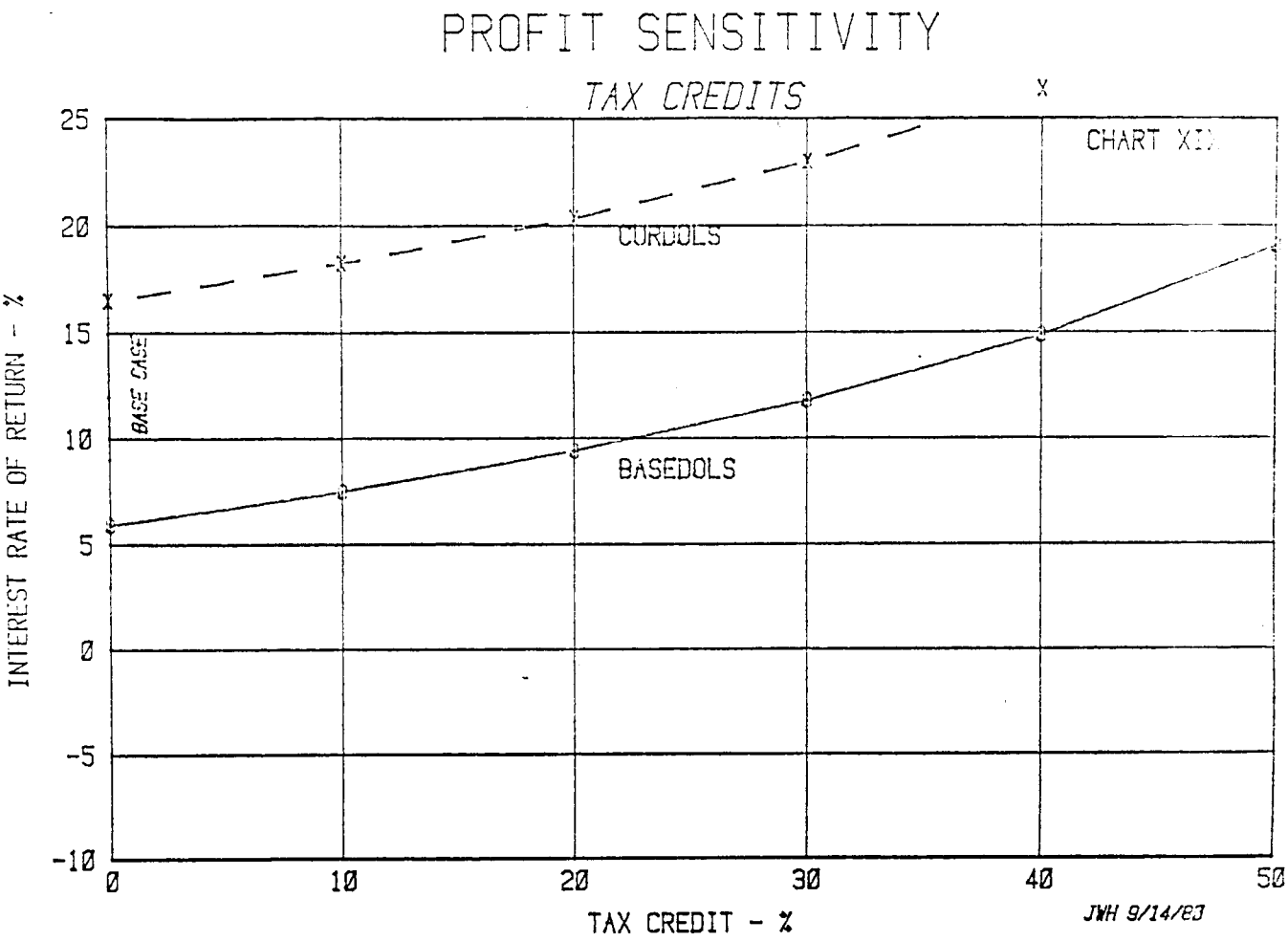

Chart 19. Going back to our sensitivity diagrams, this is the plot of profit sensitivity to tax credit. The base case is over at the left side, with zero tax credit. I just happened to select that value for the base case. Of course, actually there is a tax credit for investment right now, which yields a return of about 6 percent to about 7-1/2 percent. As the tax credit increases, your return on investment also increases, at an accelerating rate.

- GRANTS

  FIXED -

    IMPROVE RETURN RELATIVE TO THRESHOLD

    INCREASE SENSITIVITY TO GROWTH PROBLEMS AND INFLATION

    ENCOURAGE CONSTRUCTION EFFICIENCY

  PERCENTAGE -

    MORE RELIABLY IMPROVE RETURN RELATIVE TO THRESHOLD

    REDUCE SENSITIVITY TO GROWTH PROBLEMS AND INFLATION

    REDUCE PENALTIES OF CONSTRUCTION INEFFICIENCY

Chart 20. Grants: These appreciably improve project return relative to threshold values. But they also increase sensitivity to problems of growth and problems of inflation, because the person providing the equity investment, the portion of the investment that is not a grant, is in a leveraged position. As we discussed before, his gains will be high if he finds he is operating in a favorable economic environment, and his losses will be high if the environment is unfavorable. Fixed grants tend to encourage construction efficiency.

There is no added equity capital available when you're operating at highly leveraged positions. Therefore there is a very strong incentive to build the plant for what you said it would cost; otherwise the equity investors may just walk away and leave the plant to be finished by others, or not finished at all.

Percentage grant: these will improve return more reliably. They also reduce the penalties of construction inefficiency. If your grant is based on a certain percentage of actual cost, it is a different ballgame than if you're granted a fixed amount regardless of actual cost. However, percentage grants may be difficult to administer.

Conclusions

- Pioneer process plant economics have a high order of complexity
- Pioneer process plant return predictions are unreliable in the present economic environment
- Incentive plans for energy-related projects should focus on containing uncertainties within normal bounds of decision-making

Chart 21. Let's summarize and take a look at some conclusions. Pioneer process plant economics have a very high order of complexity. They comprise a multidimensional economic system which is almost impossible to show on a flat chart. We can, however, produce a computer model, as I have done here, which can answer the significant "what if" questions, and show what happens when we take profit sensitivity "excursions" out along the significant economic dimensions. As a whole, this dimensional field is difficult to comprehend. It can be mastered

by sectioning to produce understanding of its parts. This is important, because the people who are making these energy decisions need all the help they can get in understanding this complex economic environment. Pioneer process plant return predictions are unreliable in this environment. It is difficult to pin down the economic future, and say with reasonable certainty that you have a project. It seems to me that incentive plans for making the United States more energy self-sufficient should try to reduce the uncertainties of a project's economics to the point where a reasonable man can make a sound judgment and implement it.

Q. If I heard you correctly in your pros and cons, it would appear to me that perhaps a price guarantee is the most favored incentive. It eliminates the most uncertainty. None of the other ones take any uncertainties out; some might reduce an uncertainty, but none eliminates it.

A. That's right. The others tend to raise potential profitability. They may make a project economically feasible.

Q. Even a price guarantee tied to inflation doesn't affect relative price changes that might make your costs higher.

A. That is correct, yes. Also, even with an indexed product price you're gambling to some extent because although inflation indexes tend to correlate with each other, each one moves differently. You have to be selective about

the index you use for your prices.

Q1. I want to comment on the price guarantee. It's only useful if the plant produces anything. If the plant doesn't work, the price guarantee won't be any good at all.

Q2. But it minimizes the risk to the government of that occurring, because it puts the pressure on the venture people to produce. Some of these other incentives don't apply that much pressure. From our standpoint all the risk of producing is on the producers' side, but the producer gets elimination of one element of uncertainty--one of the biggest being future government price action.

Q3. But the potential costs are extremely high from the government point of view, too, unless you limit it by some absolute dollar ceiling.

Q. Although it is true that nominal dollar cost may be very high, it is also true that the government revenues over time increase rather faster than inflation.

A. The key, though, is that you have left in place strong incentives for the producer to keep construction costs down, to keep operating costs down, to make it work.

Q1. There might be some technology which needs heavy front-end loading because you have a consortium which, for whatever reason, cannot raise the funds. There might be technological ranges where certain subsidies are more appropriate than for other technologies.

Q2. Isn't the question comparing how the government would want to reduce risk as contrasted to how the firm wants to control its risk? It seems to me that firms with higher assets would want product price guarantees. You know that the gas industry backs loan guarantees because they have lower assets and need that up-front money. It depends on the firm and the market under which they're operating as to what guarantees they prefer. In general, for the government trying to reduce its risk, while still encouraging firms to invest, price guarantees are probably the most logical incentives.

A. You're quite right that these things depend on "where you're coming from." For a given industry, you have a given set of economic characteristics. This is going to influence your thinking with respect to incentives, and how much good the incentives are going to do; how much <u>real incentive</u> they provide.

PROJECT MANAGEMENT FOR PIONEER PROCESS PLANTS

Richard Summers

I am going to talk about what we at Mallinckrodt have learned about the organization required for successful project execution of first-of-a-kind plants. Relative to an energy project, our projects are quite small--roughly around $10 million. I don't know how to measure the difference between small and large projects since we don't do $100+ million projects, but I can say there is no difference between a $1 million project and a $10 million project as far as results and as far as problems are concerned. We have recently changed the way in which we do our projects, and we've had a significant improvement in results. We hope that what we've learned about management can be applied to some of the coming energy projects.

At Mallinckrodt, Corporate Engineering handles all of the capital projects, and virtually all of them are first-of-a-kind process plants. We rarely go on to build a second duplicate plant. We have a wide variety of projects reflecting virtually all of the different types of unit operations.

We reorganized a few years ago into a matrix organization which included a project management concept. Prior to this time, a project would move stepwise from R&D to pilot plant to process engineering to drafting to construction to start-up, with each step a separate department. Now, one person is responsible for a project from conception of the project through start-up. In other words, the project manager starts working on the job from the time that somebody conceives

of the project; and he carries responsibility all the way through start-up.

Whether the same matrix approach can be applied to a gigantic project is problematic. But the improvements in our projects from the approach are striking. Before our restructuring, the performance of our projects was pretty consistent with what was shown by The Rand Corporation pioneer plant study. Since we've gone to this new system, we have found that the average of all projects is on target for the capital that is approved; and virtually all individual projects fall within a plus or minus 10 percent variation of the approved amount. This 10 percent does not apply to the estimate done back in the basic concept stage, during which people are still kicking around ideas on how to do things. Our predictions of that stage can go anywhere from minus 50 percent to plus 200-300 percent of what the final project will cost. If we do a lot of kicking around before we define what we're going to do, then stick with our decisions, we are able to bring the projects to within 10 percent of the costs that are approved by management.

At the same time we installed the project manager concept, we changed our philosophy about how a project should be executed. We said a project must work, must come within costs, must come within schedule, and must be low risk. Now how can you have a pioneer plant and still have a low risk? The answer is, of course, that in many respects you can't. But many high risks are unnecessary. For example, suppose you need filtration to carry out a unit operation. There are several different ways of filtering, and certainly none of them is ideal. You can invent a new filtration machine; or you can take the newest design

on the market that promises a lot; or you can use an existing, reputable piece of equipment. Our philosophy is that we do not design our own piece of equipment if somebody else makes it commercially, and we will not use an existing one that will perform the job.

We have also taken steps to identify risk to our management. At the beginning of a project's development, we make sure that we use a couple of "Doctor Glooms"--people who always think that nothing will work. They are very valuable people to have in this phase of project development because they are able to identify many of the things that can go wrong with a particular project. Once these items are identified, we can reduce the risk by correcting or compensating for those items in the design phase. We use the potential problem analysis technique to identify these areas.

Having identified the risks, we then put a few creative people together to come up with some plans to be able to say, "Okay, I'm willing to take this risk and if it doesn't work, then we can do this, this, or this to back it up." We've found that it is a big advantage when you get into a start-up problem to have something in your hip pocket as a way out. If you have designed a $1 million reactor and it doesn't work at all, you obviously have a very serious problem. But if you have thought about all the things that could go wrong, you can often zero in quickly on the nature of the problem and solve it.

All of the earlier speakers talked about front-end work, and it's impossible to over-emphasize its importance. R&D and Engineering work very closely together in the early stages of the project--R&D comes up with the different basic ideas and trys them out in the laboratory;

Engineering evaluates the ideas and at the same time assigns costs and risks. This evaluation is under the supervision of the same project manager who will be responsible for project costs and schedules, and this continuity greatly enhances the ultimate success of the project. Instead of allowing each person to say, "My job is to design the plant," or "My job is to draw the P&ID's," a good project manager will require his people to contribute to each other's work. The project manager himself can't be an expert in all areas. Rather, he must be a managerial/technical person, one who can organize and put things together and can also properly evaluate the technical concepts through all phases.

Once we have done a good job of defining and reviewing the steps and making a professional cost estimate, there are usually no significant problems in building a plant within budget. However, problems arise when people decide to change the scope of the project. We control scope from a corporate standpoint by requiring everybody who is concerned to sign off on the project scope--including the operations people who are going to use it, the R&D people, the engineering people, and our management. We have lots of review meetings until we finally agree on the scope; then everyone puts his name on the dotted line, and we proceed from that standpoint. If there is any deviation from the fundamental plan, it requires (depending on the dollar value) approval of upper management. If somebody discovers something won't work and a change in scope is required, then we must get a new approval--perhaps taking it all the way to the Board of Directors if the impact is large enough. Top management is very firm in not allowing any scope changes

without their knowledge. This gives us the support we need with plant operations people and with R&D to prevent them from bringing in changes unless they are absolutely mandatory. In other words, we exert our efforts up front in debating and testing, with lots of "give and take" to establish the scope before we submit the project. Once we agree, then everybody pulls together and is committed to building the plant as scoped. Without a strong project manager and management team, it is easy for changes to creep into projects. Creeping changes are virtually impossible if top management structures the system so that changes go through heavy scrutiny before being presented for approval.

As an example of the success of our management system, I'd like to cite a plant that came on-stream just about two months ago. We made some significant modifications to an existing plant by converting several steps from batch to continuous. Five of the ten steps were new, as classified by the Rand system. It was important that we keep production interruptions of the plant to an absolute minimum. We were allowed the time and budget to do a lot of front-end work, with the expectation that we not have any significant problems when we made the modifications. That particular experience was better than we anticipated: after only 24 hours of down time, we had all the units up and operating.

In summary, we feel two things are important to help in the success of a project: (1) to have as broad a responsibility as possible for a single individual working with a project team so that he feels responsible from concept all the way through start-up, and (2) to have a strong management that expects and demands results and is willing to

allocate sufficient time and money to perform the necessary front-end work.

Q. Can you then relate this relatively small project that you've identified to some of the fossil projects? That is, can you translate or transfer any of that experience to a group of firms?

A. I have no way of relating except to say in the chemical industry our processes will be of the same complexity as somebody who is building a $100 million plant or a $200 million plant. That is, the number of steps and the types of reactions in our plants are the same as a $100 million plant. The difference is the scale--we'll have a 4,000 gallon tank, they'll have a 40,000 gallon tank. But I have no way of putting a measure on how much that affects management style. It is true that a smaller organization is easier to manage than a large organization. And it is obviously easier to work with a small, compact group rather than a consortium. One suggestion would be to try to split a large organization into smaller units with broader responsibilities. It works a lot better if the small units have broad responsibilities rather than narrow ones. Another possibility is to structure the consortium so that one corporation is responsible for the whole project. Still another is to offer three different corporations a chance to do something on a smaller scale--such as each one build a 1/2 billion dollar synfuels plant instead of a 5 billion dollar plant, and at the end of some period of

years, evaluate the results. If you could key the financial incentives to the results and give them an opportunity to make a profit on the basis of those results, you would be better off than letting them make a profit based upon the size of the project and how many people they assign.

A TECHNOLOGICAL SCALE FOR PIONEER PROCESS PLANTS

J. R. Nelson

Chart 1 (Title Chart). One highly significant point of the Rand Pioneer Plant Study is that the extent of technological innovation is a very important determinant in predicting performance, schedule, and cost outcomes for new plants. Technological innovation means not only significantly new process technology or particular process steps, but also integrating existing technology in a different way, and significantly scaling up previous experience. John Fisher's discussion of scale-up underscores the effect of scale-up on such concerns as plant performance and reliability.

PROBLEM

Extent of technological innovation in pioneer energy process plants can affect cost-schedule-performance outcomes

- o High technology efforts can have disappointing outcomes
  - --Cost growth
  - --Schedule slip
  - --Performance degradation
- o Bias toward understanding effects of technological advance early in decision process
  - --More mature technologies suffer comparative disadvantage
  - --Planning process difficult

Chart 2. We are concerned about the extent to which technological innovation is an important ingredient in pioneer process plant performance, schedule, and cost outcomes. The Pioneer Plant Study focused not only on cost growth, but also looked at performance degradation and schedule slippage. These can be of equal if not greater concern than investment cost per se, particularly when performance can suffer and affect product cost severely. I'd like to make clear at the outset that we're not saying technological innovation is a bad thing. That is not the case at all. The possible effects of new technology--on not only cost, but also on performance and schedule--must be explicitly considered. There is a bias toward underestimating such effects early in the decision process. When initial cost estimates are being made,

it is important not only to understand what the cost bias might be for a given technology but to understand and compare such effects across competing technologies. Is there a bias toward underestimating the more advanced technologies? Do you estimate that they cost less because you know less about them? If so, the more mature technologies will be at a disadvantage in any comparison. So we would like to understand how innovative a particular technology is in order to gain some insight early in the planning process.

OUTLINE

- o Previous experience
  - --Subjective approach
  - --Objective approach
- o Pioneer process plants
  - --Approach
  - --Results
  - --Application
- o Findings

Chart 3. What we have done is to construct a technological scale of pioneer process plants across a broad range of technologies. Our method for constructing the scale falls between a subjective approach, or expert opinion, and an objective approach, or modeling of technical data. After a short discussion of these approaches, we will present our technological scale, an example of its use, and a summary of our findings.

PREVIOUS EXPERIENCE

- Subjective approach
  - --Rate technical advance
  - --Relate to cost growth
- Objective approach
  - --Collect technical data
  - --Relate technical characteristics to time trend
  - --Include time trend in cost explainers

Chart 4. In the subjective approach the idea is to have experts rate the technical advance of a system or item of interest, and then in some manner to relate that technical advance to the cost, performance, and schedule for that system or item. As an example of the subjective approach, consider a study done by Rand for the Department of Defense about a decade ago. In examining the cost differences for weapon systems of the 1950s versus those of the 1960s, we asked weapons experts to rate the technical advance of specific new weapon systems. The scale was from 0-20, where zero represented a system requiring no new knowledge, such as the F-104 aircraft, and 20 represented a radically new concept employing highly advanced technology, such as the Concorde SST.

At the other end of the spectrum is the objective approach, which entails collecting the available technical data, notably cost, performance, and schedule information, for a particular technological area. The data are analyzed to produce a technological scale that will quantify the technology's state of the art, or produce a time trend that shows when a particular technology might be expected to arrive. In the past

we at Rand have successfully applied this approach to light water reactors and to aircraft turbine engines.

PIONEER PLANT STUDY APPROACH

- o Collect industry data
  - --Plant rating
  - --Company self-rating
  - --Some technical information and data
- o Develop "modified technological scale"
- o Relate modified technological scale to cost growth

Chart 5. In the Pioneer Plants Study, we used both these approaches. About three dozen companies, representing about 50 pioneer process plants, supplied the data. We collected technical industry data in order to develop a technological scale. The data also included subjective ratings of a particular plant's state of the art from experts within the company that built the plant. We also asked where each company rated itself in terms of technological innovation compared with the industry as a whole; that is, did they consider themselves a leader or a follower in technological innovation. We combined plant ratings and company ratings to obtain a third rating--a modified subjective technological scale--that we then used with the technical information to produce a predictive technological scale.

RESULTS

- Modified technological scale related to
  - --Portion of plant investment that is new
  - --Portion of new integration process steps
  - --Fraction of scale-up
  - --Rating of pressure-related problems

MOD TECH = 1.03 + 2.12 PORTNEW + 3.20 PORTNEWINT - 1.03 FRACSCALE
+ 0.62 PRESS

R^2 = .84

SE = .71

F = 23.9

(All coefficients are significant at the 5 percent level)

Chart 6. Using multiple regression, we developed a model that related the subjective ratings of the experts, the modified technological scale, to the following: how much of the plant was new as a proportion of investment, the portion of the process steps that represented new integrations, what the scaleup was relative to previous experience with that plant, and what pressure-related problems there were during development. The subjective ratings of the experts were explained by a linear combination of these variables. Note that the fraction of scale-up is negative because that variable is expressed as a decimal fraction. If the scale-up were ten, it would be expressed as 1/10; therefore, as scale-up increases, this number becomes smaller. All of the signs on the coefficients are as one would expect: an

increase in the portion of new integrations, a large scale-up, and severe pressure-related problems all point to a process plant of high technological innovation.

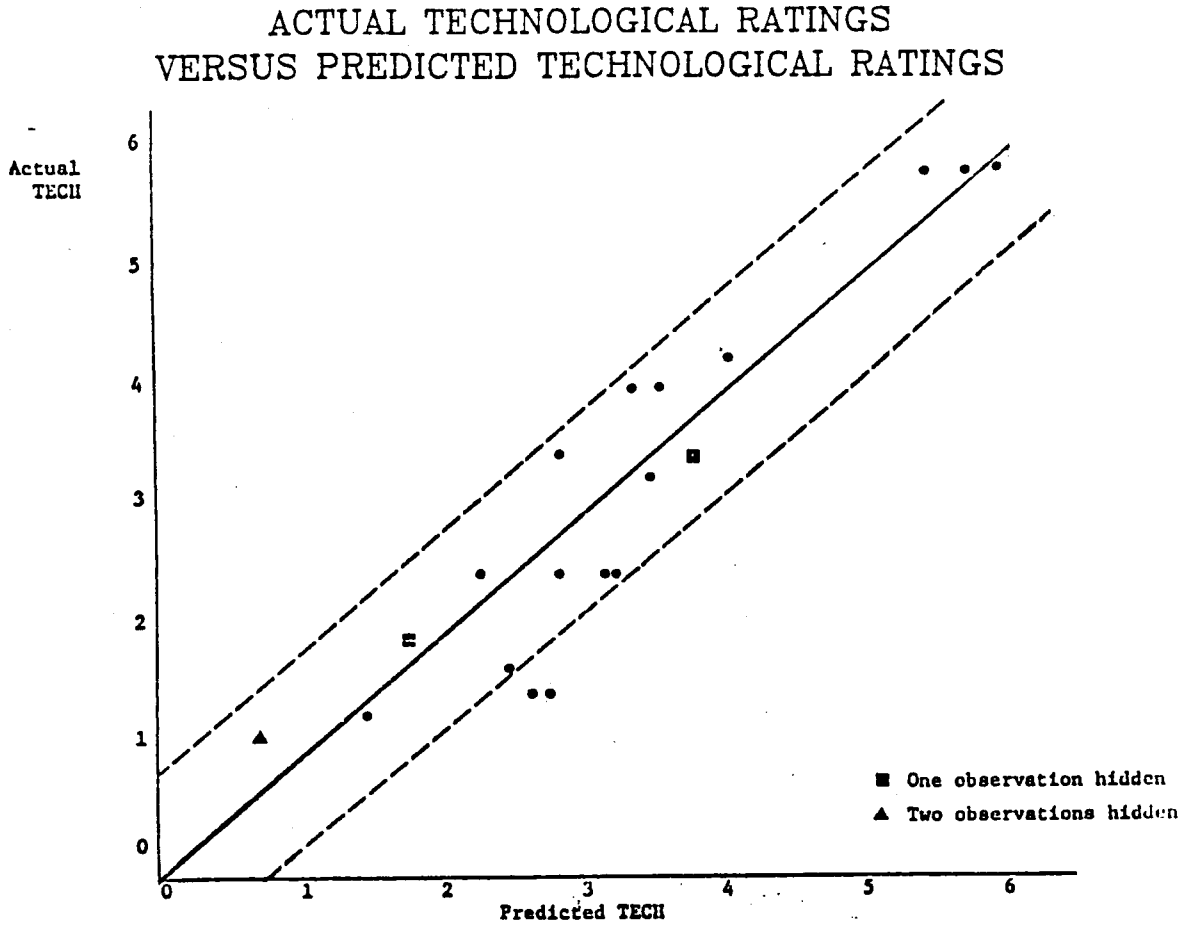

Chart 7. This chart shows that the linear regression model we used predicts the technological ratings of the experts quite well. The actual technological ratings of the experts are plotted on the ordinate, and the predicted ratings from the model are plotted on the abscissa. All but two of the plants fall within one standard deviation, denoted by the dashed lines. The plants in the data base spanned a wide range of innovation levels, from nearly duplicate plants (rated near "one" on the scale) to plants in which virtually all of the process steps were new (rated near "six").

RELATIONSHIP BETWEEN COST GROWTH AND ESTIMATE CLASS FOR TWO LEVELS OF TECHNOLOGY CHANGE (MOD TECH CUTOFF = 3)

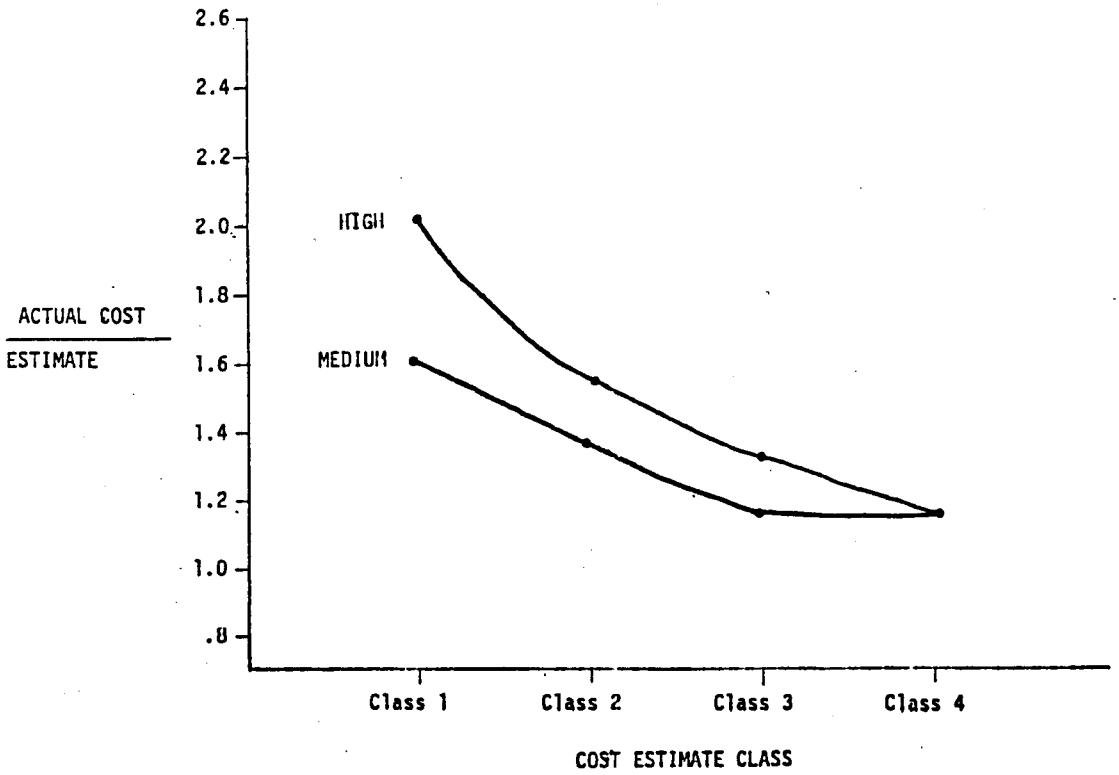

Chart 8. In order for a technological scale to be useful, it would have to be related in some way to cost growth. In examining this relationship we compared our technological scale with the cost growth for the plants in the data base. We found that higher cost growth was experienced by those plants with higher ratings on the technological scale. We demonstrated this relationship by dividing the plants so that half had a technological rating below three and half above three, and plotting the average cost growth on the ordinate against the average technological rating on the abscissa for each of four estimate classes. These estimate classes span a process plant's development from project

definition through start-up. Our research indicates a statistically significant difference between high and medium technologies at the Class-1 estimate stage (when a project is still being defined). The difference is not as significant at later estimate stages. However, it is precisely at the early stages that decisionmakers within both DOE and industry need to know what the most likely cost growth will be.

HIGH TECHNICAL INNOVATION RELATED TO LOWER INITIAL PERFORMANCE

	Moderate Technical Innovation (<3)	High Technical Innovation (>3)
Percent of Design Performance during Months 7-12 (significant at .1 level)	72%	58%
Start-up Slippage in months (significant at .01 level)	1.0	5.7

Chart 9. In addition to the cost growth, we also looked at performance and the start-up schedule with respect to new technology. Again, we separated innovation by lesser and greater than three on the technology scale. In terms of the design performance in months 7 through 12 after start-up, we see a significant difference of 14 percent between moderate and high technology plants. As we would expect, the high technology plant suffers a lower plant performance than the plant of moderate technology. We also looked at start-up slippage and again the moderate and high technology plants show a significant difference. There is a modest one-month slip in schedule for moderate technology, but a half-year slip for the high technology case.

SUMMARY TECHNICAL CHARACTERISTICS OF TWO HYPOTHETICAL TECHNOLOGIES

	Technology A	Technology B
Plant capacity	50,000 b/d	50,000 b/d
Total estimated plant cost	$3.0 B	$2.9 B
Amount of new equipment investment	$ .6 B	$1.8 B
Total number of new process steps	16	20
Number of new integrations	1	2
Development units built	50 b/d pilot plant	None: Scaleup factor of 10
Pressure-related problems (1-5 scale)	2	3

Chart 10. How might DOE or industry use this scale to evaluate technologies? Let's take a hypothetical example: Technology A and Technology B, which have the same plant capacity. Technology A is slightly higher in cost, but has a smaller portion of investment in new technology and a smaller portion of the total number of process steps in new integrations. Technology A scale-up was from 50 to 50,000 barrels per day, or 1000 to 1. Technology B scale-up was a factor of 10. The pressure-related problems (on a scale from one to five, with five being severe problems) are shown. What kind of information can our technology scale give us concerning the probable accuracy of initial cost estimates for these technologies?

HYPOTHETICAL FACTORS FOR USE IN TECHNOLOGICAL SCALE

	Technology A	Technology B
PORTNEW	.20	.62
PORTNEWINT	.06	.10
FRACSCALE	.001	.10
PRESS	2	3
Technological Scale	2.9	4.4

Chart 11. By plugging the numbers you see here above the line into our linear equation shown earlier, we can determine that Technology A is under three on the scale while Technology B will encounter a higher cost growth than will Technology A. Technology B also runs a higher risk of plant performance and schedule problems. Since the capital cost of the Technology B plant was only slightly less than that of the Technology A plant, and Technology B is significantly more advanced than Technology A, perhaps Technology A makes more sense in terms of lower overall risk.

FINDINGS

- Proposed pioneer process plants can be classified by technical risk to distinguish potential cost growth and performance differences
- Technique should be useful to DOE and industry in comparing new technologies
  - --Project selection
  - --Program planning and budgeting
  - --Strategic planning

Chart 12. We think we have made some interesting progress in the area of technological scaling. Certainly there is more to be done. Better data bases may make it possible to develop more detailed scales. Still, we feel that this technique will be useful to DOE and to industry as an additional tool for assessing individual technologies, as well as for comparing technologies in order to select projects and plan and budget their development.

USE OF COST ESTIMATING RELATIONSHIPS (CERs) IN ENERGY TECHNOLOGIES

Ron Hess

The Rand Corporation
Santa Monica, California

Chart 1. The purpose of this briefing is to discuss how cost-estimating relationships (CERs) might be used by DOE.

CERs

- Background
- Development
- Proposed application

Chart 2. The briefing is divided into three broad areas.

- o What CERs are and how they've been used in the past.
- o What problems are associated with their development.
- o A brief description of the ongoing effort aimed at the development of coal-gasification CERs.

Before getting into a discussion of what CERs are, let us first examine the motivation for their use. Energy analysis has an estimating problem: in the early stages of planning, engineering estimates do not accurately reflect final cost.

COST GROWTH IN PIONEER ENERGY PROCESS PLANTS (CONSTANT DOLLARS)

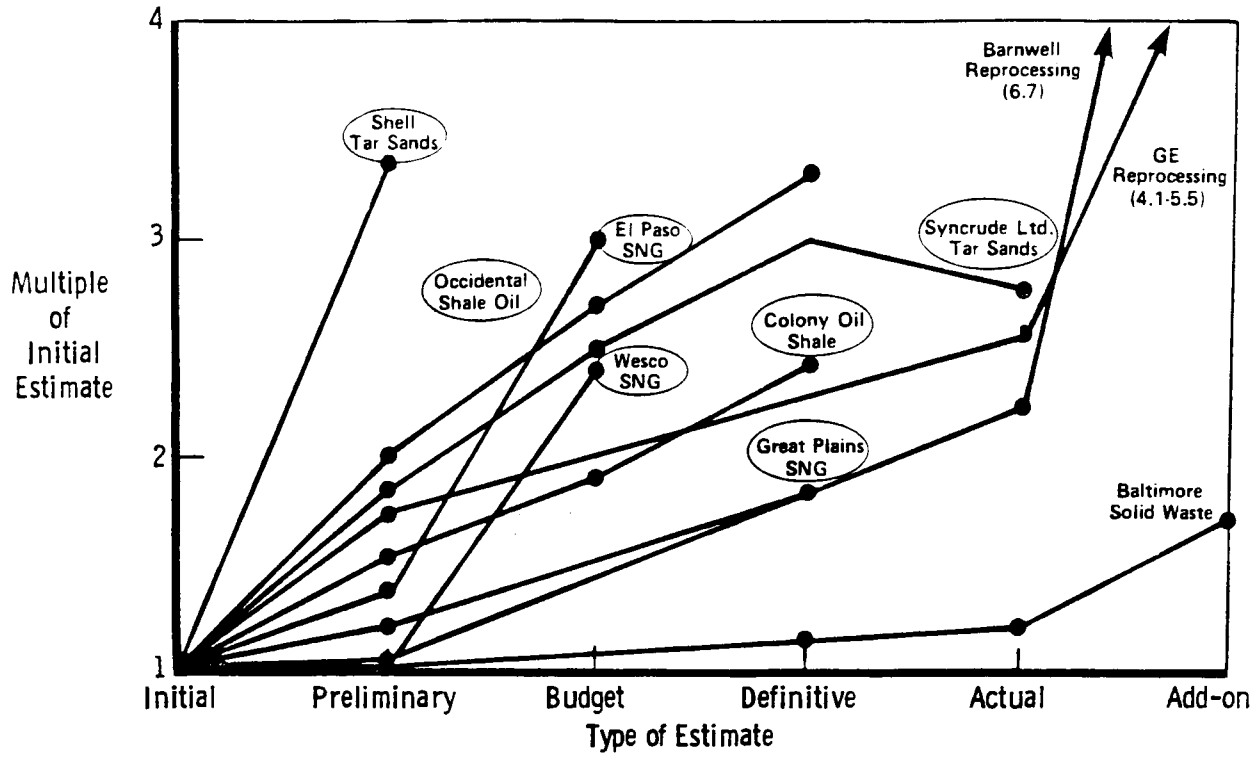

Chart 3. This figure illustrates the problem. It shows the cost growth for ten energy process plants planned or constructed in the 1970's. With one exception (the Baltimore Solid Waste plant which did not and does not operate as originally envisioned), actual costs exceed initial estimates by a factor of two. There are many causes for this cost growth, including:

- o Technical uncertainty.
- o Incomplete plant definition.
- o Scope change (to take "advantage" of latest technology or in response to change in government regulation).

- Poor management.
- Inherent optimism of advocacy process.

We believe that statistically derived CERs can help alleviate this estimating problem by linking the characteristics of a system or subsystem to cost. Because the CERs are usually based on historical actual costs, they incorporate all the normal difficulties associated with plant construction, are definitionally complete, but exclude advocate optimism.

DEFINITION OF CER

- CER is analytic device which relates item characteristics to item cost
  - Physical characteristics
    - Size
    - Performance
  - Management characteristics
    - Experience
    - Development philosophy

- Forms of CERs
  - Rules-of-thumb
  - Analogy
  - Graphs or plots
  - ➡ Formal mathematical functions
    - Two-variable linear
    - Multi-variable non-linear

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Chart 4. What is a CER? It's an analytic device which relates item cost to item characteristics. These characteristics can be categorized into those which describe physical attributes and those which describe project management. The management characteristics are normally more subjective than the physical characteristics and are therefore usually more difficult to define and quantify.

The form of a CER can vary from a simple rule-of-thumb such as $/lb or $/kWe to multi-variable non-linear mathematical functions. Our focus today will be on the formal mathematical functions.

POTENTIAL DOE USES OF CERs

- Early in planning stage when plant characteristics are not well-defined and are highly uncertain:
  - Ballpark estimates
  - Sensitivity analysis with respect to major technical uncertainties
  - Preliminary comparisons of alternative configurations
  - Preliminary comparisons with alternative technologies

- Later in planning stage:
  - Independent checks of detailed estimates

However, CERs are not intended to replace engineering estimates in later stages; when better information is available, it should be used.

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Chart 5. How can DOE make use of CERs?

In the early planning stages, CERs can be used to answer questions such as:

- o Approximately how much will the plant or plant components cost?
- o What would the impact on cost be of not achieving the desired temperature or pressure?
- o What would the impact on cost be of an alternative configuration such as an alternative heat exchanger or an alternative component material?

- Approximately how do the costs of this technology compare with the costs of alternative technologies for satisfying the same goal?

In the later stages of planning, CERs can be used as independent checks on contractor and other advocate estimates. However, in the later stages of planning when better information is available, they should never be used as substitutes for more-detailed, engineering-based estimates.

Let me now turn to some examples of how CERs are used.

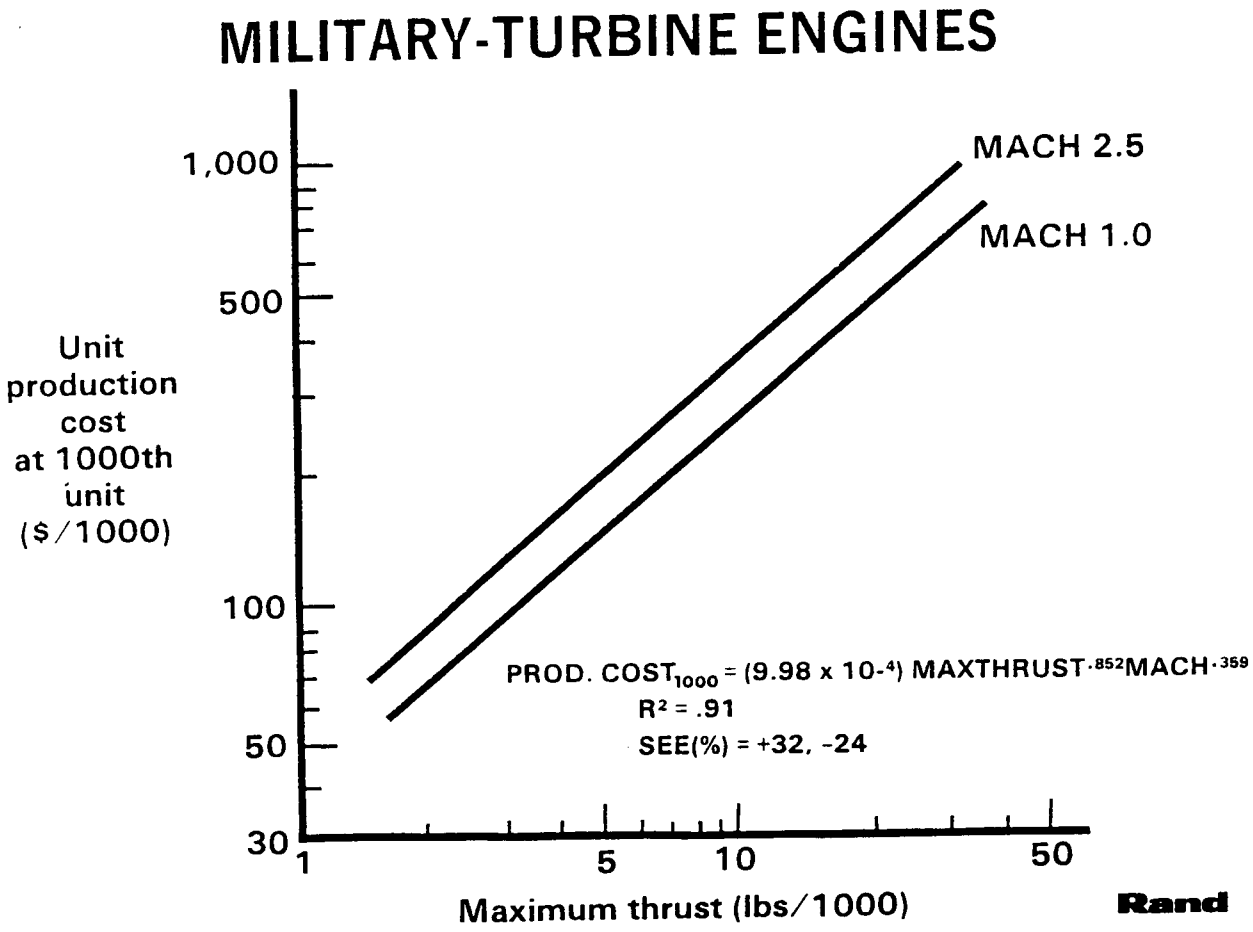

Chart 6. The most widespread use of CERs within the federal government is undoubtedly in DoD. This figure shows a plot of an aircraft turbine engine CER. The 1000th unit production cost is estimated as a function of the maximum engine thrust and the maximum Mach number in the flight envelope. As indicated, this CER explains 90 percent of the observed variance in turbine engine cost. Similar types of CERs exist for airframes, missiles, spacecraft, and other military equipment.

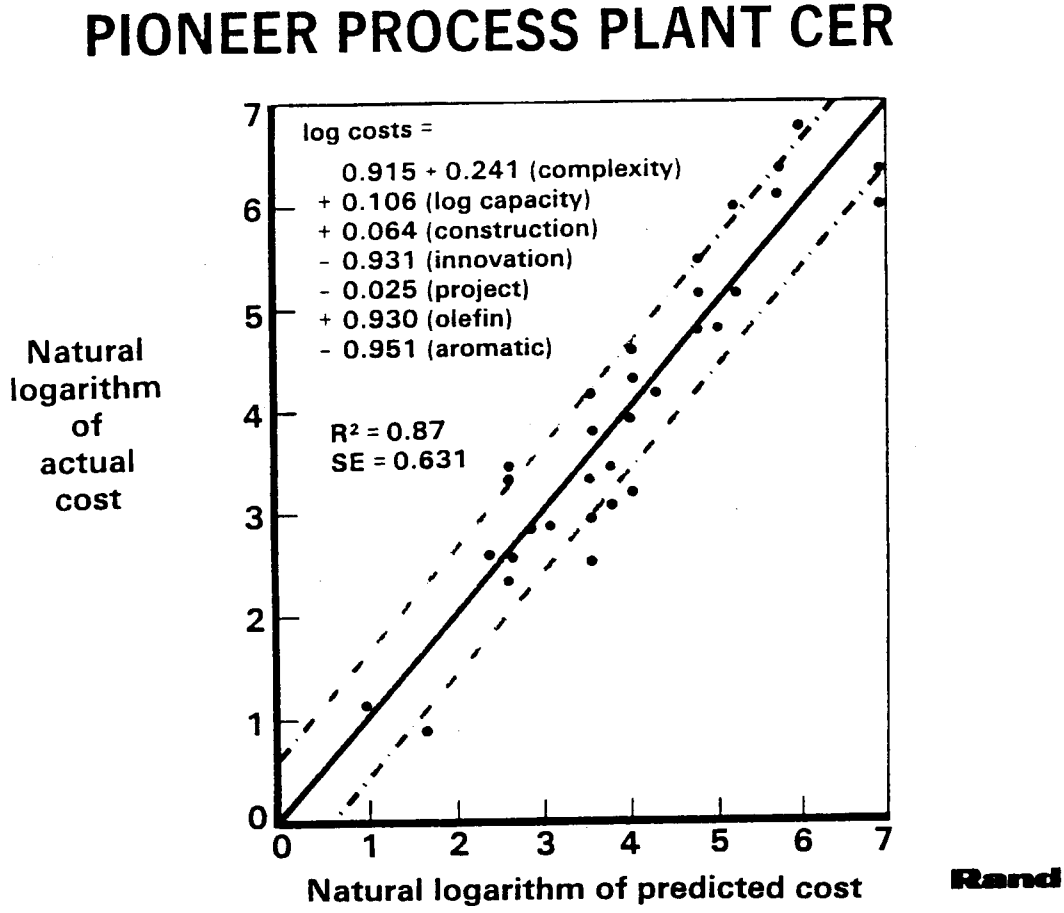

Chart 7. This example, from the energy field, is for capital cost of pioneer process plants. Actual costs are plotted against predicted costs where predicted costs are estimated as a function of:

- A complexity index (the number of continuously linked process units).
- Plant capacity (output in millions of pounds per year).
- The length of the construction period (in years).
- An innovation index (knowledge of heat and mass balance equations).

- A measure of project planning (the length of time between the start of project definition and the start of design engineering, in years).
- Dummy variables distinguishing olefin and aromatic plants.

The resulting equation explains about 87 percent of the variation in cost of the very heterogeneous set of plants in the Pioneer Plants Study. In principle, equations that predict costs more precisely should be possible when a more homogeneous data set is used.

RAND OTEC STUDY

- Combined CERs at subsystem level with engineering performance analysis

- Key results
  - Rand total cost estimate at considerable variance with DOE estimate
  - Cannot expect dramatic reductions in total system cost with large cost reduction or performance improvement in any single component

Chart 8. Another example from the energy area is the Rand OTEC Study. The OTEC example differs from the pioneer process plant example in that it is oriented to the subsystem level rather than the system level, and it is for a generation technology rather than a chemical processing technology. The Rand OTEC methodology combined subsystem level CERs with engineering performance analysis to produce estimates of total system capital cost. The two most important cost-related results were:

1. The Rand capital cost estimate was at considerable variance with DOE's cost estimate.
2. No technical cost breakthroughs on a single component would have a significant impact on total system cost.

I am now going to briefly amplify on these results.

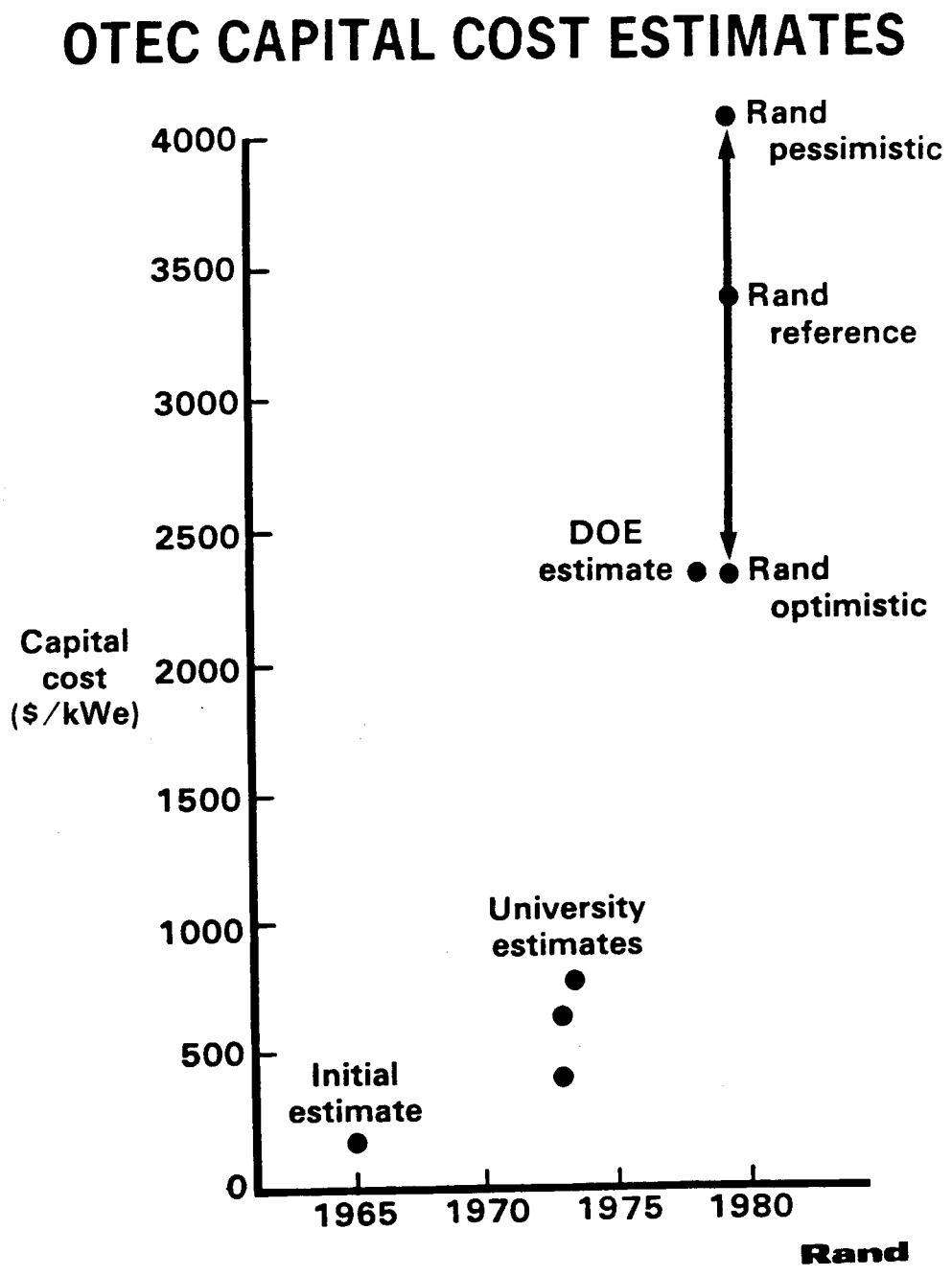

Chart 9. This figure shows both the DOE estimate and the Rand estimates. The Rand reference case is approximately $1000/kWe greater than the DOE estimate. Furthermore, our analysis suggests that the DOE estimate could be achieved only with the most optimistic of assumptions.

However, there is a considerable degree of uncertainty involved as indicated by the $1700/kWe range between the optimistic and pessimistic cases.

Also shown on this figure are some early estimates, largely performed early-on by universities, which further serve to illustrate what happens to cost as design is refined.

CERs were utilized to obtain estimates of cost for a number of elements of the OTEC system. They also provided the basis for the sensitivity analysis shown on the next chart.

COST SENSITIVITY: PERCENT CHANGE IN COST DUE TO 1 PERCENT INCREASE IN SINGLE ENGINEERING VARIABLE

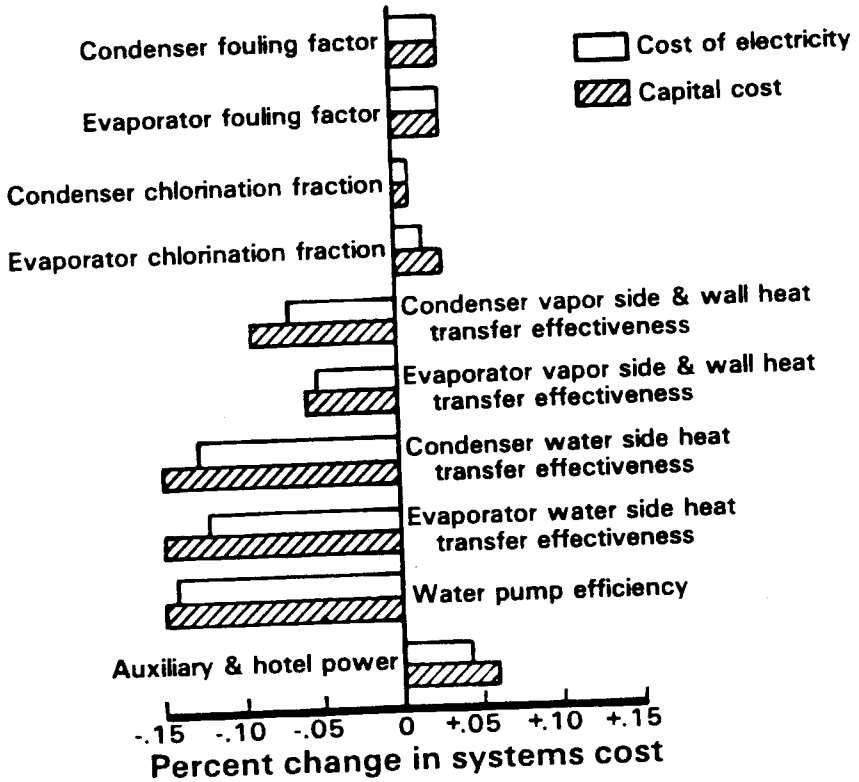

Chart 10. Our second major conclusion was that no breakthroughs on a single component will reduce total cost significantly. This chart shows the effect of a 1 percent increase in a single engineering variable on system capital cost and the cost of electricty (COE). No effect is greater than .15 percent. Thus, system cost is not particularly sensitive to changes in any single engineering variable.

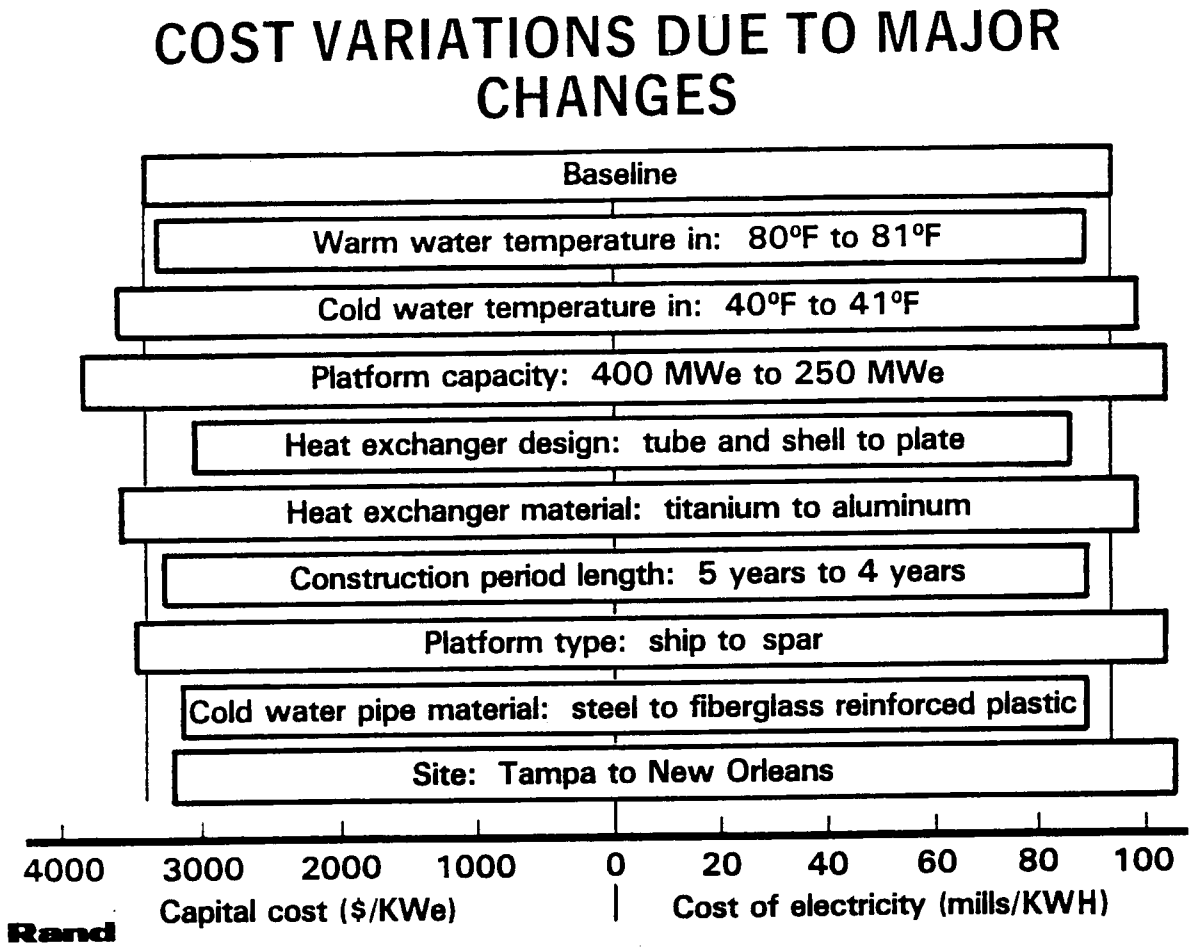

Chart 11. We also looked at major configuration changes. As before, no single change produces a significant change in total cost. Thus, it appears that significant cost reductions will occur only if a total systems approach is taken.

CERs

- Background
- ➡ Development
- Proposed application

Rand

Chart 12. That concludes the section on what CERs are and how they have been used in the past. We now turn to the problems associated with CER development.

SELECTING THE APPROPRIATE LEVEL

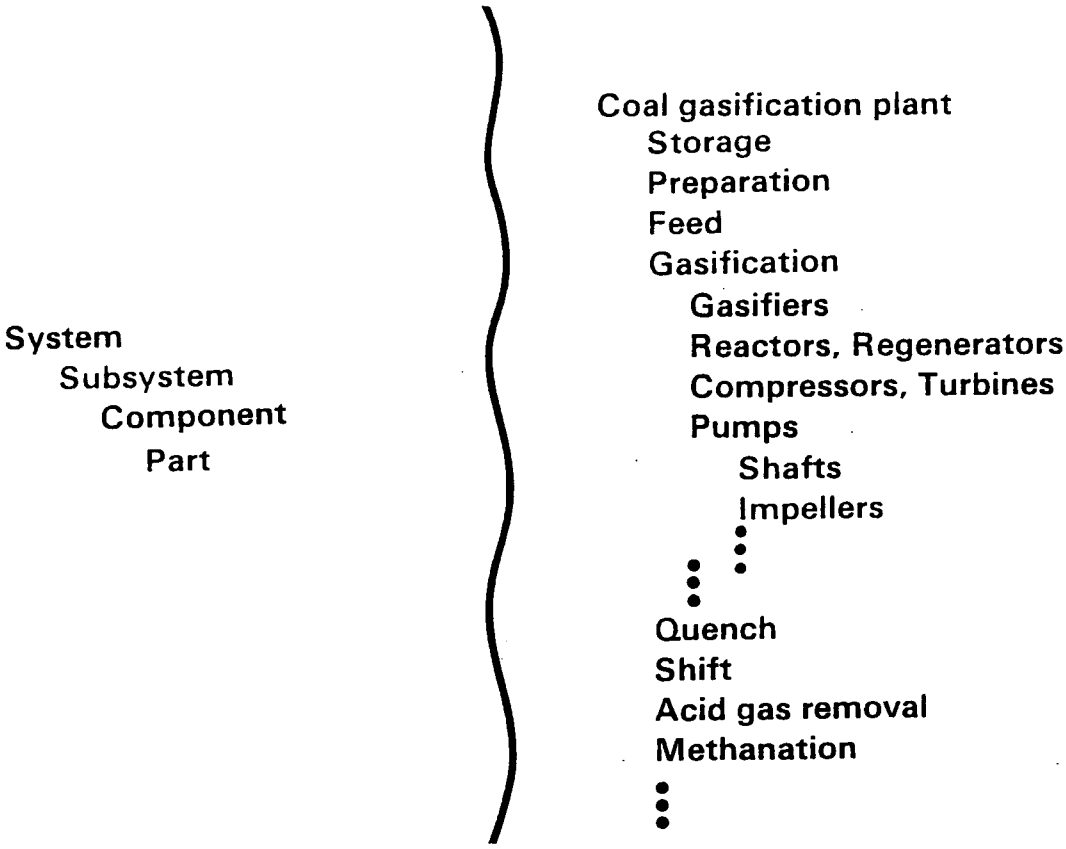

Chart 13. The first issue faced in developing CERs is selecting the appropriate estimation level. We have identified four possible levels--system, subsystem, component, and part. This breakdown is illustrated on the right-hand side of this chart for a coal-gasification plant. The system and subsystem are regarded as higher (or more aggregate) levels while component and part are regarded as lower (or more detailed) levels. The coal gasification plant is an example of a system. Storage, preparation, feed, and gasification are examples of subsystems.

CHOICE OF CER LEVEL AFFECTS:

- Range of alternatives which can be investigated
- Accounting of subsystem and component interactions
- Completeness
- Estimate turnaround time
- Required manpower
- Quantity of historical data
- Comparability across systems

Rand

Chart 14. The CER level selected should reflect an organization's purpose and available resources: (1) Lower levels favor the range of alternative configurations which can be investigated and the accounting of subsystem and component interactions are favored; (2) Higher levels favor completeness (especially in the early stages of planning), faster turnaround , lesser manpower, a smaller volume of historical data, and easier comparability between technologies. Given DOE's oversight responsibility and limited in-house resources, higher levels (system or subsystem) seem appropriate for CER development.

STEPS IN CER DEVELOPMENT

- Hypothesis development
  - Identification of potential cost drivers
  - Development of a priori rationale
- ➡ Collection of historical data
  - Assembly
  - Refinement
- Statistical analysis
- Documentation

Rand

Chart 15. These are the four usual steps in CER development: forming hypotheses, collecting historical data, performing statistical analysis on the data, and documenting the results. By far the most difficult is the collection of historical data.

DATA PROBLEMS

- Common problems
  - Economic differences
  - Quantity differences
  - Geographical location differences
  - Scale differences

- Data resides in industry
  - Proprietary concerns
  - Completeness
  - Fragmentation
  - Inconsistency in account definitions

Rand

Chart 16. We have categorized data problems into two areas. Common problems are those which can be dealt with through the use of standard procedures. This includes such things as putting estimates in constant year dollars and normalizing for quantity differences. The most difficult aspects of the data problem are caused by the fact that the data reside in private industry. In addition to the proprietary concerns, much of the cost data is incomplete, fragmented between divisions of the same company, and subject to definitional inconsistency.

The whole data problem is exemplified by the fact that DOE has sponsored over thirty pilot and demonstration coal conversion plants, and yet to the best of our knowledge, nobody had collected and centralized the cost and technical data for these projects.

CERs

- Background
- Development
- ➡ Proposed application

Rand

Chart 17. We now turn to a brief description of our ongoing effort to develop CERs for coal gasification.

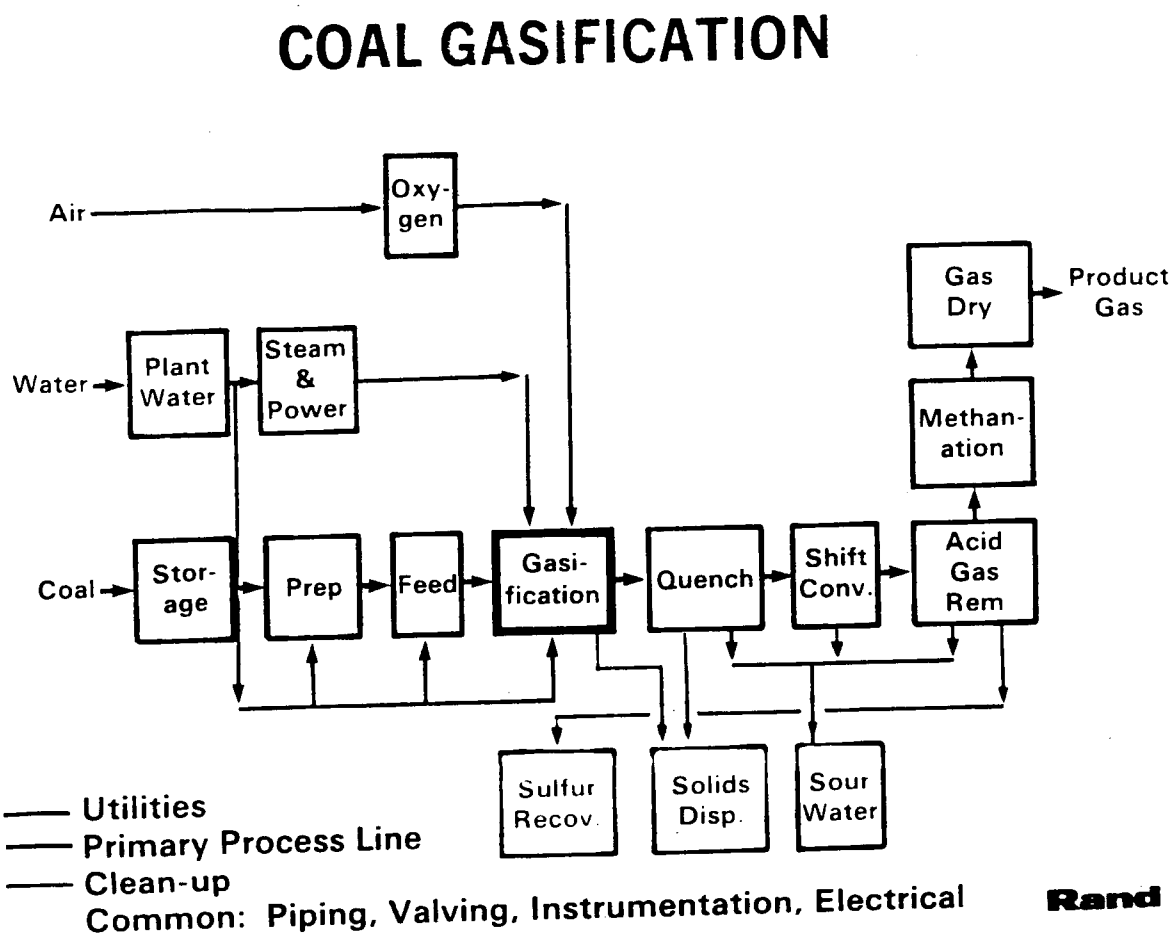

Chart 18. Under sponsorship of the Office of Independent Cost Estimation, Rand is currently attempting to develop CERs for coal gasification plants as a whole, and for the gasification subsystem thereof.

CLASSIFICATION OF COAL GAS PROCESSES

MOVING BED	ENTRAINED FLOW	FLUIDIZED BED	MOLTEN MEDIA
LURGI*▲	KOPPERS-TOTZEK*▲ TEXACO*■ BI-GAS*■	WINKLER*▲ STEAM-OXYGEN HYGAS*■ STEAM-IRON HYGAS*■ CO_2 ACCEPTOR*■ SYNTHANE*■ COGAS ■ HYDRANE ■	ATGAS ● MOLTEN SALT ●

▲ COMMERCIAL OPERATION
■ PILOT OR DEMONSTRATION PLANT
● EXPERIMENTAL
* PROCESSES TO BE ANALYZED

Chart 19. In order to accomplish this task, we are attempting to collect cost and technical data for those technologies designated by an asterisk. In a moving bed technology, the coal rests on a rotating grate. In entrained flow the coal (in the form of fine particles) is injected into the gasifier and carried through by steam and oxygen. Fluidized bed technologies suspend the coal in particulate matter. Molten media technologies suspend the coal in a molten material, such as salt.

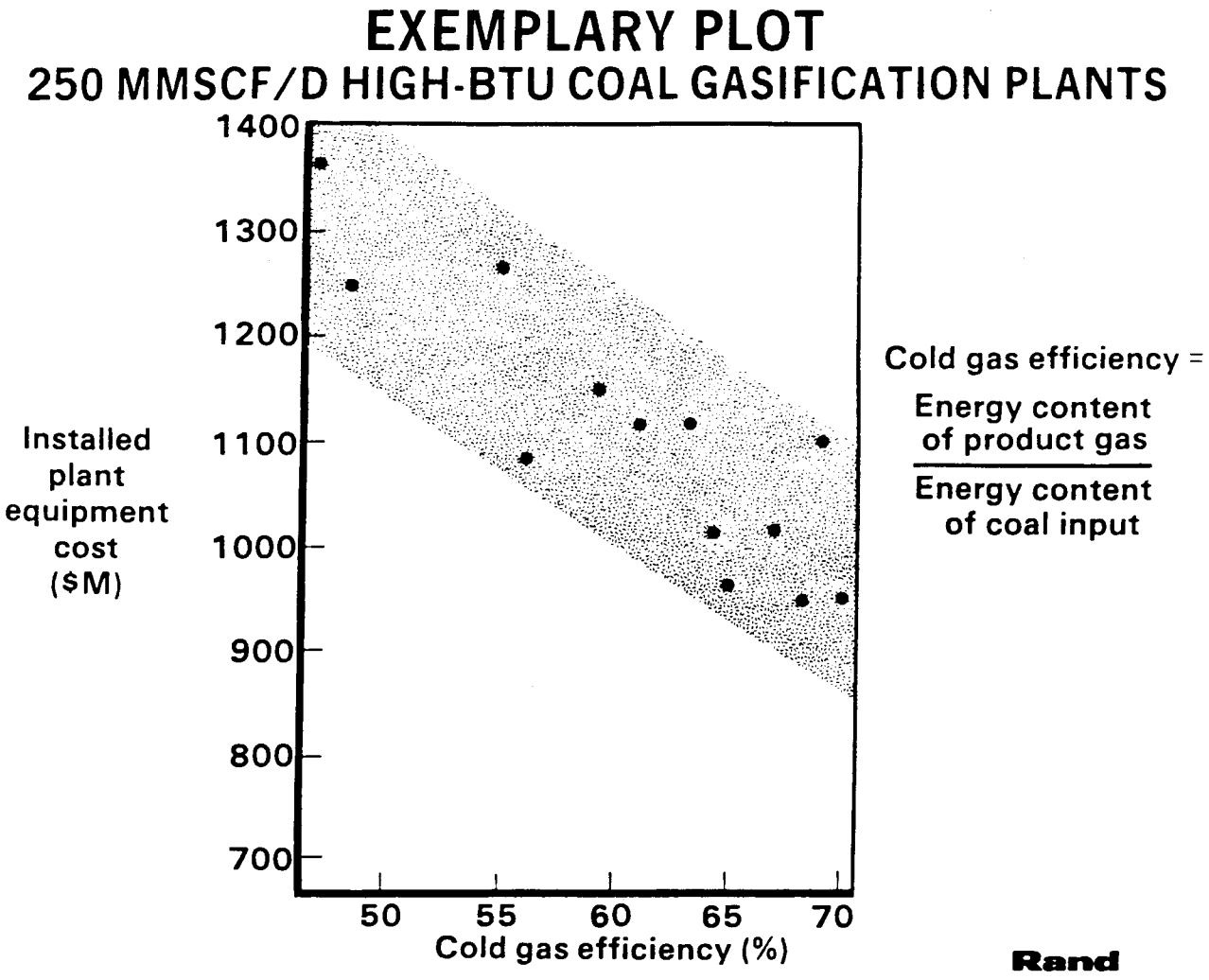

Chart 20. So far, data have been collected for 13 standard commercial-scale high-BTU coal gasification plants encompassing three coal types and six gasifier types. This figure shows our dependent variable, installed plant equipment cost (in June 1980 dollars), plotted as a function of one possible explanatory variable, cold gas efficiency (a measure of a plant's overall thermal efficiency). As indicated by the bad which has been "eyeballed" around the observations, as cold gas efficiency increases, the installed plant equipment cost decreases.

CER FOR HIGH-BTU COAL GASIFICATION PLANTS

Technical characteristic	Impact on plant equip. cost
——	$2160 M (constant)
Cold gas efficiency (%)	-$13 M per % point
Methane portion of dry crude gas (%)	-$16 M per % point
Ratio of hydrogen to carbon monoxide in dry crude gas	-$24 M per integer increase in ratio

- 92% of variation in cost (±3%)

Rand

Chart 21. A more rigorous statistical analysis, although still preliminary in nature, suggests that plant equipment cost is related to cold gas efficiency, the methane portion of the dry crude gas, and the ratio of hydrogen to carbon monoxide in the dry crude gas. As indicated, for each percentage point increase in cold gas efficiency, plant equipment cost drops, on average, by $13 M. Similarly, for each percentage point increase in the methane portion, plant equipment cost drops, on average, by $16 M. Finally, for each integer increase in the ratio of hydrogen to carbon monoxide, plant equipment cost drops, on average, by $24 M.

SUMMARY

- CERs would be useful to DOE
- Single biggest problem is obtaining historical data
- Parametric ERs have also been developed for performance and schedule
- Possible DOE initiatives
  - Begin data collection
  - Facilitate exchange of data, ideas, and results with industry

Rand

Chart 22. CERs would be extremely useful to DOE, but their successful development would be severely hampered by data problems. To address that problem, DOE must begin a data collection effort that is definitionally consistent, functionally oriented (as opposed to accounting oriented), and centralized in one location. It should be noted that the Office of Independent Cost Estimation is taking steps in this direction. Additionally, DOE should try to facilitate the exchange of data, ideas, and study results both with and within industry. One possible method for accomplishing this is to sponsor semi-annual meetings at which both DOE and industry representatives would discuss pre-arranged topics. Ideally, the core attendance group would not change drastically from meeting to meeting.

Thus, in addition to serving as a forum, these meetings would also supply points of contact between DOE and industry.

PERFORMANCE AND MAINTENANCE IN COAL CONVERSION SYNFUELS PLANTS

Kenneth E. Phillips

This presentation outlines a proposed Rand study for examining the feasibility of developing statistical estimating relationships for coal conversion systems in synthetic fuels process plants. This study focuses on the performance and associated maintenance effort required for some of the coal conversion technologies presently under consideration. Recent research shows that plant failures and forced production outages tend to occur with higher-than-expected frequency for technologies that are new at commercial scale.[1] This suggests that target synfuels production levels may prove unrealistic within currently specified budgets and time constraints. More accurate expectations about plant performance can play an important role in formulating policies to establish a viable U.S. synfuels industry while minimizing the likely risks associated with commercializing new technologies.

DOE's ROLE IN COMMERCIALIZING ENERGY TECHNOLOGIES

The Department of Energy remains involved at the front end of technology development, primarily through continued sponsorship of basic R&D. However, the focus of the proposed study would be to develop for DoE's use a set of tools to aid in evaluating the many technologies considered as candidates for commercialization. The task of stimulating private sector development of a national synthetic fuels industry places

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

the department in a somewhat precarious position. The task requires that emphasis be placed on those technologies that are not far enough developed for the private sector to sponsor without government support. Clearly this approach could result in government displacement of private sector investment. On the other hand, the department must not support the commercialization of technologies that clearly pose insurmountable obstacles to development. In the latter case the probability is great that both government and private sector spending would be wasted--resulting neither in an operating facility nor in resolution of the technical difficulties. Consequently, the department needs an evaluative framework in order to assess varying technologies and determine their appropriateness for government financial support.

PLANT PERFORMANCE AND PRODUCT COSTS

Among the most important criteria for evaluating candidate technologies is the product cost of the fuel produced. Both capital costs and plant performance must be considered simultaneously in any financial analysis to determine required product selling prices. Product costs are directly influenced by changes in plant capital costs. Figure 1(a) illustrates this relationship for a hypothetical synfuels plant. A shale oil plant was chosen for this example; however, the financial analysis applies equally well to other synfuels projects. The cost growth ratio of three (shown along the horizontal axis) corresponds to a tripling in plant capital costs over a six-year period between 1972 and 1978. Following this growth in capital costs, the required product selling price increases from 12 to 32 dollars per barrel. As shown by

Figure 1(a)

SHALE OIL COSTS

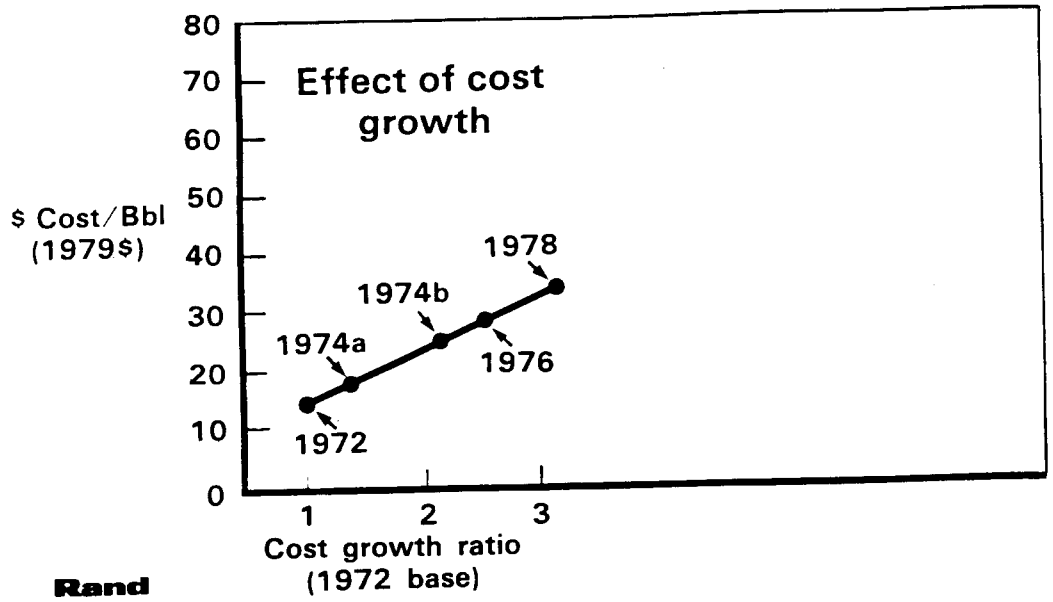

Figure 1(b)

SHALE OIL COSTS

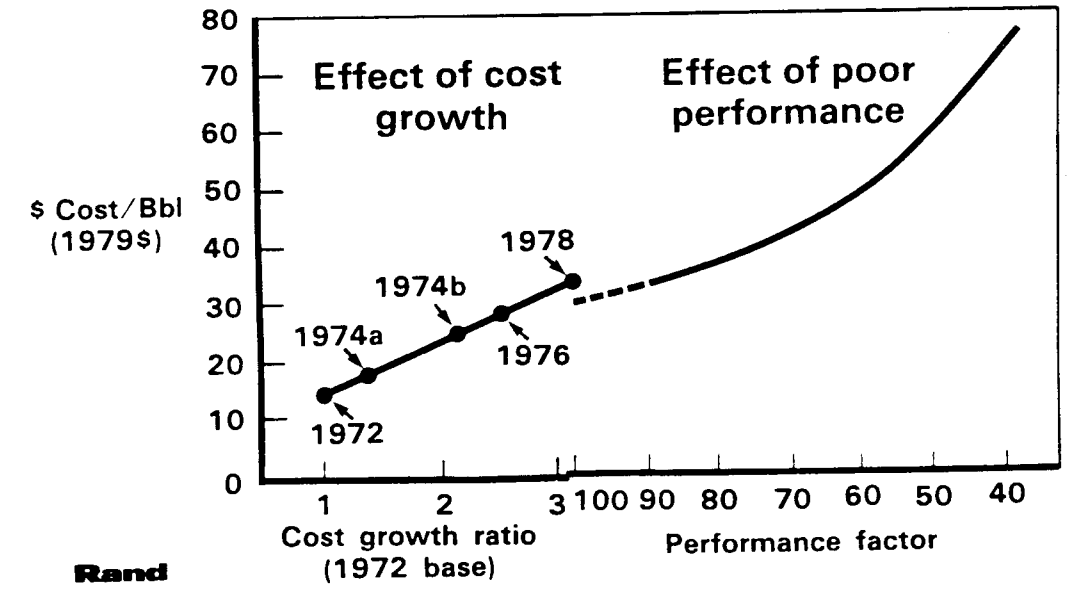

Figure 1(b), poor plant performance acts independently. A plant that operates at only 60 percent of its design capacity shows product costs nearly 12 dollars per barrel higher than for a plant that operates at 90 percent of its design. In most instances, candidate processes are evaluated based upon product cost calculations that assume an 85-90 percent of design. In view of the relationship between product costs and plant performance, this assumption is particularly critical.

Data provided for the Pioneer Plants Study by firms in the oil and chemicals industries afford a unique opportunity to examine the realism of performance assumptions of 85-90 percent. Figure 2 illustrates the distribution of performance outcomes that was observed for the 42 plants in the data base. The horizontal axis illustrates the performance as the ratio of actual plant performance to design capacity, measured during the second six-month period after plant start-up. The second six-month period was chosen to allow an initial six months for plant debugging. The vertical axis illustrates the fraction or percentage of plants that performed at those levels indicated on the horizontal axis. Approximately 16 percent of the plants performed at 60 percent of design capacity during the second six-month period after startup; several plants failed to achieve performance altogether. Fully one-third of the plants in the data base failed to operate at more than 50 percent of their design capacity.

The Pioneer Plants Study identified several measurable technical characteristics that help explain the wide variation in plant performance. These include the amount of commercially unproven technology embodied in the plant; the level of understanding about the

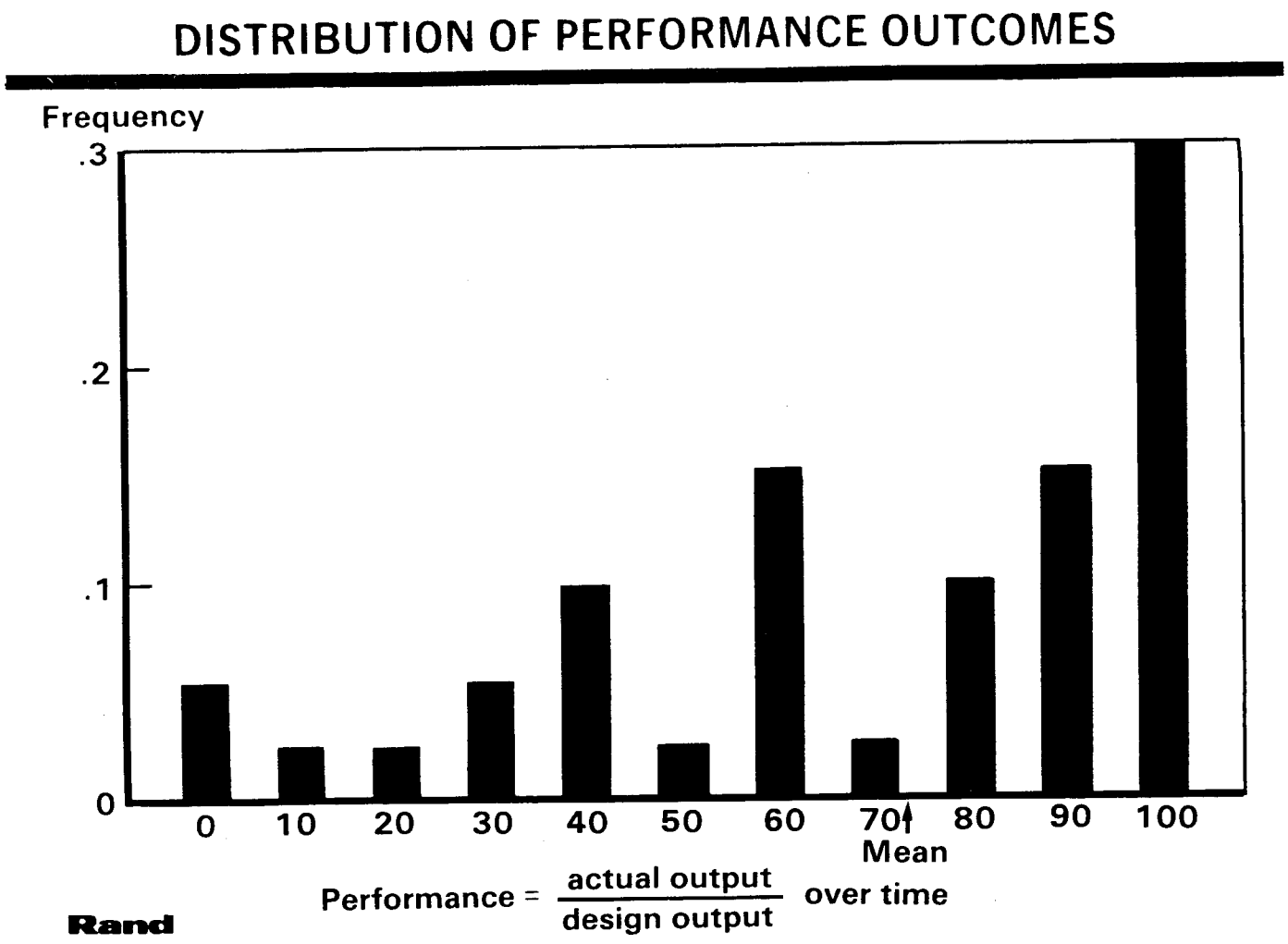
DISTRIBUTION OF PERFORMANCE OUTCOMES
Frequency
.3
.2
.1
0
0
10
20
30
40
50
60
70
80
90
100
Mean
Performance = actual output / design output over time
Rand

Figure 2

process chemistry itself; characteristics about the feedstock(s) and the difficulty involved in waste handling. Figure 3 isolates the effects of unproven technology and feedstock characteristics on plant performance--rated again as the percentage of design capacity in the second six months after start-up. Performance declines with an increase in the number of functional process units that embody technology new at commercial scale. Furthermore, after controlling for the number of new process units, solid feedstocks are associated with an estimated 20 percent loss in plant performance. Figure 4 presents similar information about the relationship between waste treatment difficulties and plant performance. Lower levels of production correlate with greater difficulty in waste handling. The distinction between plants having mainly solid feedstocks and those utilizing primarily liquids and gases remains clear.

PERFORMANCE PROBLEMS IN COAL CONVERSION SYSTEMS

As indicated in the available literature on coal conversion technology, such systems embody the precise set of characteristics that affect plant performance so significantly. In general, synthetic fuels production from coal involves:

- Solid and abrasive feedstocks
- Waste treatment requirements at several stages in the process
- New physical and chemical steps in some units

Aside from these general characteristics, the literature on failures in coal conversion systems identifies severe difficulties in

SOLIDS HANDLING PLANTS PERFORM MORE POORLY THAN LIQUIDS AND GASEOUS PROCESSES

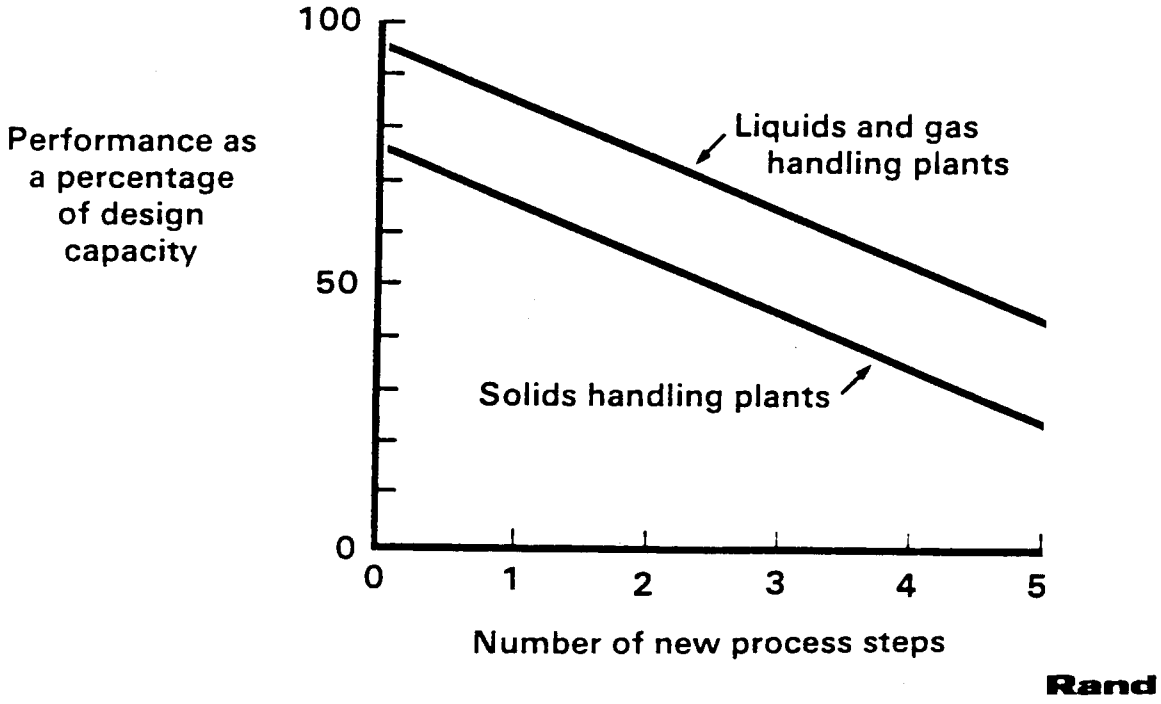

Figure 3

PERFORMANCE DECLINES AS WASTE HANDLING DIFFICULTIES INCREASE

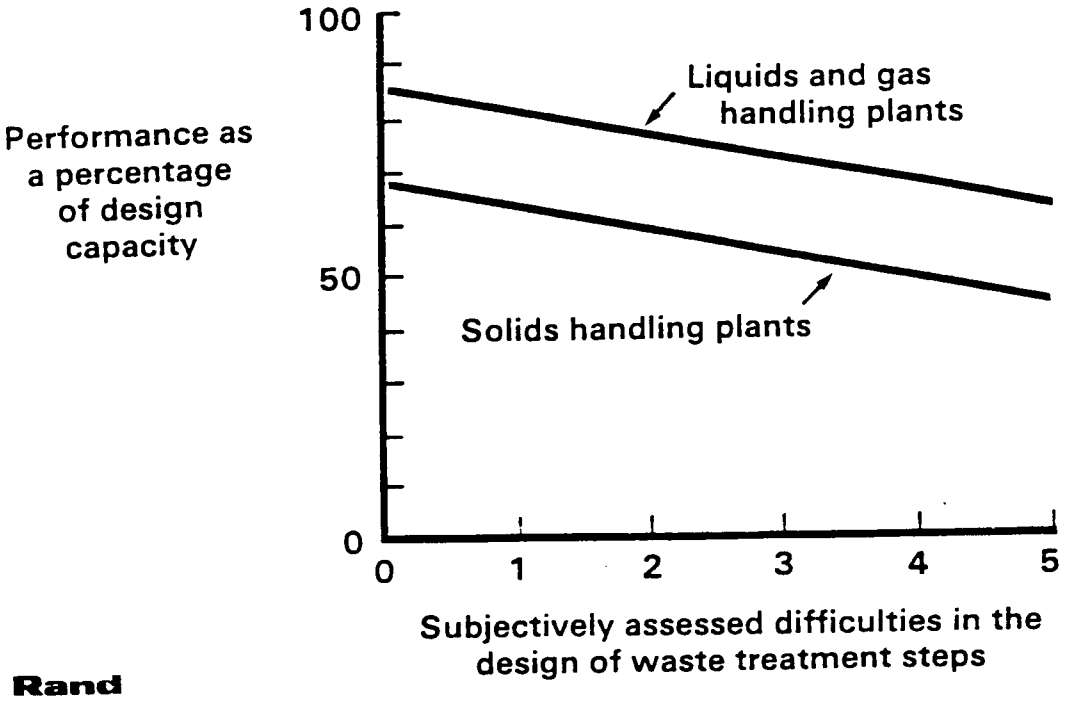

Figure 4

process control that link directly to the process operating parameters.[2] Plants that embody units to gasify coal, for example, maintain hostile environments inside the main gasifiers. The difficulties that derive are largely associated with:

- o High operating temperatures
- o High operating pressures
- o Feedstock impurities (especially elemental sulfur)
- o Abrasive suspended solids in product gas streams
- o High velocity gas streams
- o Compression requirements

Laboratory analyses of plant failures in experimental and pilot facilities reveal, further, the most frequently discovered linkages between the hostile process environment and resulting performance outages. This relationship is demonstrated in Figure 5. The critical stresses set up by coal conversion processes induce key material failures and mechanical breakdowns in major items of equipment. As shown in the figure, the most frequently reported causes cluster broadly into five generic categories. Analyses of materials' structure highlight certain weak points in plant design and equipment fabrication. This research alludes to certain limitations on the likely maximum periods of plant performance and suggests that binding constraints may exist until significant breakthroughs in materials research occur.

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[2]T.R. Shives and W.A. Willard, eds., Prevention of Failures in Coal Conversion Systems; Proceedings, 24th Meeting, Mechanical Failures Prevention Group, Battelle, Columbus Laboratories, Columbus Ohio, April 1976.

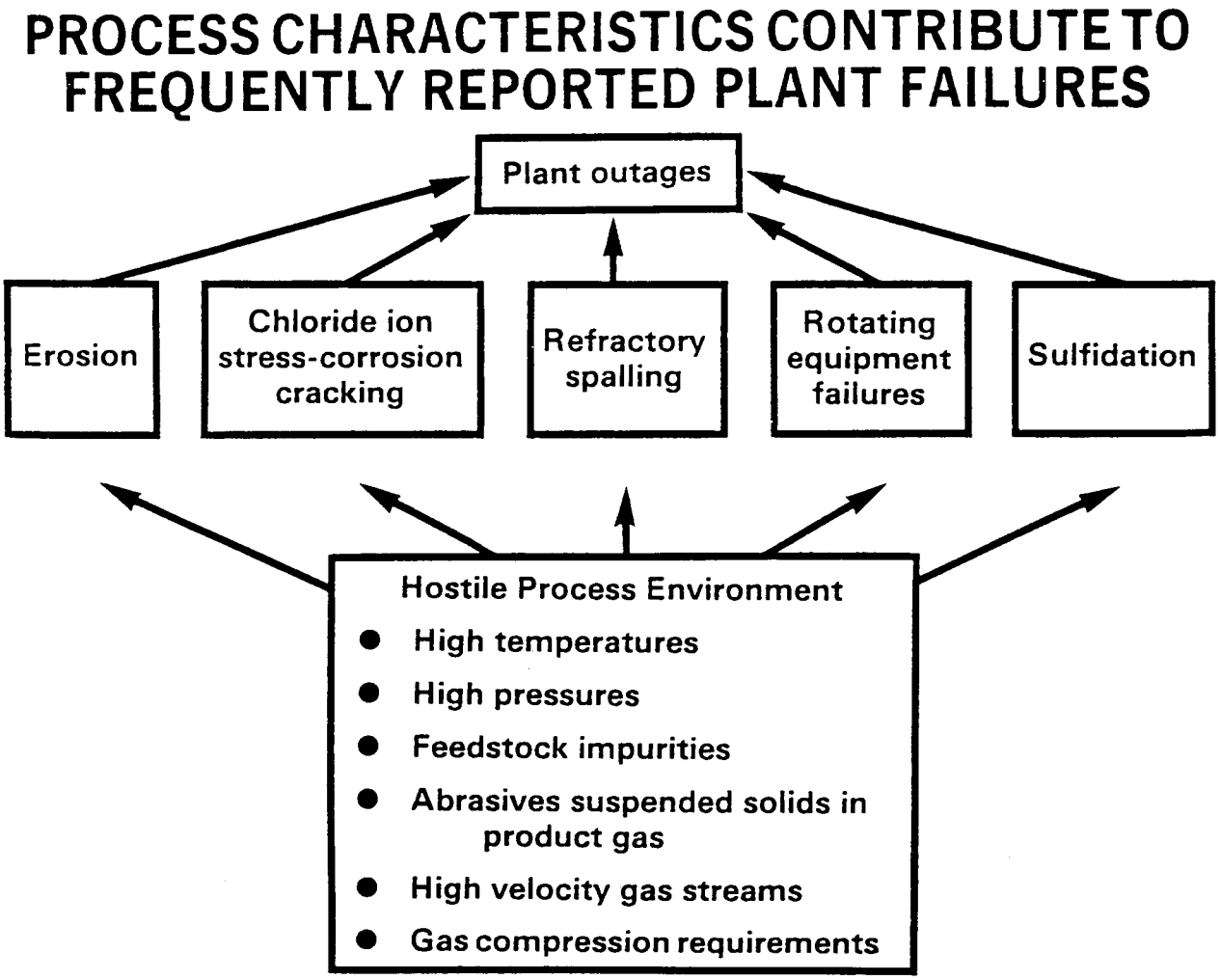
PROCESS CHARACTERISTICS CONTRIBUTE TO FREQUENTLY REPORTED PLANT FAILURES
Plant outages
Erosion
Chloride ion stress-corrosion cracking
Refractory spalling
Rotating equipment failures
Sulfidation
Hostile Process Environment
High temperatures
High pressures
Feedstock impurities
Abrasives suspended solids in product gas
High velocity gas streams
Gas compression requirements

Figure 5

A FRAMEWORK FOR ANALYSES

The generic characteristics of coal conversion plants suggest that such facilities will incur performance difficulties not unlike many plants in the Pioneer Plants Study. Synfuels product prices based upon plant performance assumptions of 85-90 percent of design capacity most likely deserve revision. The proposed study incorporates several goals. First, it is important to identify the performance differences among coal conversion technologies. Not all processes utilize the same set of operating parameters. There are, in fact, significant differences in the specified pressures and temperatures from one technology to the next. Second, the study seeks to understand the relationship between required maintenance levels and plant performance. Probable first measures of maintenance effort include variables like the frequency of preventive actions, but exclude explicit indices of dollar cost. A third study goal involves examining the tradeoffs that might exist between the level of capital investment and resulting maintenance requirements. One such tradeoff includes building excess plant capacity and deliberately tolerating lower average performance. Another option calls for restricting plant capacity through lower capital investment, but incurring higher maintenance costs by refusing to sacrifice plant output. A final study goal involves identifying how these tradeoff opportunities may vary across technologies.

Developing statistical relationships between plant performance and characteristics of the technology constitutes the basic study approach. The Pioneer Plants Study sketched the general set of variables that explain poor performance in first-of-a-kind plants. Separate research

on pilot plant failures identified the key process control parameters that critically affect plant performance. These studies also identified the most frequently diagnosed causes of plant failure deriving from these parameters. Statistically calibrated relationships between observed performance and the set of variables that describe the process in some detail can provide a useful tool for anticipating production constraints early in the planning process.

DATA SOURCES

Several sources exist as potential suppliers of data for this study. The absence of an established synfuels industry prohibits extensive data on coal conversion systems operating at commercial scale. Pilot plant facilities and scattered small scale commercial installations may, however, offer insights into several key process steps that first-of-a-kind synfuels plants will probably incorporate.

Pilot Plants

Under DoE's sponsorship, considerable information was gathered during the operating lives of several piloted coal conversion processes. The Technology Centers in charge of recording data on plant runs serve as a potentially rich source of basic information. Files in storage at the Pittsburgh Energy Technology Center (PETC) are one such promising source of operational data. Other locations may also prove valuable as sources of information on plant outages. The Institute of Gas Technology (IGT) has considerable experience in the piloting of other DoE-supported, advanced coal conversion technologies.

Bureau of Standards

Perhaps the most comprehensive source of compiled information about plant failures exists at the Bureau of Standards in the Information Center for Failure Prevention in Fossil Energy Plants. The center functions partly as a depository for data and background information about plant outages and their associated causes. Much of the information pertains to DoE sponsored pilot plant runs.

Small Commercial Gasifiers

Although no synthetic fuels plants exist at commercial scale in the U.S., a number of small gasifiers operate on a daily basis both domestically and throughout Europe. Many of these systems are considered as first generation in design. Their operating parameters remain far less severe than those for the more advanced gasification technologies. Furthermore, most such installations produce a low BTU or producer gas and not a medium or high BTU gas. Although different from the coal conversion technologies now offered as candidates for commercialization in the United States, these smaller installations offer a potentially valuable source of information. If data can be obtained from plant owner/operators, much can be learned about the requirements for maintaining continous operation in coal conversion processes. The full range of performance and maintenance problems for small coal gasification systems may not precisely reflect the difficulties in the first synfuels plants; however, the smaller installations should help establish at least a lower bound on the likely future problems.

Appendix

INDUSTRY PERSPECTIVES WITH PIONEER PROCESS PLANTS

17 September 1980

ATTENDEES

Department of Energy

Bill Adair
Controller/Independent Cost Estimating

Ted Ankrum
Conservation Solar Energy/Commercialization

Dick August
Resource Application/Uranium Enrichment

Russ Bardos
Resource Application/Coal Resource Management

Gil Blake
Resource Application/Industrial Planning and Development

Ed Blum
Policy Evaluation/Advanced Technology R&D

Jay Braitsh
Fossil Energy/Plans and Technology

Charlie Brooks
Policy Evaluation/Coal and Synthetics

Tony Cordesman
Resource Application/Policy and Program Planning

Bob Crockett
Energy Information Administration/Applied Analysis

Ramesh Dandekar
Energy Information Administration/Applied Analysis

Lucio D'Andrea
Resource Application/Oil and Natural Gas

Gene DeLatorre
Conservation Solar Energy/Commercialization

Jerry Eyster
Energy Information Administration/Energy Information Validation

James Finucane
Energy Information Administration/Energy Information Validation

Richard Gilbert
Resource Application/Policy and Program Planning

Fred Glaser
Resource Application/Coal Resource Management

John Green
Energy Information Administration/Energy Information Validation

Bob Grubermann
Resource Application/Small Hyrdo

Suraj Kanhouwa
Energy Information Administration/Applied Analysis

John Korbel
Policy Evaluation/Economic Analysis

Ed Lazur
Resource Management/Nuclear Energy

Bonnie Mampe
Policy Evaluation/Coal and Synthetics

Dave McNicol
Energy Information Administration/Applied Analysis

John Mitrisin
Energy Information Administration/Applied Analysis

Jim Powers
Under Secretary

David Pumphrey
Resource Application/Oil and Natural Gas

Chris Robitscher
Energy Information Administration/Energy Information Validation

Ed Rutkowski
Resource Application/Uranium Enrichment

Bob Scarlett
Controller/Independent Cost Estimating

Jack Sheerin
Resource Application/Oil-Shale

Marvin Singer
Resource Application/Coal Resource Management

Jack Smithson
Policy Evaluation/Coal and Synthetics

Don Teague
Resource Application/Industrial Planning and Development

Margo Thorning
Energy Information Administration/Applied Analysis

Mark VanSchilffgaarde
Energy Information Administration/Energy Information Validation

Paul Werbos
Energy Information Administration/Energy Information Validation

Ivar Ylvisaker
Resource Application/Coal Resource Management

Industry

John Fisher
Consultant

John Hackney
Consultant/Mobil Oil Company

Larry Nault
Chem Systems, Inc.

Allen Normon
E. I. Dupont, Inc.

Richard Summers
Mallinckrodt, Inc.

The Rand Corporation

Sue Bodilly
Ron Hess
R. E. Horvath
Marc Lieber
Ed Merrow
J. R. Nelson
Ken Phillips

RAND/N-1709-DOE

SELECTED PAPERS FROM THE ENERGY WORKSHOP: INDUSTRY PERSPECTIVES ON PIONEER PROCESS PLANTS

R. E. Horvath