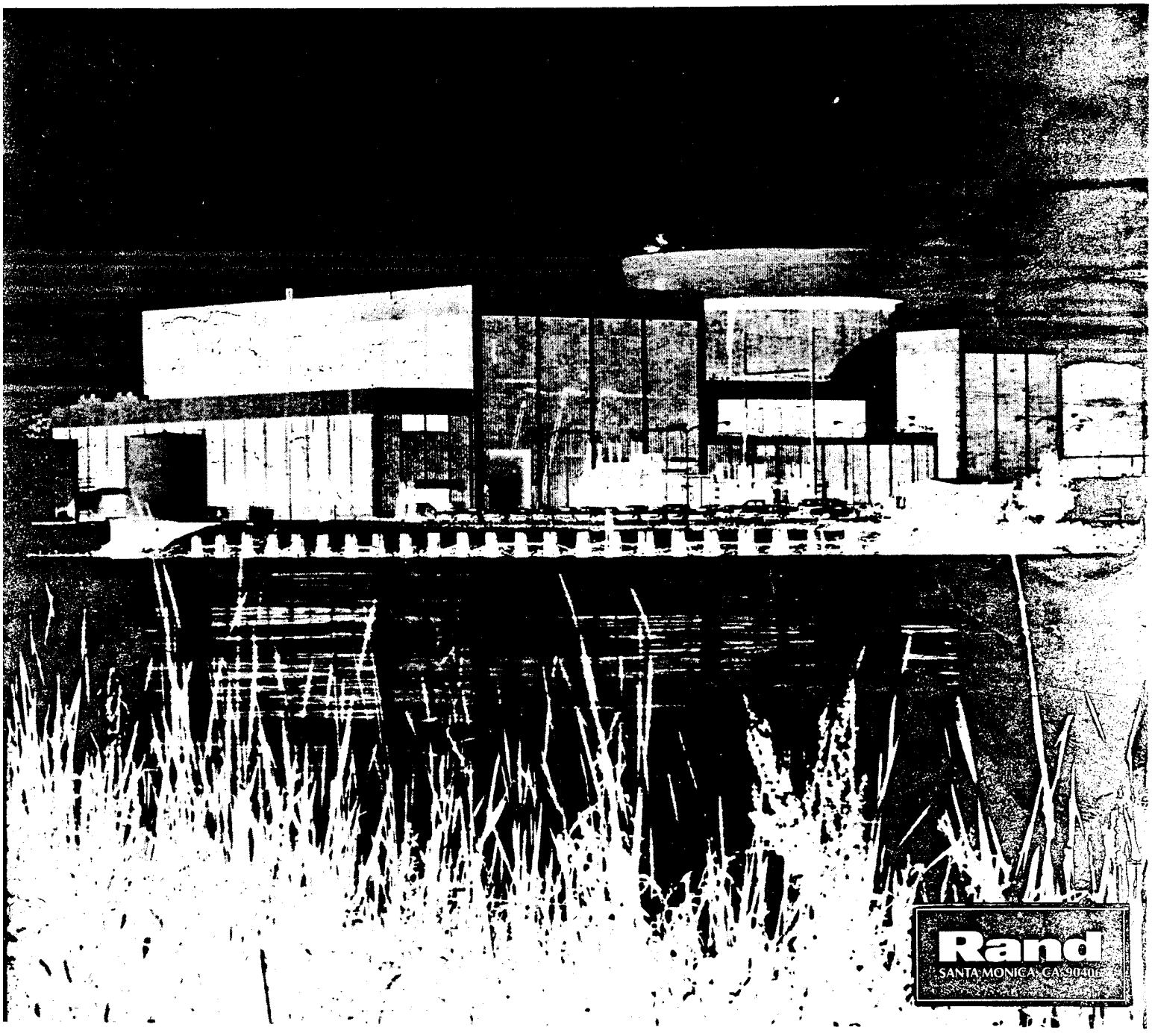
A SECOND COST ANALYSIS OF LIGHT WATER REACTOR POWER PLANTS

WILLIAM E. MOOZ

R-2504-RC

DECEMBER 1979



This research was supported by The Rand Corporation as part of its program of public service.

Library of Congress Cataloging in Publication Data

Mooz, W E
A second cost analysis of light water reactor power plants.

([Report] - Rand Corporation ; R-2504-RC)
1. Atomic power plants--Estimates--United States. I. Title. II. Series: Rand Corporation. Rand report; R-2504-RC.
AS36.R3 R-2504 [TK1343] 081s [338.4'36214834]
ISBN 0-8330-0187-6 79-26852

The Rand Publications Series: The Report is the principal publication documenting and transmitting Rand's major research findings and final research results. The Rand Note reports other outputs of sponsored research for general distribution. Publications of The Rand Corporation do not necessarily reflect the opinions or policies of the sponsors of Rand research.

Published by The Rand Corporation

PREFACE

This report is an update of a Rand study made in 1978.* The earlier effort analyzed statistically the construction permit time, construction time, and capital costs of all light water reactor (LWR) power plants in the United States for which data were then available. One of its major findings was that capital costs were increasing at the rate of $158 per kWe** per year (1978 dollars), and that there were no signs of this rapid increase leveling off. From the standpoint of energy policy, this finding had alarming implications. Without relief from the upward march of these costs, nuclear power plants might lose the chance to become an economic alternative to other forms of electricity generation. Further, it graphically portrayed the dilemma of attempting to project LWR capital costs very far into the future; the observed annual cost increases were so large that extrapolating them to the year 2000 gave a capital cost (in constant dollars) of over three times present costs.

The earlier study also found that average construction times for LWRs were increasing, again at a steady rate, and again with the implied result that if the rate continued, plants in the year 2000 might take eight years longer to build than they now do. Again, this confounds attempts to perform meaningful future analyses.

The seriousness of these two findings alone was sufficient to merit their reexamination as soon as additional data became available. Key issues were:

- Whether the cost and time increases were the same as before.
- If they were, whether any signs of leveling off could be detected.

In addition, a number of subsidiary findings were to be retested.

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*William E. Mooz, *Cost Analysis of Light Water Reactor Power Plants*, The Rand Corporation, R-2304-DOE, June 1978. This earlier study was funded by the U.S. Department of Energy.

**kWe refers to kilowatts of installed electrical capacity.

Since the time of the first study, many more data have become available. This report examines the new data base for the light it can throw on the issues above, for a deeper understanding of what is happening with capital costs, and for confirmation of the results of the previous study. The results should help policymakers, utility planners, and energy analysts attempting to discern cost differences among options.

The study was supported by The Rand Corporation with its own funds, as part of a program of research on major issues of public policy.

SUMMARY

The available data on light water reactor (LWR) capital costs were studied by the author in 1978. One of the principal findings of that study was that average LWR capital costs had risen steadily over the period of the data at the rate of about $158/kWe per year (1978 dollars). Extrapolating this trend produced cost estimates that exceed any other known estimates, and which would appear to rapidly reduce any economic advantages of LWRs to zero. Some other findings of the study were that

- Plants built in the Northeastern United States cost about $143 per kWe (1978 dollars) more than in the rest of the United States.
- Plants with cooling towers cost about $100/kWe (1978 dollars) more than those without.
- Cost learning was evident, with a cost reduction of about ten percent for each doubling of the number of plants built by a given architect-engineer.
- Economies of scale were shown, but their statistical significance was not as strong as the other effects discussed above.

The previous study used all of the then available data, but some of the findings had such strong implications that it appeared desirable to rerun the analysis when the data base was expanded. One particularly strong implication related to the very large temporal increases. Verification of the rate of increase was of obvious interest, and it seemed important to seek signs that that trend was leveling off. During 1978 such an expansion of the data base occurred, and this study is the result of an analysis of it.

The first study relied upon capital cost data from 39 plants, of which data from 25 were either subject to later revision or were only estimates. The present study had the benefit of a 54 plant data base, and only 20 of the points were subject to later revision. Thus, this study had almost 40 percent more data, and more of the data points were "hard" ones (34 compared with 14).

The first study found that the time required to obtain a construction permit had increased steadily at the average rate of about five months per year for applications made between 1966 and 1971, reaching an average of about 34 months in 1971. The present study confirmed that trend but found evidence not only that after 1971 the increase abated but that average permit processing time declined, reaching about 29 months for applications filed in 1973. No significant statistical relationships were found linking the permit processing time to various descriptors of the plants to be built.

Construction time was found in the first study to be strongly related to the plant size, whether the nuclear steam supply system was built by Babcock-Wilcox, the degree of experience of the architect-engineer, and the date the construction permit was granted. In the present report, a fifth variable--whether the power plant is a duplicate unit of another plant on the site--was also helpful in explaining construction time. Coefficients of the independent variables were found to be roughly the same as for the first study. Average construction time is still increasing at the rate of about 4.5 months per year. The duplicate plants were found to take almost a year longer to build, a finding that probably results from actual construction being delayed for a year or so after the construction permit has been issued, since construction permits for both units are usually issued at the same time. Attempts to detect construction time economies of scale* were unsuccessful.

Statistical analyses of capital costs produced several results of interest. The 1978 study had found that average capital costs had increased at the rate of $158 (1978 dollars) per kWe per year for plants whose construction permits were issued between 1966 and 1971. The data now show that the average increase is about $140 (1978 dollars) per kWe per year. Several tests were made to see if this reduction indicated a leveling off of costs, and such an indication was actually found.

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*Construction time economies of scale refer to the hypothesis that larger plants require less time to construct than would be inferred by linear extrapolation of the time required for smaller plants.

However, it was due to the position of four data points, three of which were estimates. Therefore, whether or not an actual leveling off of costs has begun depends upon the soundness of these estimates, which only time can verify. Whereas the construction time regressions showed discernible differences for duplicate plants, statistically significant cost differences for duplicate plants were not found. The 1978 study found weak evidence of cost economies of scale. The present study finds the evidence statistically insignificant. It has also found that the costs of LWR power plants with cooling towers are not statistically different from those without them, in contrast to the earlier study, which found that plants with towers cost about $100/kWe (1978 dollars) more.

Cost learning was again confirmed, with the learning curve being slightly steeper than the earlier study indicated (although still a moderate slope). The cost differential between FERC Region I (the Northeast) and the rest of the United States was found to still exist and to be substantially greater than the first study indicated. The comparison is $221/kWe (1978 dollars) in the present study compared with $143/kWe (1978 dollars) in the earlier study, with the higher costs being found in Region I.

Last, a logarithmic form of the regression equation was found to be a slightly better fit of the data than the linear form previously used. Over the range of the data, both linear and logarithmic forms give similar results, and consequently the use of either one is satisfactory. However, beyond the range of the data, the two forms diverge sharply, and could imply vastly different future capital costs. No theoretical defense of either form is offered, primarily because the major independent variable is a surrogate for a multitude of other factors that are presently neither well identified nor understood. More definitive insights into the basic reasons for cost increases will require field work in an attempt to isolate and quantify the effects that may increase capital costs. These include environmental and safety regulations, costs caused by backfitting during construction, and similar items.

ACKNOWLEDGMENTS

Since publication of his earlier study on the same subject, the author has discussed LWR power plants and their costs with a large number of interested parties representing diverse points of view. Each of these people helped, in one way or another, to shape this present study, and each has the author's thanks. Data for the analyses constituted a particular problem, and the assistance of several individuals was a key factor in rounding out the data base. These were Joseph Koden of the Federal Energy Regulatory Commission (FERC), Christopher Bassett of the Public Utilities Commission of Ohio, and Andrew Reynolds of the Energy Information Agency of DOE. Rand review by John Shank and Joseph Hall greatly strengthened the presentation.

Any remaining errors, of course, are solely the author's.

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NOTATION

CPAP	Date of construction permit application (May 1965 = 65.33, etc.)
CPAPSQ	$(CPAP)^2$
CPIS	Date construction permit issued (January 1970 = 70.00, etc.)
CPISN	CPIS-65
CPISNSQR	$\sqrt{CPISN}$
CPISN2	$(CPISN)^2$
T1	Construction permit time, equal to CPIS-CPAP, expressed in months
LOGT1	Natural logarithm of T1
T2	Construction time, equal to OLIS-CPIS expressed in months
N	Used only on graphs; refers to FPC Region I
C	When used on graphs, refers to FPC Regions II and IV
S	Used only on graphs; refers to FPC Region III
M	Used only on graphs; refers to FPC Regions V and VI
W	Used only on graphs; refers to FPC Regions VII and VIII
LOC1	FPC Region I; denoted by N on graphs
LOC2	FPC Region III; denoted by S on graphs
LOC3	FPC Regions II and IV; denoted by C on graphs
LOC4	FPC Regions V and VI; denoted by M on graphs
LOC5	FPC Regions VII and VIII; denoted by W on graphs
SIZE	Power plant net capacity, MWe; taken from DOE/ET - 0030/7(78)
TOWER	Denotes the use of a cooling tower
B	Indicates that the architect-engineer was Bechtel
GE	General Electric manufactured the NSSS
W	Westinghouse manufactured the NSSS
CE	Combustion Engineering manufactured the NSSS
BW	Babcock-Wilcox manufactured the NSSS
N	Denotes the cumulative number of LWR power plants by each architect-engineer
LN	Natural logarithm of N
DUP1	Denotes that the plant is the first of a pair of duplicate plants

DUP2	Denotes that the plant is the second plant of a pair of duplicate plants
OLIS	Date operating license issued (December 1975 = 75.92, etc.)

I. INTRODUCTION

In June 1978, we published an analysis of construction permit time, construction time, and capital costs for light water reactor (LWR) power plants in the United States.* That analysis used publicly available data on these subjects in a multivariable statistical regression analysis to attempt to gain insights into the changes taking place in the domestic nuclear industry. The observed changes were examined by statistical techniques that simultaneously took into account the effects of concurrent changes in many variables. By these techniques, the contributions of each variable were isolated from each other and the results presented in a form that uncovered previously hidden perspectives.

For example, the long-held notion that capital costs were rapidly increasing, but at an unknown rate, was given substance. Even after accounting for the effects of inflation by reducing all cost data to constant dollars, it was found that average costs increased about $158 dollars/kWe (1978 dollars) per year over the five-year period of the data base. The concept that this was due, in part, to delays in obtaining construction permits, and to delays in construction itself, could not be verified statistically.

It was also found that the expectation that capital costs would be lowered by a systematic process of learning (or learning curve) was realized. The effects of this process had been masked by other factors so that its contribution could not be isolated. What was found was that an *experienced* architect-engineer could reduce both construction time and capital cost by about 8 percent for each doubling of the number of plants built. This learning curve slope is rather modest compared with slopes often quoted in the industry, and puts into perspective the kind of long-range effects learning can have on capital costs.

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*William E. Mooz, *Cost Analysis of Light Water Reactor Power Plants*, The Rand Corporation, R-2304-DOE, June 1978. This earlier study was funded by the U.S. Department of Energy.

In the earlier study about half of the observed variance in the construction time data was explained by the size of the power plant, the architect-engineer's experience, whether the nuclear steam supply system was built by Babcock-Wilcox, and the date the construction permit was issued. This last variable was used as a surrogate for a variety of other determinants that were difficult (if not impossible) to measure quantitatively. Examples of these might be increased levels of quality assurance, greater environmental protection, etc.

Capital costs were somewhat better explained (about 75 percent of the observed variance) by the plant size, the architect-engineer's experience, the date the construction permit was issued, whether a cooling tower was used, and whether the plant was located in FERC Region I (the Northeastern United States). Of these, the construction permit date term was the most compelling, indicating an average yearly increase of about $158 per kWe (1978 dollars) over the five-year period. A variety of tests were performed to determine whether this increase was linear, and from the results it was not possible to assume otherwise. We were left with the (disquieting) impression that unless the various forces behind this temporal increase abated, nuclear capital costs would eventually increase beyond any previous estimates.

The results of our earlier study were, of course, no better than the data. At that time, the cost data base was limited, for various reasons, to only about 39 plants, and a number of the costs were only estimates. Thus, after a year had passed, and the data base had expanded by about 40 percent (together with a substantial increase in the reliability of the values), an opportunity to reexamine the results of the earlier study presented itself. Checking the results of the first study was clearly one objective. But more exciting was the possibility of detecting some signs of change in the trends that had been found earlier. Without signs of change, the nuclear industry might face the continued upward march of capital costs, with all its ramifications for energy policy and the debate between nuclear generation and generation by alternative fuels. The data base used in the present report is expanded to include a minimum of 54 plants, and the quality of the data is better.

The format of the present study closely resembles that of the previous one. First, a statistical examination of both the construction permit time and the construction time is made. Then capital costs are analyzed, and the results compared with those of the earlier study. The appendix describes the data base used in the present report.

II. CONSTRUCTION PERMITS AND CONSTRUCTION TIME FOR LWR POWER PLANTS

Time and capital costs of LWR power plants are equated in the minds of many who study the costs of these plants. It has been alleged by some in the industry that delays in the issuance of construction permits for new plants, or delays in construction itself, contribute to higher capital costs. In the sense that inflation must be contended with, these contentions are correct. But if one deals in constant dollars, the connection between delays and increased costs is not so clear.

The previous study of LWR capital costs reported in Mooz (1978) investigated the relationship between time data and costs. The study offered reasonable evidence that lengthened construction application times were not, in themselves, related to increased costs. However, delaying the issuance of the construction permit causes the construction of a plant to become more expensive, simply because construction costs have increased as time has passed. The earlier that construction can commence, the less costly it will be. In a way, the period of time required to obtain a construction permit can be described as a time period which, by itself, has only relatively nominal costs, but which is one key to what the capital costs of the plant will be. The earlier study found that average LWR capital costs had increased at the rate of about $158 per kWe per year from 1966 through 1972. During that period, plants whose construction permit applications were processed a year earlier than others that applied at the same time essentially cost $158 per kWe (1978 dollars) less.

Because plant capital costs continue to change over time, the time required to obtain a construction permit is of vital interest to those planning new capital additions. In the earlier study, statistical relationships were sought between the construction permit time and various other physical and locational characteristics of the plants. Essentially, only one relationship was found--that the construction permit time increased linearly as a function of the date of the permit application. Approximately 56 percent of the observed variance in the sample

could be explained by the date of permit application, and the average increase in construction permit processing time was about five months per year (that is, applications submitted in 1970 took an average of five months longer to be approved than applications submitted in 1969). These conclusions were based on data from 93 plants. Since the 1978 study, the issuance of more construction permits has increased the data base to 115 plants, spanning dates of application from late 1965 to mid 1973. Visual scanning of the original data base gave some indication that the close relationship between application date and construction permit time might be changing, particularly after 1971. This could have been due to the events that occurred after the appointment of James Schlesinger as AEC chairman in July 1971. In a recent study,* Rolph points out that a five-pronged overhaul of the licensing process was undertaken in 1972 to make the process more efficient and more responsive to the public interest. As a result, the backlog of construction permit applications began to clear out. Mooz (1978) found that the time required to obtain a construction permit was related to the date of application, and this was simply a reflection of the backlog of applications. With the larger data base now available, we have the opportunity to examine how things have changed. The objectives of the updated study are to check the earlier study's finding that the physical and locational characteristics of the plants are not determinants of the permit time, and then simply to try to mathematically describe what has happened to the permit time over the period of interest.

DATA ON CONSTRUCTION PERMITS

A plot of construction permit application time versus the date of application is presented in Fig. 1 for all plants for which applications have been made. There are 180 such plants, classified as follows:

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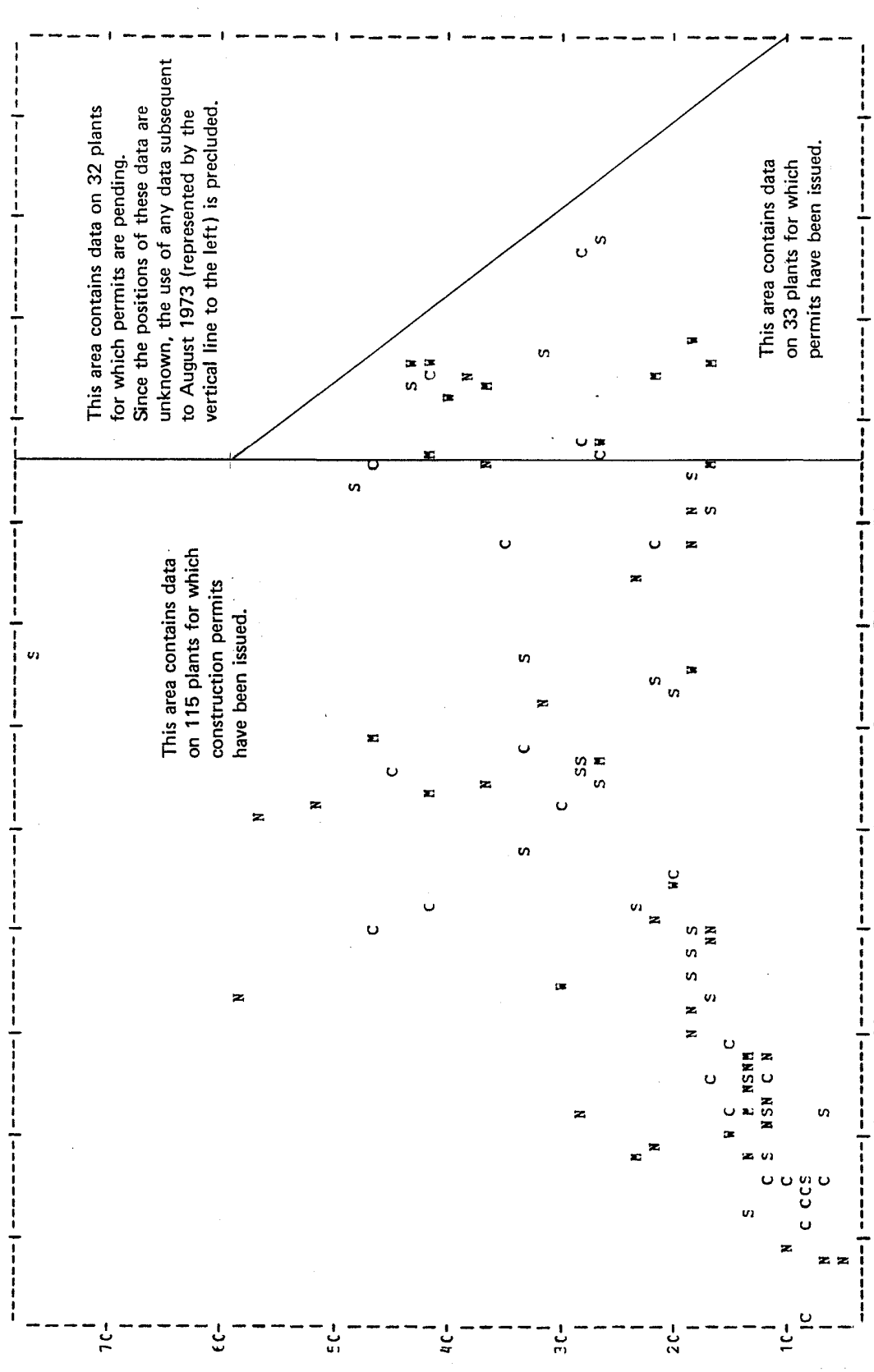
*Elizabeth S. Rolph, *Nuclear Power and the Public Safety: A Study in Regulation*, Lexington Books, 1979 (p. 133).



Note:
N = FERC Region I (N.E. United States)
C = FERC Regions II and IV (N. Central United States)
S = FERC Region III (S.E. United States)
M = FERC Regions V and VI (Mountain Central states)
W = FERC Regions VII and VIII (Pacific United States)

Fig. 1 — Time required to obtain a construction permit (T1) plotted against the date of permit application (CPAP)

Plants for which construction permits have been issued, and which applied for these before August 1973	115
Plants for which construction permits have been issued, and which applied for these after August 1973	33
Plants for which construction permits are pending, and which applied for these after August 1973	32
Total	180

As in the previous study, the 115 plant data set is statistically complete with regard to the application date. Inclusion of plants for which the application date was after August 1973 in statistical analyses is either improper or requires estimation of the construction permit times for the 32 pending applications in order for the data to be complete with regard to the application date.

CONSTRUCTION PERMIT TIME REGRESSIONS

Proceeding in the manner of the previous study, we first test for the effect of the various physical and locational variables on the permit time by postulating the model

$$T1 = \beta_o + \beta_1 \text{ CPAP} + \beta_2 \text{ SIZE} + \beta_3 \text{ LOC1} + \beta_4 \text{ LOC2} + \beta_5 \text{ LOC3}$$

$$+ \beta_6 \text{ LOC4} + \beta_1 \text{ TOWER} + \beta_8 \text{ GE} + \beta_9 W + \beta_{10} \text{ CE}$$

$$+ \beta_{11} B + \beta_{12} \text{ DUP2} + \varepsilon$$

(See p. xiii for a definition of the variables.)

We use data on 115 plants, and the results of this regression appear in Eq. (1), with the t statistics shown in parentheses beneath each coefficient.*

*As in the previous study, a significance of 0.05 or less is used as the criterion for inclusion of the variable in the final equations. There were virtually no borderline cases, i.e., the significance of the coefficients was generally either far less or far more than 0.05.

$$T1 = -256.0 + 4.1\,CPAP - 0.01\,SIZE + 1.5\,LOC1 + 1.0\,LOC2 + 0.1\,LOC3 - 4.2\,LOC4 + 2.7\,TOWER + 3.6\,GE + 1.5\,W + 6.8\,CE - 1.5\,B - 1.0\,DUP2 \quad (1)$$

$$(-5.5)\quad (5.6)\quad (-1.2)\quad (0.2)\quad (0.2)\quad (0.02)\quad (-0.5)\quad (0.9)\quad (0.8)\quad (0.3)\quad (1.2)\quad (-0.5)\quad (-0.4)$$

$R^2 = 0.33$; S.E. = 13.8; F = 4.2; and n = 115.

From the t statistics we see that the date of permit application, CPAP, is still the only factor that appears to be significantly related to the time required to process the application.

The earlier suspicion that trends in permit time might be changing is strengthened by the fact that the coefficient of the CPAP term is now smaller (4.1 months compared with 5 months), and the amount of variance explained is less (33 percent rather than 56 percent). Further, an examination of the regression equation residuals in Fig. 2 gives a clue that the linear equation may not fit the data points as well as some other form. By interpreting the residual plots, and by some trial and error, an equation form is found that raises the explanation of the variance to 60 percent.* This regression is given in Eq. (2).

$$\text{Log } T1 = -262.31 + 7.4573\,CPAP - 0.0523\,(CPAP)^2 \quad (2)$$

$$(-7.4)\quad (7.3)\quad (-7.1)$$

$R^2 = 0.60$; S.E. = 0.38; F = 84.94; and n = 115.

*Several methods could have been used to characterize the average permit times, including dividing the data into pre-1972 and post-1972 sets and examining these separately. The purpose of this portion of the analysis is just to draw some general conclusions about changes that have been taking place in length of permit times. The method used here satisfies this objective.

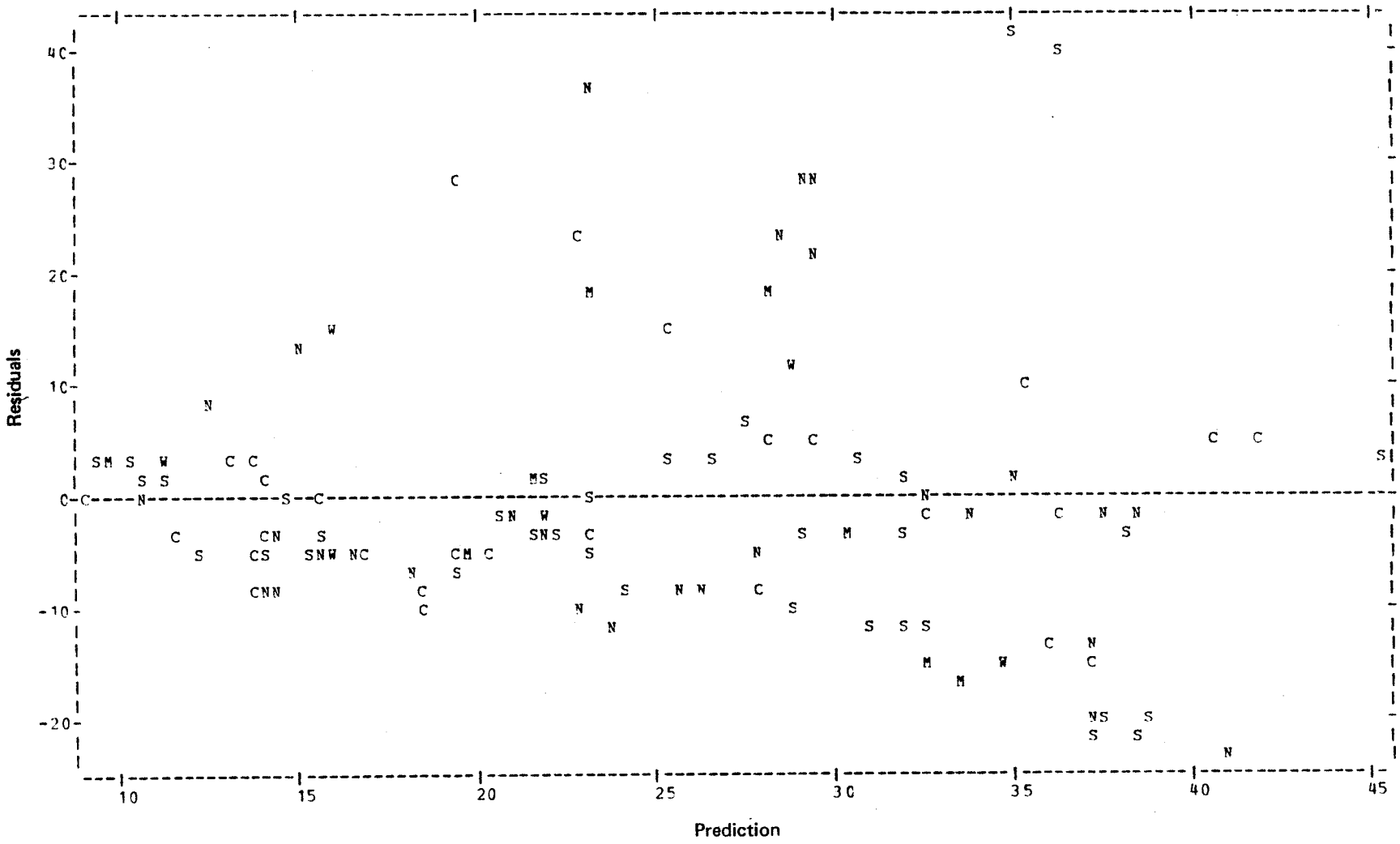


Fig. 2 — Residual plot for Equation (1)

The average construction permit times represented by the regression equation are plotted in Fig. 3. After a period of rapid increase in permit processing time, the rate of increase tapered somewhat, and then reversed, actually dropping some four months or so from 1971 to 1973. This curve is solely a representation of the data through 1973, and carries with it no implications for permits applied for after that date. There are 32 plants for which applications are still pending. The length of time required for these applications to be completed will determine the shape of the curve in Fig. 3 after 1973. What can be said about the process of obtaining a construction permit is that the rapid increase in the amount of time required to obtain the permit that occurred from 1965 to 1971 appears to have changed in character. The amount of time is no longer increasing in the same way, but may either be stabilizing or even slightly decreasing. Permits issued in 1979 and 1980 should provide enough additional data to allow estimation of the character of any new trends that might be established after the period of rapid change between 1970 and 1973, and may particularly show the effects of more careful scrutiny of applications that were in process at the time of the Three Mile Island incident.

DATA ON CONSTRUCTION TIME

The analysis of construction time in the previous study relied upon a data base consisting of 55 completed plants, and ten plants for which the construction time estimates of DOE were used. This data base is now also larger. There are now 59 completed plants, plus eight more for which construction time estimates ought to be very good. There are another 81 plants that are under construction. Figure 4 illustrates the construction time data base, with the construction time plotted against the date the construction permit was issued. From this plot, one can see that if the date the construction permit was issued is to be used as an explanatory variable for the construction time, two plants must be deleted from the data base because their permits were issued after August 1972. The data for these two plants coexist with yet unknown construction times for plants still being built. There are also two plants that appear to be outliers, with construction times of 126 and 123 months, respectively. The first of these is Diablo Canyon 1,

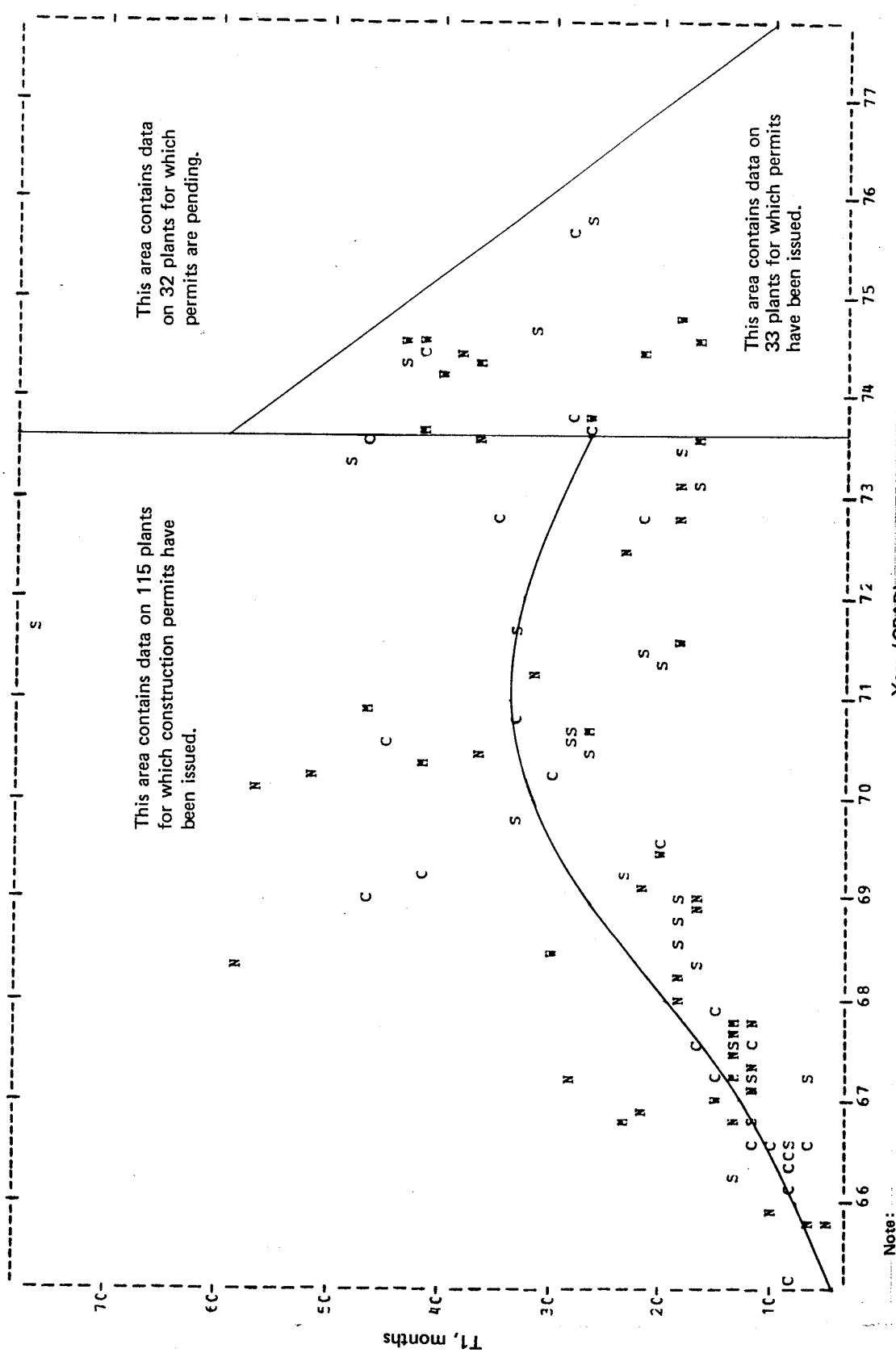


Fig.3 — Plot of regression equation for construction permit time

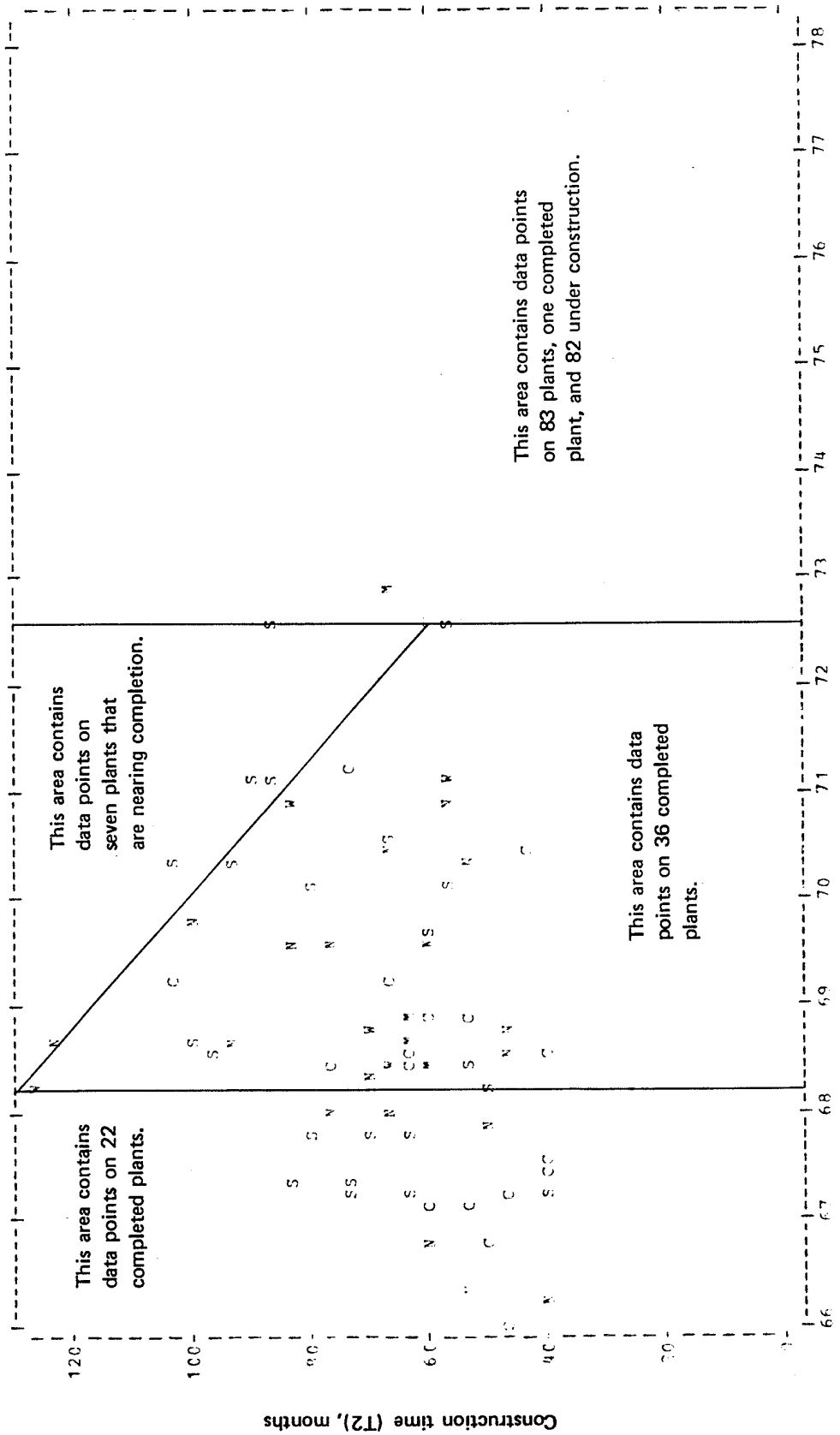


Fig. 4 — Construction time (T2) data for all 148 plants that are either completed or under construction

on which construction is completed, but for which an operating license has been withheld because of seismic questions. Since the definition of construction time used in this study is the elapsed time between the issuance of the construction permit and the issuance of the operating license, the estimated value for Diablo Canyon 1 is not representative of the construction time. The other apparent outlier is Salem 2, which, after 123 months elapsed time since the construction permit was issued, appears to be a special case. These two plants will also be dropped from the data base, as will Fort St. Vrain, which is not an LWR, leaving 62 plants for which data may be analyzed.

CONSTRUCTION TIME REGRESSIONS

The previous study used a 65 plant data base, or three plants more than were available for this study. The difference is due to dropping the two outliers discussed above and Fort St. Vrain. Also, whereas the earlier study used estimates for ten plants, the present data base uses seven, and these estimates ought to be closer to their ultimate values, since a year has passed.

Regression analysis of the construction time in the previous study showed that only four variables appeared to be related to it. These were the date of construction permit issuance, the plant size, the number of plants that had been previously built by the architect-engineer, and whether the nuclear steam supply system (NSSS) had been supplied by Babcock-Wilcox. Tests for the effects of other variables on the construction time showed none of significance.

With the revised data base, we begin by duplicating the regression analyses made in the first study. However, where the first study included an indicator variable for whether there was already another plant on the site (whether nuclear or not), we revise this to include an indicator for whether there is a duplicate plant on the site. There is a great similarity between these two indicators, since if there is a duplicate plant, there is also another plant. In the 62 plant data base, there are 24 plants that have other plants on the same site. Of these, 19 are duplicates of others on the site.

Some idea of the probable results of including the duplicate plant indicator can be had by examining the data in Table 1, which lists

Table 1

CONSTRUCTION TIMES FOR DUPLICATE PLANTS[a]

Plant Name	DOE Number		Construction Time, Months	
	Unit 1	Unit 2	Unit 1	Unit 2
Dresden 2 & 3	21	28	47	51
Turkey Point 3 & 4	27	60	63	72
Point Beach 1 & 2	31	52	39	40
Quad Cities 1 & 2	33	38	55	61
Brown's Ferry 1 & 2	34	35	73	85
Oconee L & 2	36	37	63	71
Peach Bottom 2 & 3	39	40	67	78
Salem 1 & 2	41	64	95	123
Surry 1 & 2	44	45	50	55
Diablo Canyon 1 & 2	46	87	128	83
Prairie Island 1 & 2	53	66	62	76
Zion 1 & 2	56	69	52	59
Calvert Cliffs 1 & 2	61	62	60	85
Donald Cook 1 & 2	67	68	67	105
North Anna 1 & 2	74	99	86	91
Edwin Hatch 1 & 2	75	102	59	66
Brunswick 2 & 1	79	78	58	79
Sequoyah 1 & 2	81	82	104	92
Jos. Farley 1 & 2	92	112	58	86

[a]Construction time is defined as the elapsed time between issuance of a construction permit and issuance of an operating license.

construction times for the 19 pairs of duplicate plants. In reviewing this table, one must keep in mind that the definition of construction time is the elapsed time between the date the construction permit is issued and the date the operating license is granted. This is a simple way to estimate the construction time, but it is not without pitfalls (as the example of Diablo Canyon 1 points out). Similarly, the construction permits for both of the duplicate plants may be issued at the same time, but construction might not begin on the second unit until some time after the first unit has been started. Again, the apparent construction time might be longer than the true time. Be that as it may, Table 1 rather clearly indicates that construction time, as defined, is usually longer for the second unit than for the first one.

We begin by considering the model

$$T2 = \beta_o + \beta_1 \text{ CPIS} + \beta_2 \text{ SIZE} + \ldots + \varepsilon$$

and by including the full range of independent variables that were tried in the previous study. Then, after discarding variables that show no statistical significance, we arrive at the results shown in Eq. (3).

$$\begin{aligned} T2 = &- 268.37 + 4.53 \text{ CPIS} + 0.035 \text{ SIZE} + 15.92 \text{ BW} \\ &\quad (-3.63) \quad (4.03) \qquad (4.17) \qquad (3.80) \\ &- 6.91 \text{ LN} + 11.54 \text{ DUP2} \\ &\quad (-4.12) \qquad (3.37) \end{aligned} \tag{3}$$

$R^2 = 0.63$; S.E. = 11.0; F = 18.82; and n = 62.

The same variables that were found significant in the first study were also found significant in the present study, and their coefficients were similar, as might be expected from the similar data base. In addition, the indicator for duplicate plants emerges as significant, and with the addition of this variable the total variance that is explained in the data is 62 percent, in comparison to 53 percent in the earlier study. Examination of the equation residuals does not provide any evidence to suggest that any of the linear terms are improperly specified. There are two variables of particular interest in this regard, though. The first is the CPIS term, which we have seen shows that the construction time increased at the average rate of about 4.5 months per year for plants starting construction between 1966 and 1972. Since prolonged construction times have been a complaint of the utilities and the engineering firms, it would be helpful to know whether or not there are any signs of change in the data, and particularly, whether the trend has shown any evidence of slowing in the more recent data. The second variable of interest is plant size, where one might expect to realize economies of scale in construction time.

To examine whether the construction time is linearly related to CPIS, we test three models, as follows:

(1) $T2 = \beta_o + \beta_1 \sqrt{CPIS-65} + \beta_2 \text{ SIZE} + \beta_3 \text{ BW} + \beta_4 \text{ LN} + \beta_5 \text{ DUP2} + \varepsilon$

(2) $T2 = \beta_o + \beta_1 (CPIS-65)^2 + \beta_2 \text{ SIZE} + \ldots \text{ etc.}$

(3) $T2 = \beta_o + \beta_1 (CPIS-65) + \beta_2 (CPIS-65)^2 + \beta_3 \text{ SIZE} + \ldots \text{ etc.}$

The results are as follows:

$$\underset{}{T2 =} \underset{(0.88)}{7.2} + \underset{(4.33)}{18.6 \sqrt{CPIS-65}} + \underset{(4.38)}{0.04 \text{ SIZE}} - \underset{(-4.32)}{7.23 \text{ LN}} + \underset{(3.78)}{15.8 \text{ BW}} + \underset{(3.28)}{10.6 \text{ DUP2}} \quad (4)$$

$R^2 = 0.63$; S.E. = 11.0; F = 18.9; and n = 62.

$$T2 = \underset{(4.33)}{31.5} + \underset{(3.76)}{0.51 (CPIS-65)^2} + \underset{(4.60)}{0.04 \text{ SIZE}} - \underset{(-4.01)}{6.99 \text{ LN}} + \underset{(3.82)}{16.6 \text{ BW}} + \underset{(3.16)}{10.6 \text{ DUP2}} \quad (5)$$

$R^2 = 0.60$; S.E. = 11.4; F = 17.1; and n = 62.

$$T2 = 18.1 + \underset{(1.88)}{8.4 (CPIS-65)} - \underset{(-0.85)}{0.45 (CPIS-65)^2} + \underset{(4.32)}{0.04 \text{ SIZE}} - \underset{(4.16)}{7.1 \text{ LN}}$$

$$+ \underset{(3.63)}{15.6 \text{ BW}} + \underset{(3.27)}{10.7 \text{ DUP2}} \quad (6)$$

$R^2 = 0.63$; S.E. = 11.1; F = 15.4; and n = 62.

From these results, and particularly the t statistics of the various CPIS terms, we conclude that there is insufficient evidence to suggest that the CPIS term is nonlinear.

Failing to find an alleviation of the trend to longer construction times as time passes simply says that those who expect this to happen must wait for a cessation of the effect of whatever forces are causing construction to be ever longer. A way of looking at it graphically

can be illustrated in Fig. 5. This figure depicts a hypothetical curve for average construction time, in which the time increases rapidly, but then levels off, becoming asymptotic to some final value. The data sample that is available for this study can be thought of as being representative of a *portion* of the center section of the curve. How large a portion is not known, nor is the relative position known. Only time and more data will provide the answer to these questions.

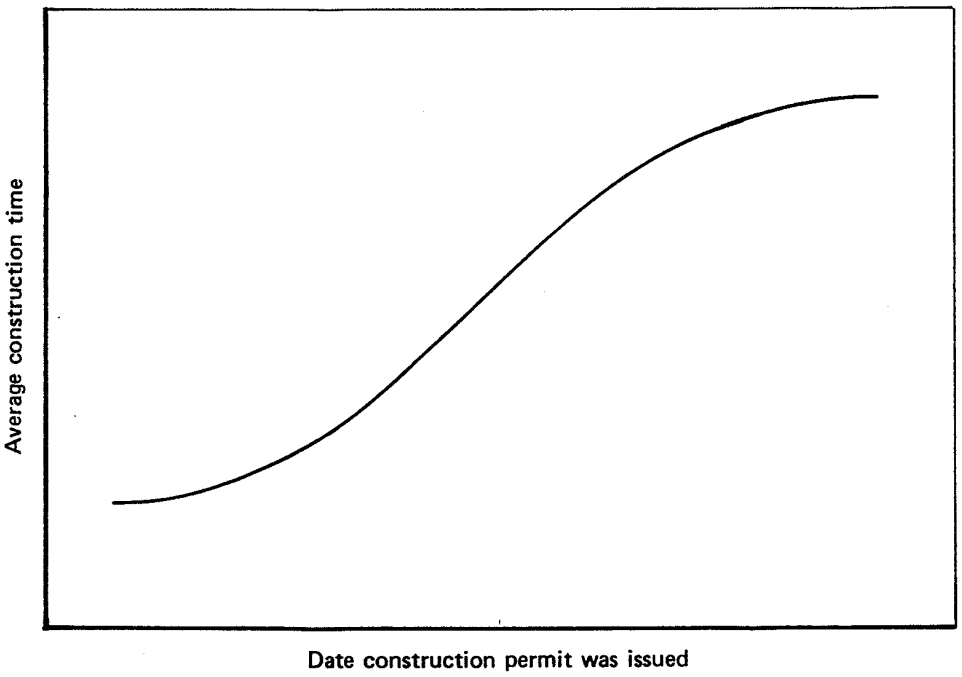


Fig. 5—Hypothetical relationship between construction time and date construction permit was issued

Using similar models and procedures, we also test whether construction time is linear with respect to plant size. As was found in testing the CPIS term, we are unable to discriminate among the SIZE term when entered as the square root, the square, or in quadratic form. We then test the model

$$\frac{T2}{KW} = \beta_o + \beta_1 \text{ SIZE} + \ldots \text{ etc}$$

where T2/KW is equal to T2 divided by SIZE and represents the construction time per kWe of installed capacity.

This regression has the following result:

$$\frac{T2}{KW} = \underset{(-3.04)}{-\ 0.30} + \underset{(4.30)}{0.006\ CPIS} - \underset{(-5.63)}{0.00006\ SIZE}$$

$$+ \underset{(2.59)}{0.01\ DUP2} + \underset{(3.21)}{0.02\ BW} - \underset{(-4.44)}{0.01\ LN} \qquad (7)$$

$R^2 = 0.63$; S.E. = 11.4; F = 17.1; and n = 62.

The negative SIZE coefficient is statistically significant and can be interpreted as a confirmation of economies of scale in construction time.

When the magnitude of these economies is examined, however, the reasons for the initial assumption of linearity of the SIZE term are apparent. Figure 6 illustrates the relationship between construction time and plant size as plotted at the data means for the linear equation (Eq. (3)) and the nonlinear equation (Eq. (7)). The data span a size range of 457 MWe to 1148 MWe, and slightly over 60 percent of the data points are such that the difference in construction time represented by the two equation forms is one month or less. To the extent that economies of scale in construction time exist, they are quite small over the range of plant sizes in the data base. For an 1150 MWe plant, one can say only that the time saving would be about 5 percent over what would be estimated by assuming no economies of scale at all.

The inability to demonstrate sizable economies of scale with respect to construction time may be both surprising to some and contrary to experience in other construction projects. What it may be indicative of is that the construction time is influenced by factors other than the actual time required for the physical activities, or that nuclear power plants increase in complexity along with their size in such a way as to nullify expected economies in construction time.

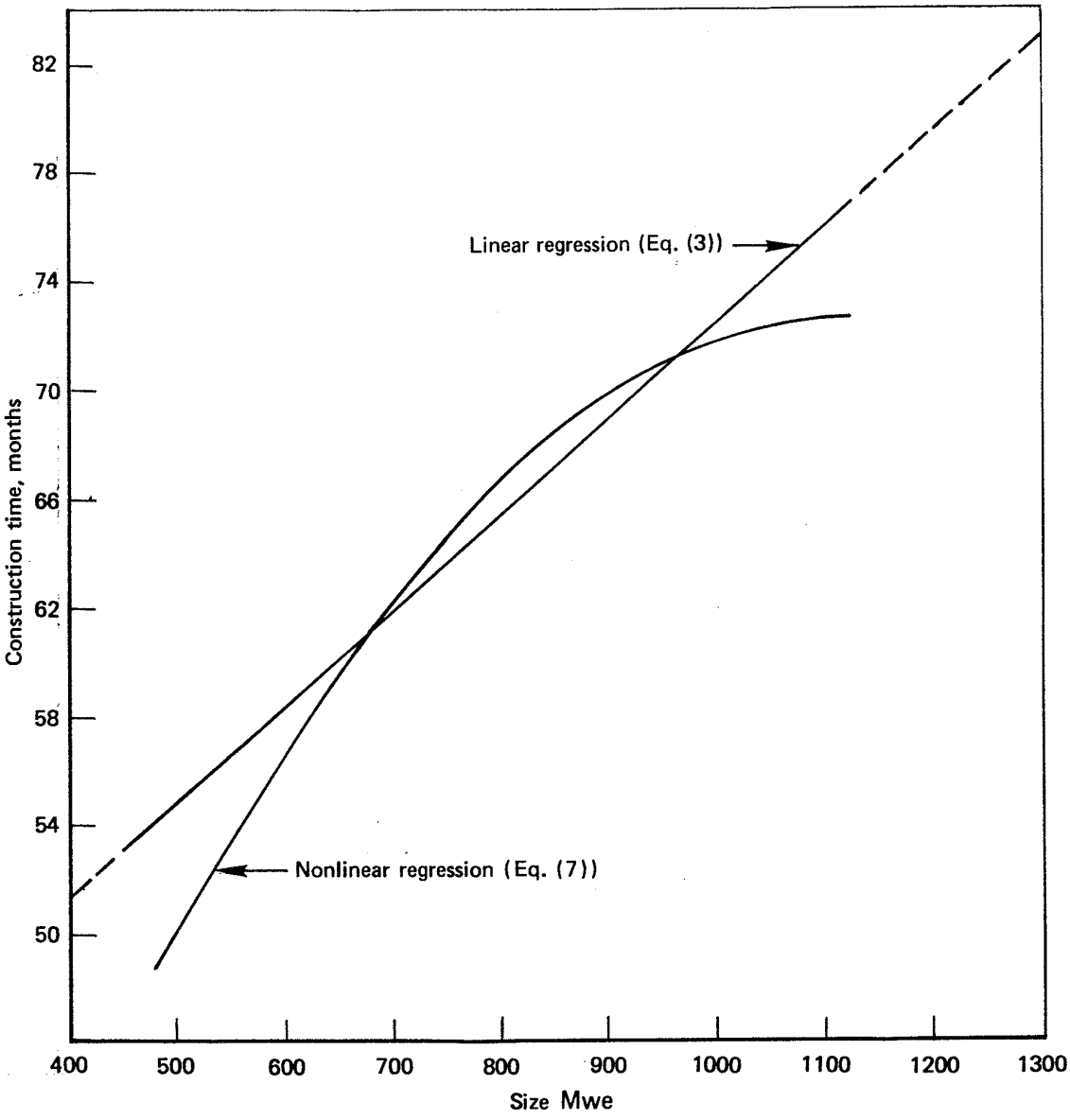


Fig. 6—Comparison of linear and nonlinear regressions of equations for construction time as a function of plant size

We now compare the findings of this study with those of the previous study.

The regression equation coefficients of Eq. (3) are compared with those reported in Mooz (1978) in Table 2. They are roughly similar, but there is a modest change in the learning effect, which appears to be slightly less than previously measured. The learning curve indicates that each time the number of plants built by an architect-engineer is doubled, the construction time is reduced to 92-93 percent of what it was. The inclusion of the term for duplicate plants shows what would be expected from Table 1. On average, the second plant on a site takes almost a year longer from the time the construction permit is issued until the operating license is issued. As mentioned earlier, this may not connote a construction time that is actually longer, but may result from the construction start being (purposely) delayed for a year after the construction permit is issued.

Table 2

COMPARISON OF REGRESSION EQUATION COEFFICIENTS FOR CONSTRUCTION TIME

	Coefficients	
Variable	Previous Study	This study (Eq.(3))
Constant	-270.82	-268.37
CPIS	4.55	4.53
SIZE	0.04	0.04
BW	13.07	15.92
LN	-8.00	-6.92
DUP2	--	11.55

IMPLICATIONS FOR THE FUTURE

We have noted that the length of time required to obtain a contruction permit appears to be uncertain, in that the trend showing strongly increasing times seems to be changing, and that there may even be a reduction in the average time required to process a permit. Those who have hoped for a speedier process for obtaining construction permits

might take hope from this change in what was initially a strong trend. With regard to the construction time itself, there is no indication of any change in the strong temporal trend that was originally described in Mooz (1978). It is not possible to imply that the trend will continue, but by the same token, the existence of a trend as consistent as this one places the burden of proof of much different construction times than would be suggested by the regression equation on the shoulders of the estimator.

The findings with regard to plant size should be noted. Large economies of scale in construction time were not found. We will later examine whether cost economies of scale exist, but if they do, they will apparently be unrelated to the construction time, which appears to be substantially linear with respect to plant size.

Last, the apparent longer time required to construct a duplicate plant is troubling. We will later see that the cost data are such that the question of whether a duplicate plant has different costs is difficult to address. To the extent that cost and construction time go hand in hand, one might be led to believe that a duplicate plant would cost more than the first plant. There are conditions under which this could occur, but it is generally not true.

III. COST ANALYSIS OF LWR POWER PLANTS

The large increase in available data on LWR power plant capital costs in the past year provides an opportunity to reexamine the analysis reported in Mooz (1978). That study, based on a more limited data set, found that the capital cost per kilowatt was statistically related to the plant size, location, presence of a cooling tower, and to "cost learning" on the part of the architect-engineer. The costs per kWe were also found to be increasing linearly along with calendar date at the rate of about $158 (1978 dollars) per year, a trend that could be alarming if it were to continue very far into the future.

As we will see, the cost data base is substantially improved from the previous study and should allow the validation or rejection of the previous findings, plus some investigation into other questions of interest that were not previously addressed. Specifically, the primary objectives of this cost analysis are to

1. Reexamine the findings of the previous study,
2. Attempt to determine whether the increasing linear cost trends have been altered, and in particular whether any slowing of the trend is evident, and
3. Reexamine the form of the cost equation.

THE COST DATA BASE

Just as care was required in selecting the data base for the regression analysis of construction time, it must be exercised for cost analysis regressions. The data base used in the previous analysis consisted of 39 plants, of which

13 plants had reported capital costs to the FERC for two consecutive years,*

*Two year reporting assures that all costs are accounted for.

19 plants had reported their costs only once, and 7 plants had not reported costs, but estimates from DOE sources were available.

The data base now consists of

34 plants that have reported capital costs to the FERC for two consecutive years,

6 plants that have reported their costs only once,

7 plants that have costs reported by the utility owners, and

8 plants for which DOE sources had recent estimates.

Thus there are data on 55 plants compared with 39 in the earlier study, and 40 of the data points are from FERC. Tables 3 and 4 list these data, together with the costs as adjusted to 1978 dollars. The data listed in Tables 3 and 4 include all plants that were issued construction permits through December 1972, except for those that were turnkey plants or were subsidized by the government in some way. Reviewing the data reveals one apparent anomaly in the cost of Salem 2. The estimated cost of $3160 per kWe is over twice the cost of the next most expensive plant, and there are no obvious reasons for it in the data. For the purposes of the statistical analysis of costs, Salem 2 is an outlier and is dropped from the data base. This leaves 54 plants.

FIRST REGRESSION ANALYSES

The first analysis duplicates the cost analyses of the previous study and is directed at testing the capital cost effects of the time required to obtain a construction permit and the construction time, to the extent that the effects of these variables are not captured by other variables in the regression. The technique used is to represent the construction permit time, T1, by the equation

$$T1 = \beta_o + \beta_1 \text{ CPIS} + \beta_2 \text{ SIZE} + \beta_3 \text{ TOWER} + \beta_4 \text{ BW} + \beta_5 \text{ LOC1} + \beta_6 \text{ LN} + \varepsilon_1$$

and to compute the equation residual, T1RSID, for each observation of the dependent variable, T1. The same technique is used to represent the construction time, T2. Having performed these regressions

Table 3

CAPITAL COST DATA FOR LWR POWER PLANTS, BILLIONS OF DOLLARS

DOE NO.	NAME	DATE NSSS ORDERED	DATE OF COM OPER	FERC COSTS YR OF COM OP	FERC COSTS YR AFTER COM OP	COSTS, $1978 ALL STEAM ADJ	COSTS, $1978 NUC PLANT ADJ
24	PILGRIM 1	8/65	12/72	231.54	239.33	514.27	489.29
27	TURKEY PT 3	11/65	12/72	108.71	(4)	231.94	220.67
29	PALISADES	1/66	12/71	NR	146.69	322.56	306.88
34	BROWN'S FERRY 1	6/66	8/74	NR	276.18(1)	543.57	516.10
35	BROWN'S FERRY 2	6/66	3/75	256.33	276.18(1)	531.82	504.42
36	OCONEE 1	7/66	7/73	155.61	(4)	318.24	302.62
37	OCONEE 2	7/66	9/74	160.42	160.42(1,3)	313.86	297.93
39	PEACH BOTTOM 2	8/66	7/74	371.08	376.99(1)	740.12	702.71
40	PEACH BOTTOM 3	8/66	12/74	371.08	376.99(1)	728.64	691.26
41	SALEM	8/66	6/77	850.32	(5)	1486.57	1411.35
42	VERMONT YANKEE	8/66	11/72	172.04	184.48	385.97	367.19
43	FT. CALHOUN 1	10/66	9/73	173.87	175.80	354.27	336.79
44	SURRY 1	10/66	12/72	146.71	(4)	304.34	289.52
45	SURRY 2	10/66	5/73	250.15	(3) (4)	510.63	485.63
47	THREE MILE ISL	11/66	9/74	398.34	400.93	775.55	736.90
49	CRYSTAL RIVER 3	2/67	3/77	365.54	(5)	634.50	601.95
50	KEWAUNEE 1	2/67	6/74	202.19	203.39	393.74	373.70
51	MAINE YANKEE	2/67	12/72	NR	219.23	449.78	427.90
53	PRAIRIE IS. 1	2/67	12/73	233.23	(4)	460.20	437.23
56	ZION 1	2/67	12/73	275.99	(4)	544.57	517.39
57	ARKANSAS ONE 1	4/67	12/74	233.03	238.75	451.02	427.47
58	COOPER	4/67	7/74	246.27	269.29	516.69	490.19
60	TURKEY PT. 4	4/67	9/73	122.53	(3),(4)	242.71	230.68
61	CALVERT CLIFFS	5/67	5/75	428.75	430.67	798.72	756.29
62	CALVERT CLIFFS 2	5/67	4/77	335.32	(3) (5)	574.48	545.25
63	OCONEE 3	5/67	12/74	160.42	160.42(1,3)	302.18	286.36
65	BROWN'S FERRY 3	6/67	3/77	300.97	(3) (5)	516.03	489.62
66	PRAIRIE IS 2	6/67	12/74	172.14	176.98(3)	332.42	314.96
67	DONALD COOK 1	7/67	8/75	583.61	544.65	994.93	941.47
69	ZION 2	7/67	9/74	289.83	292.00(3)	551.98	523.24
70	RANCHO SECO 1	8/67	4/75	343.62	343.44	633.50	599.63
71	BEAVER VALLEY	9/67	10/76	NR	598.72	1036.63	982.03
75	EDWIN HATCH 1	10/67	12/75	390.39	390.39	697.99	660.12
76	ST LUCIE 1	12/67	6/76	NR	486.23	846.70	801.19
77	MILLSTONE 2	12/67	12/75	418.37	426.27	757.82	716.51
78	BRUNSWICK 1	1/68	3/77	318.44	(5)	534.14	507.08
79	BRUNSWICK 2	1/68	11/75	382.25	389.12	692.10	654.25
80	DUANE ARNOLD 1	2/68	2/75	288.82	279.93	510.80	483.11
90	TROJAN	11/68	5/76	451.98	451.98	764.86	723.35
92	JOS. FARLEY 1	5/69	12/77	727.43	(5)	1106.68	1064.06
	PLANTS IN COMMERCIAL OPERATION						
59	INDIAN POINT 3	4/67	8/76	551.(A)		975.34	923.72
74	NORTH ANNA 1	10/67	6/78	775.(A)		1231.63	1179.00
89	DAVIS BESSE 1	10/68	11/77	650.(A)		1020.90	976.83
91	JAMES FITZPATRICK	12/68	7/75	347.(A)		606.45	572.20
	PLANTS ALMOST COMPLETED						
46	DIABLO CANYON 1	11/66	(6/79)	627.5(A,1)		984.76	946.28
55	THREE MILE IS 2	2/67	(12/78)	696.(E)		1108.80	1062.65
64	SALEM 2	5/67	(5/79)	1575.(E)		3523.51	3350.34
68	DONALD COOK 2	7/67	(7/78)	623.(E)		996.35	953.44
81	SEQUOYAH 1	4/68	(10/79)	632.(E)		911.81	886.40
82	SEQUOYAH 2	4/68	(6/80)	632.(E)		879.14	859.80
87	DIABLO CANYON 2	7/68	(6/79)	627.5(A,1)		910.94	884.50
99	NORTH ANNA 2	1/70	(3/79)	467.04(E)		634.75	624.32
102	EDWIN HATCH 2	1/70	(11/78)	520.(A) (E)		721.28	706.56
104	ARKANSAS ONE 2	5/70	(2/79)	519.86(E)		696.41	680.24
112	JOS. FARLEY 2	12/70	(4/80)	652.27(E)		792.08	796.55

(1) = HALF THE COST OF TWO UNITS
(2) = ONE THIRD THE COST OF THREE UNITS
(3) = VALUE OBTAINED BY SUBTRACTION OF PREVIOUS UNITS
(4) = CANNOT ESTIMATE, DUE TO ADDITIONAL UNITS BEING REPORTED
(5) = NO DATA AVAILABLE FOR THIS YEAR
(A) = UTILITY SUPPLIED COST
(E) = ESTIMATED
NR = NOT REPORTED

Table 4

CAPITAL COST DATA PER KWE FOR LWR POWER PLANTS, 1978 DOLLARS

DOE NO.	NAME	COSTS, $1978, MILLIONS	SIZE, MWE	COST, 1978 DOLLARS PER KWE
24	PILGRIM 1	514.27	655	785
27	TURKEY PT 3	231.94	693	334
29	PALISADES	322.56	805	400
34	BROWN'S FERRY 1	543.57	1065	510
35	BROWN'S FERRY 2	531.82	1065	499
36	OCONEE 1	318.24	887	358
37	OCONEE 2	313.86	887	353
39	PEACH BOTTOM 2	740.12	1065	694
40	PEACH BOTTOM 3	728.64	1065	684
41	SALEM	1486.57	1090	1363
42	VERMONT YANKEE	385.97	514	750
43	FT. CALHOUN 1	354.27	457	775
44	SURRY 1	304.34	822	370
45	SURRY 2	510.63	822	621
47	THREE MILE ISL	775.55	819	946
49	CRYSTAL RIVER 3	634.50	825	769
50	KEWAUNEE 1	393.74	535	735
51	MAINE YANKEE	449.78	790	569
53	PRAIRIE IS. 1	460.20	530	868
56	ZION 1	544.57	1040	523
57	ARKANSAS ONE 1	451.02	850	530
58	COOPER	516.69	778	664
60	TURKEY PT. 4	242.71	693	350
61	CALVERT CLIFFS	798.72	845	945
62	CALVERT CLIFFS 2	574.48	845	679
63	OCONEE 3	302.18	887	340
65	BROWN'S FERRY 3	516.03	1065	484
66	PRAIRIE IS 2	332.42	530	627
67	DONALD COOK 1	994.93	1054	943
69	ZION 2	551.98	1040	530
70	RANCHO SECO 1	633.50	918	690
71	BEAVER VALLEY	1036.63	852	1216
75	EDWIN HATCH 1	697.99	786	888
76	ST LUCIE 1	846.70	802	1055
77	MILLSTONE 2	757.82	831	911
78	BRUNSWICK 1	534.14	821	650
79	BRUNSWICK 2	692.10	821	843
80	DUANE ARNOLD 1	510.80	538	949
90	TROJAN	764.86	1130	676
92	JOS. FARLEY 1	1106.68	829	1334
59	INDIAN POINT 3	975.34	965	1010
74	NORTH ANNA 1	1231.63	907	1357
89	DAVIS BESSE 1	1020.90	906	1126
91	JAMES FITZPATRIC	606.45	821	738
102	EDWIN HATCH 2	721.28	795	907
46	DIABLO CANYON 1	984.76	1084	908
55	THREE MILE IS 2	1108.80	906	1224
64	SALEM 2	3523.51	1115	3160
68	DONALD COOK 2	996.35	1100	906
81	SEQUOYAH 1	911.81	1148	794
82	SEQUOYAH 2	879.14	1148	766
87	DIABLO CANYON 2	910.94	1106	824
99	NORTH ANNA 2	634.75	907	700
104	ARKANSAS ONE 2	696.41	912	763
112	JOS. FARLEY 2	792.08	829	955

for T1 and T2, we then have a series of residuals, T1RSID and T2RSID, that represent the variance that is unexplained by the variables CPIS, SIZE, TOWER, BW, LOC1, and LN.

Next, in the two separate analyses, we regress the cost/kWe and the cost of each plant on these same variables, plus the variables T1RSID and T2RSID. This results in the following equations.

$$\begin{aligned}\text{cost/kWe} = &- 9225.8 + 147.4\ \text{CPIS} - 0.141\ \text{SIZE} + 35.26\ \text{TOWER} + 82.10\ \text{BW} \\ &\quad (-6.93) \quad (7.45) \quad\quad (-1.00) \quad\quad (0.71) \quad\quad (1.20) \\ &+ 226.67\ \text{LOC1} - 111.13\ \text{LN} + 10.05\ \text{T1RSID} + 2.48\ \text{T2RSID} \\ &\quad (4.09) \quad\quad (-3.89) \quad\quad (1.05) \quad\quad (1.33)\end{aligned} \tag{8}$$

$R^2 = 0.62$; S.E. = 176.35; F = 9.22; and n = 54.

$$\begin{aligned}\text{cost} = &- 8693.1 + 128.58\ \text{CPIS} + 0.635\ \text{SIZE} + 8.78\ \text{TOWER} + 72.87\ \text{BW} \\ &\quad (-7.16) \quad (7.13) \quad\quad (4.93) \quad\quad (0.19) \quad\quad (1.17) \\ &+ 208.58\ \text{LOC1} - 102.30\ \text{LN} + 11.92\ \text{T1RSID} + 2.85\ \text{T2RSID} \\ &\quad (4.13) \quad\quad (-3.93) \quad\quad (1.37) \quad\quad (1.68)\end{aligned} \tag{9}$$

$R^2 = 0.71$; S.E. = 160.77; F = 13.90; and n = 54.

From the t statistics, we tentatively confirm that the variables BW, T1RSID, and T2RSID do not have significant coefficients, as was found in the previous study. We also see that the variables SIZE and TOWER have coefficients in the cost/kWe equation that are not significant, reversing what was found in the first study. Size, of course, is strongly significant in the cost equation.

The residual plots from these two equations are shown in Figs. 7 and 8, and suggest that a logarithmic transformation of the dependent variables might provide a better fit of the data.

When this is done the result is a more uniform distribution of the residuals, as shown in Figs. 9 and 10, and also slightly higher values of R^2. The equations are as follows:

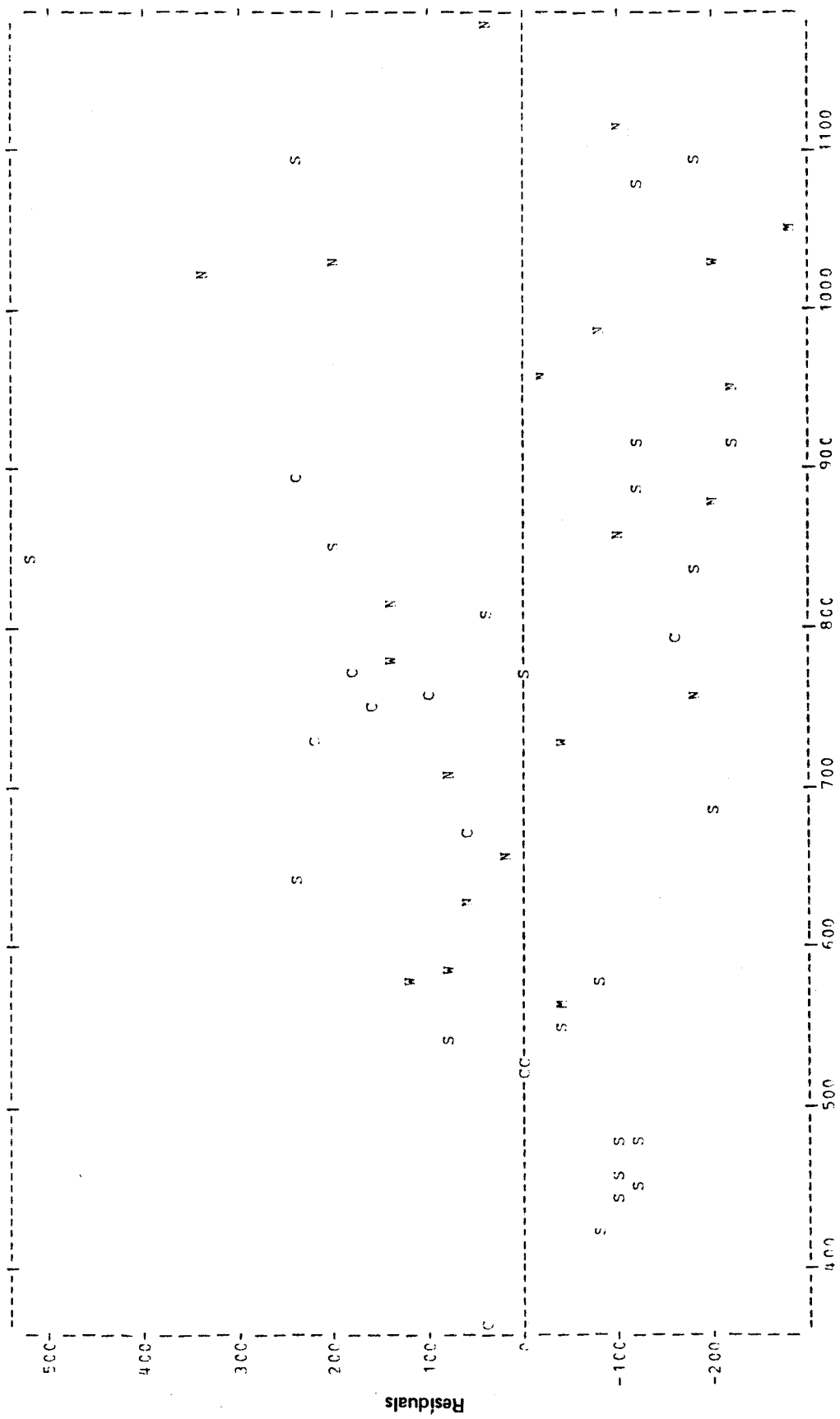


Fig. 7 — Residual plot from Equation (8)

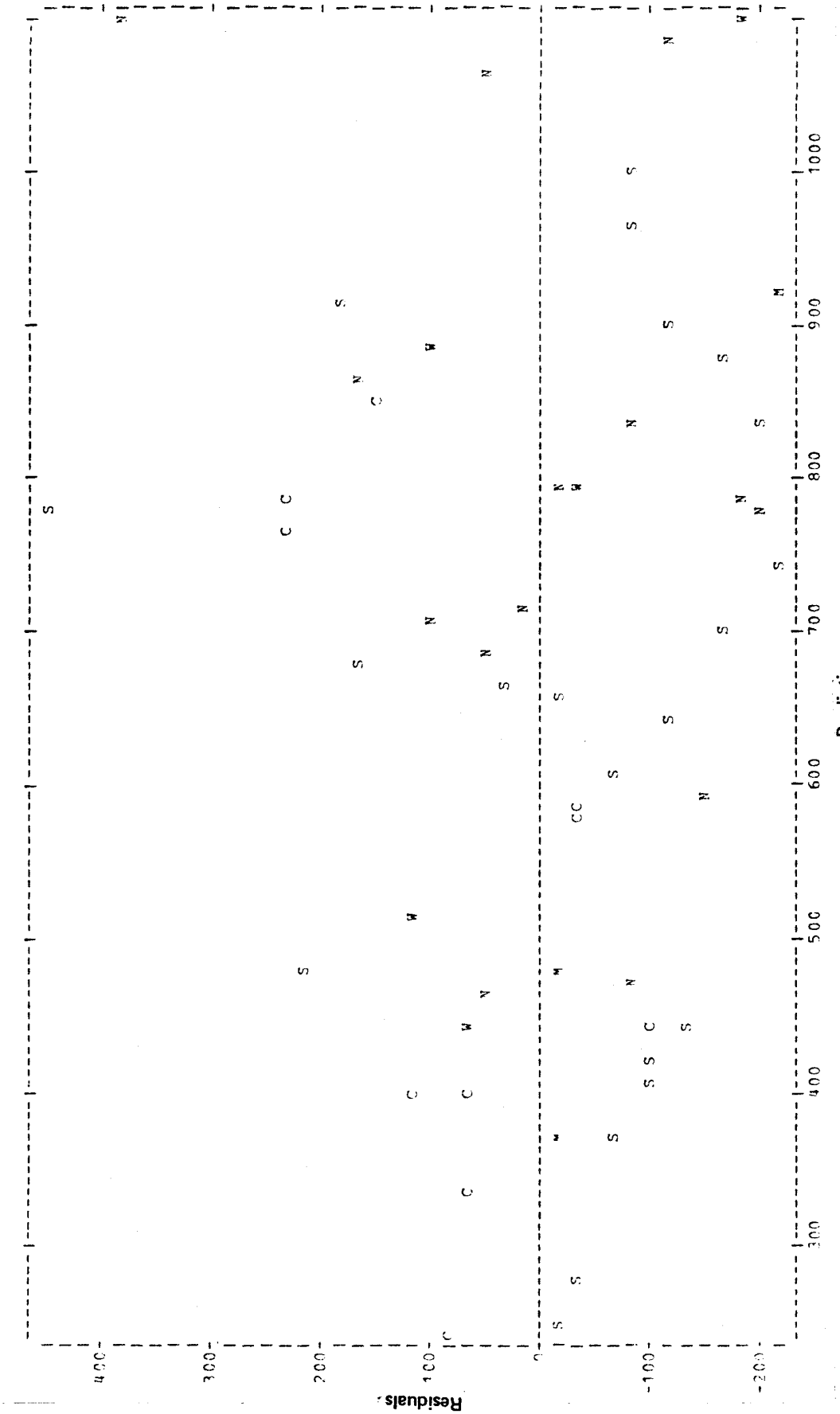


Fig. 8 — Residual plot from Equation (9)

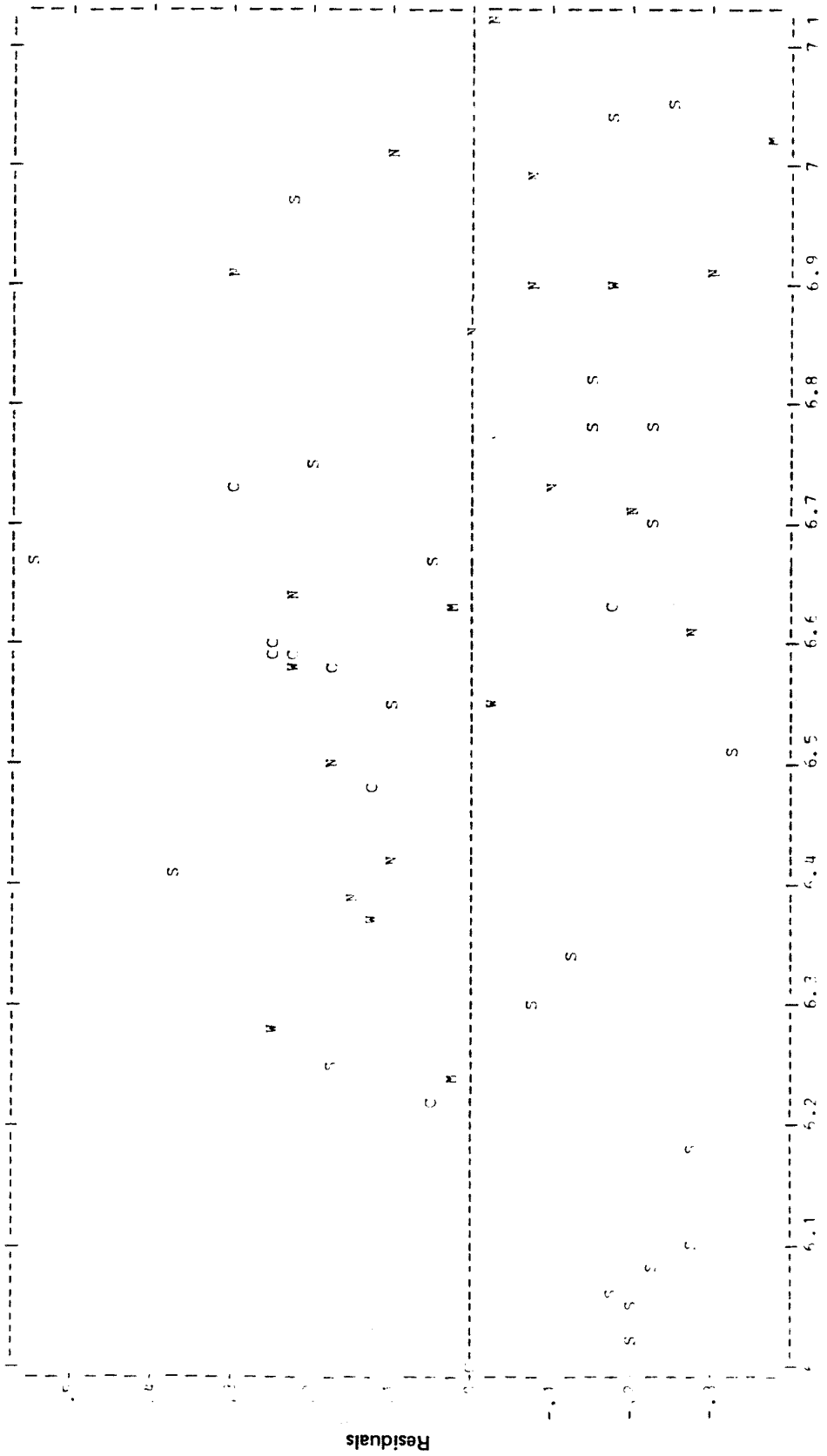


Fig. 9 — Residual plot from Equation (10)

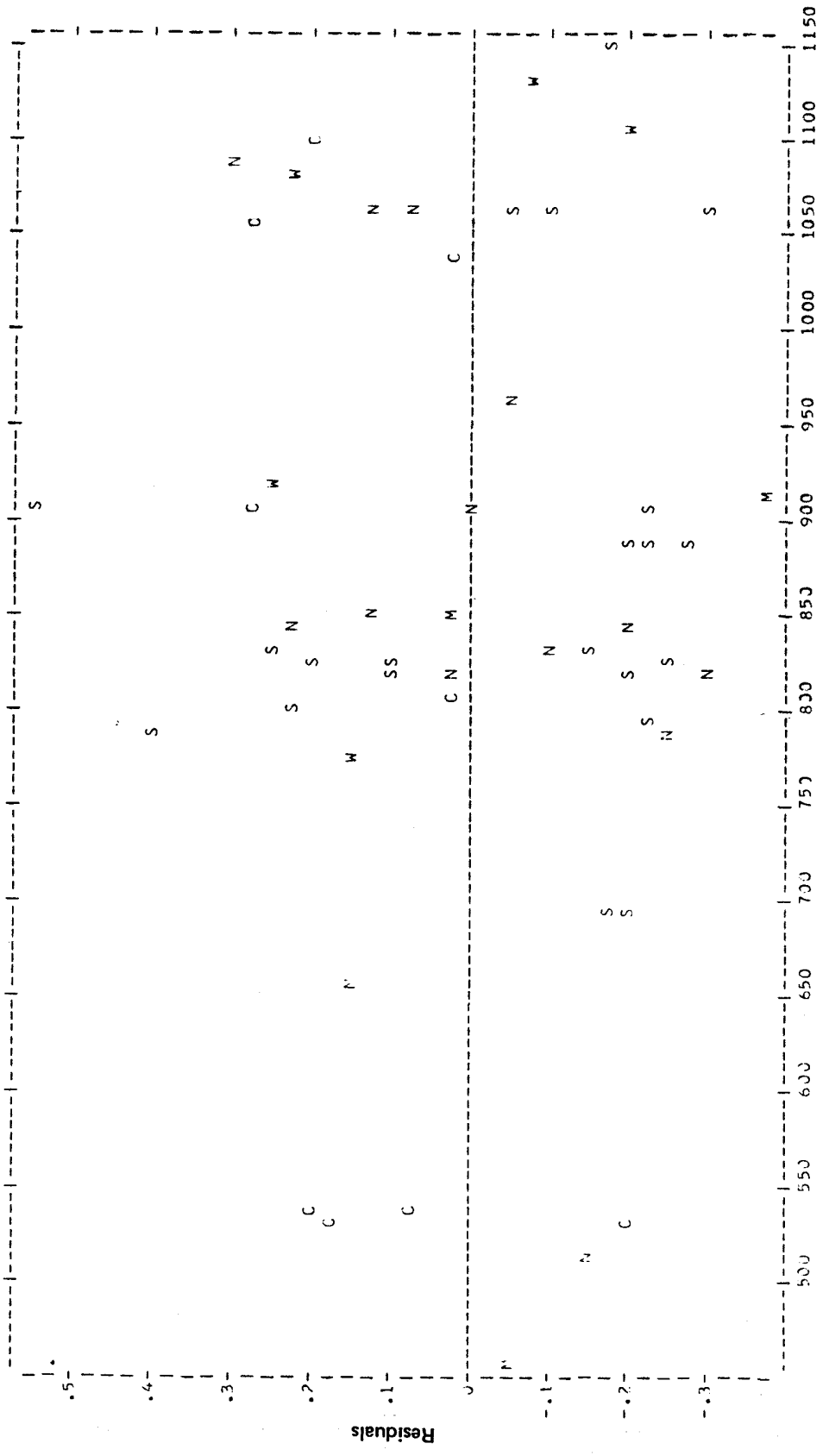


Fig. 10 — Residual plot from Equation (11)

$$\text{Log cost/kWe} = -7.9467 + \underset{(-4.62)}{0.21488}\ \text{CPIS} - \underset{(-1.26)}{2.2952(10^{-4})}\ \text{SIZE} + \underset{(1.06)}{0.068154}\ \text{TOWER} + \underset{(0.83)}{0.073946}\ \text{BW} + \underset{(4.58)}{0.3281}\ \text{LOC1} - \underset{(-4.65)}{0.17154}\ \text{LN} + \underset{(0.17)}{2.184(10^{-3})}\ \text{T1RSID} + \underset{(1.28)}{3.0768(10^{-3})}\ \text{T2RSID} \quad (10)$$

$R^2 = 0.67$; S.E. = 0.227; F = 11.78; and n = 54.

$$\text{Log cost} = -9.3275 + \underset{(8.51)}{0.21618}\ \text{CPIS} + \underset{(5.71)}{1.0371(10^{-3})}\ \text{SIZE} + \underset{(0.77)}{0.049465}\ \text{TOWER} + \underset{(1.08)}{0.094778}\ \text{BW} + \underset{(4.72)}{0.33576}\ \text{LOC1} - \underset{(-4.28)}{0.15693}\ \text{LN} + \underset{(0.15)}{1.8419(10^{-3})}\ \text{T1RSID} + \underset{(1.24)}{2.9744(10^{-3})}\ \text{T2RSID} \quad (11)$$

$R^2 = 0.77$; S.E. = 0.226; F = 18.90; and n = 54.

On the basis of these results, we next delete the variables that lack significance, and rerun the regression analyses. This results in four simple equations that are given below.

$$\text{Cost/kWe} = -8811.4 + \underset{(7.52)}{139.7}\ \text{CPIS} + \underset{(3.98)}{221.65}\ \text{LOC1} - \underset{(-3.54)}{96.22}\ \text{LN} \quad (12)$$

$R^2 = 0.57$; S.E. = 177.74; F = 22.3; and n = 54.

$$\text{Cost} = -8323.3 + \underset{(7.04)}{123.1}\ \text{CPIS} + \underset{(4.95)}{0.6506}\ \text{SIZE} + \underset{(3.96)}{203.97}\ \text{LOC1} - \underset{(-3.66)}{93.46}\ \text{LN} \quad (13)$$

$R^2 = 0.67$; S.E. = 164.57; F = 25.02; and n = 54.

$$\text{Log cost/kWe} = -7.6331 + \underset{(8.73)}{0.20759}\ \text{CPIS} + \underset{(4.55)}{0.32395}\ \text{LOC1} - \underset{(-4.42)}{0.15372}\ \text{LN} \quad (14)$$

$R^2 = 0.64$; S.E. = 0.227; F = 29.83; and n = 54.

$$\text{Log cost} = -8.9834 + 0.21116\ \text{CPIS} + 1.0610(10^{-3})\ \text{SIZE} \quad (-5.57) \quad (8.82) \quad (5.91)$$
$$+ 0.33028\ \text{LOCl} - 0.14441\ \text{LN} \quad (4.65) \quad (-4.13) \qquad (15)$$

$R^2 = 0.75$; S.E. = 0.225; F = 37.38; and n = 54.

Each of these equations suggests that the majority of the variance in the cost data may be explained by the plant size, the date the construction permit was issued, the plant location (Northeastern United States or elsewhere), and the learning curve effect. Variables that were found significant in the previous study, but not found significant with the expanded data base, are whether or not a cooling tower is used and cost economies of scale. Cost economies of scale, as found in the previous study, were noted to be of questionable statistical significance, and equations were presented both with and without a term capturing the effect of size. The additional information added to the data base since the previous study is such that the significance of the coefficient indicating cost economies of scale is degraded, as noted above, and would be of questionable significance even if the SIZE term did not appear on both sides of the regression equation. Consequently, it must be concluded that costs are similar to construction time, in that they appear to increase linearly with the size of the plant, with no sizable diminution in unit costs as the size increases.

The lack of cost significance of the term designating use of a cooling tower is puzzling, especially since the results of the previous study indicated that plants with cooling towers cost an average of $100/kWe (1978 dollars) more than those without. The cost of a cooling tower, estimated in terms of labor and materials, ought to be in the range of $15-$35/kWe. The earlier finding of $100 appears to imply that plants with cooling towers had other cost attributes of an unidentified nature, that together with the tower totalled $100/kWe. In the expanded data base, the significance of the TOWER term is extremely small. However, the coefficient of the term is

more what one would expect, i.e., about $35/kWe in the linear regressions.

The choice of a logarithmic form for the dependent cost variable was based upon an examination of the residual plots of the regression analysis. The fact that the logarithmic form produces a better fit to the data argues for its use. However, it should be recognized that there are implications in using the changed form of the equation that must not be ignored. Whereas with the linear equation the effect of changes in the continuous variables was linear, with the logarithmic equation they are exponential. Over the range of the data in this sample, both forms of the equation produce similar results, but this is due solely to the limited size of the data base. But with the linear equation, one could *imply* that capital costs increased linearly with time. With the logarithmic equation, one could *imply* that capital costs increased over time at an ever-faster rate. As mentioned, when only the data base itself is considered, the assumptions about which form is more correct have little meaning, since both forms closely describe the data. But should someone decide to extrapolate these curves, substantial differences will result. Lest the reader be tempted to believe that the underlying relationship characterizing capital costs is either linear or logarithmic (according to his preconceptions) he should reflect on the facts, which are that:

(1) The data were simply subjected to regression analysis, without any underlying theory of a model.

(2) The equation forms are determined solely by statistical fit to the data, and are designed only to describe the data base.

(3) The data base is still too meager to provide a clear picture of the curve shape.

(4) Extrapolation of the equations places squarely upon the extrapolator the onus of defending his assumption that the equation correctly represents what will happen in the future.

One variable that had been tested in the previous study that has not yet been tested with the expanded data base is the cost effect of building a plant that is a duplicate of another plant. This variable cannot be tested by using the full data base because of the way that some of the cost data have been reported. The data base contains 15 pairs of plants that are duplicates. For five of these 15 pairs, capital costs have been reported as the sum of the costs for both. The inability to apportion these costs between plants renders these data useless as a means of determining whether or not the duplicate plants have different costs. We can attempt to test the effect by deleting the five pairs of plants from the data base. Then the remaining 44 data points may be coded so that 24 points represent single plants, ten represent the first unit of a pair of duplicate plants, and ten represent the second unit of the pair of duplicate plants. In this way the costs of first and second units can be compared to single plant costs. At the same time, the effect of degrading the 54 plant data base to 44 plants may be monitored for distortions by examining the coefficients of the other independent variables and comparing them to the coefficients obtained in the earlier regressions using the full data base.

A number of regressions of the forms previously tested were run, and all have essentially the same results. Equation (16) lists the results of one of these regressions and has been selected for comparison to Eq. (8).

$$\begin{aligned} \text{Cost} = &- 10074 + 159.8\ \text{CPIS} - 0.165\ \text{SIZE} + 55.9\ \text{TOWER} + 102.2\ \text{BW} \\ &\quad (-6.60) \quad (6.97) \quad (-0.91) \quad (0.96) \quad (1.40) \\ &+ 224.6\ \text{LOC1} - 122.0\ \text{LN} + 118.1\ \text{DUP1} - 80.7\ \text{DUP2} + 18.3\ \text{T1RSID} \\ &\quad (3.60) \quad (-3.48) \quad (1.66) \quad (-1.14) \quad (1.61) \\ &+ 4.5\ \text{T2RSID} \\ &\quad (1.87) \end{aligned} \tag{16}$$

$R^2 = 0.73$; S.E. = 168.1; F = 8.98; and n = 44.

From it we can see that the removal of the ten data points has not severely distorted the data base, since the coefficients of the

variables that are common to both regressions are reasonably similar. Next we note that the t statistics for the duplicate plants lack significance, or at best are of doubtful significance at the 0.10 level, indicating that the data are such that it is difficult to perceive either the first unit of duplicate pairs, or the second unit of these pairs as different from the single plants. Last, we note that the coefficients of the DUP1 and DUP2 terms are such that they largely cancel each other. The indication from the coefficients is that the first unit of duplicate units is more expensive than a single unit and the second unit is less expensive, but when taken together these differences approximately cancel. Thus if one argues that the coefficients are significant, one must then observe that they almost cancel. As a result we conclude that there is insufficient statistical evidence to demonstrate a difference in the capital costs of plants built as duplicates when compared to single plants.

This work concludes the processing of the new data for comparison with the findings of the previous study. As we have already noted we confirm the lack of statistical significance on capital costs of the terms representing duplicate plants, Babcock-Wilcox as the NSSS manufacturer, and those portions of the variances in the construction permit time and the construction time that are not already captured by other variables in the equation. We also note that cost economies of scale, which were found to be of marginal statistical significance in the previous study, now appear to be even less significant. The data also indicate that plants with cooling towers do not cost significantly more than those without, in contrast to the findings of the earlier study. This does not mean that cooling towers can be built at no cost, but rather that the cost data are such that a statistically significant perception of the cost is not possible.

Remaining as statistically significant are the terms in Eqs. (12) through (15), specifically, the location of the plant, the degree of learning of the architect-engineer, the size of the plant, and the date the construction permit was issued. Comparison of the coefficients of the equations developed in this study with those developed in the previous study requires that the form of the equations be the same. (The previous study developed only linear equations, whereas the present

study developed both, after it was found that logarithmic forms give a slightly better distribution of the equation residuals.) Equation (12) can be used for this purpose.

Coefficient	Previous Study[a]	This study Eq. (12)
CPIS	157.95	139.70
LOC1	143.17	221.65
LN	-80.92	-96.23

[a]Table 11, Mooz (1978) adjusted to 1978 dollars by using the ratio of the Handy-Whitman power plant construction cost indices. 1976=377.8, 1978=422.2.

The comparison is taken as a rough confirmation of the temporal cost trend noted in the previous study, and the small diminution of the coefficient may be an indication that the trend is slowing. This question is to be addresed later. The increase in the LOC1 coefficient sets the Northeastern United States apart from the balance of the country in even more dramatic fashion than the previous study showed. Last, the change in the LN coefficient indicates that the cost learning curve may be steeper than previously measured, and that experience in the construction of LWR power plants has a stronger effect on cost reduction.

TEMPORAL COST INCREASES

The most significant finding of the earlier report was the identification of the powerful temporal cost increase (in real terms) that pervaded the data. In that study it was argued that if this trend did not abate, the capital costs of LWR power plants would reach levels beyond anyone's estimates. Thus a primary purpose of the present report is to attempt to identify any change in this trend that may be evident in the new data base. We have already seen that there has been no discernible change in the linear character of increases in constuction time, but we have also noted above that in Eq. (12) the coefficient of the time term was smaller than was found in the previous study.

To test the linearity of the time term, CPIS, we enter it in quadratic form as the term CPISN, which is equal to CPIS-65. This transforms the CPIS data to a sample range of CPISN from about 2 to about 8, and makes the quadratic term CPISN2, which is equal to $(CPIS-65)^2$, more manageable with a range of about 4 to 64. A regression performed with this quadratic form has a slightly higher R^2 value, which would be expected from the additional independent variable, and the $CPISN^2$ coefficient is significant and is negative, as shown in Eq. (17).

$$\begin{aligned} \text{Log cost/kWe} = {} & 5.306 + \underset{(18.79)}{0.45849}\ \text{CPISN} - \underset{(-2.09)}{0.026459}\ (\text{CPISN})^2 \\ & + \underset{(3.91)}{0.28127}\ \text{LOC1} - \underset{(-3.87)}{0.13492}\ \text{LN} \end{aligned} \qquad (17)$$

$R^2 = 0.67$; S.E. = 0.22; F - 24.97; and n = 54.

These findings are consistent with the theory that capital costs will level off after a period of increase and that the general shape of the cost curve will be an S curve. In fact, equations of the form

$$\text{Cost} = e^{(\beta_o + \beta_1\ \text{CPISN} + \beta_2\ (\text{CPIS})^2 + \beta_3\ \text{SIZE} \ \ldots \text{ etc.})}$$

are S shaped.

Before hailing this finding as the long sought sign of cost mitigation, a careful examination of the results is in order. Equation (17) is a comparable regression analysis to that of Eq. (14) with CPIS as a quadratic variable. Using these equations, capital costs are plotted at the data means in Fig. 11. It is easily seen that there is scant difference between the way that the equations describe the data except after CPIS = 1972. Here the equations diverge markedly, as they describe exactly opposite trends. A review of the equation residuals plotted against CPIS in Figs. 12 and 13 shows that the quadratic form of the equation has a slightly more uniform distribution of the post 1972

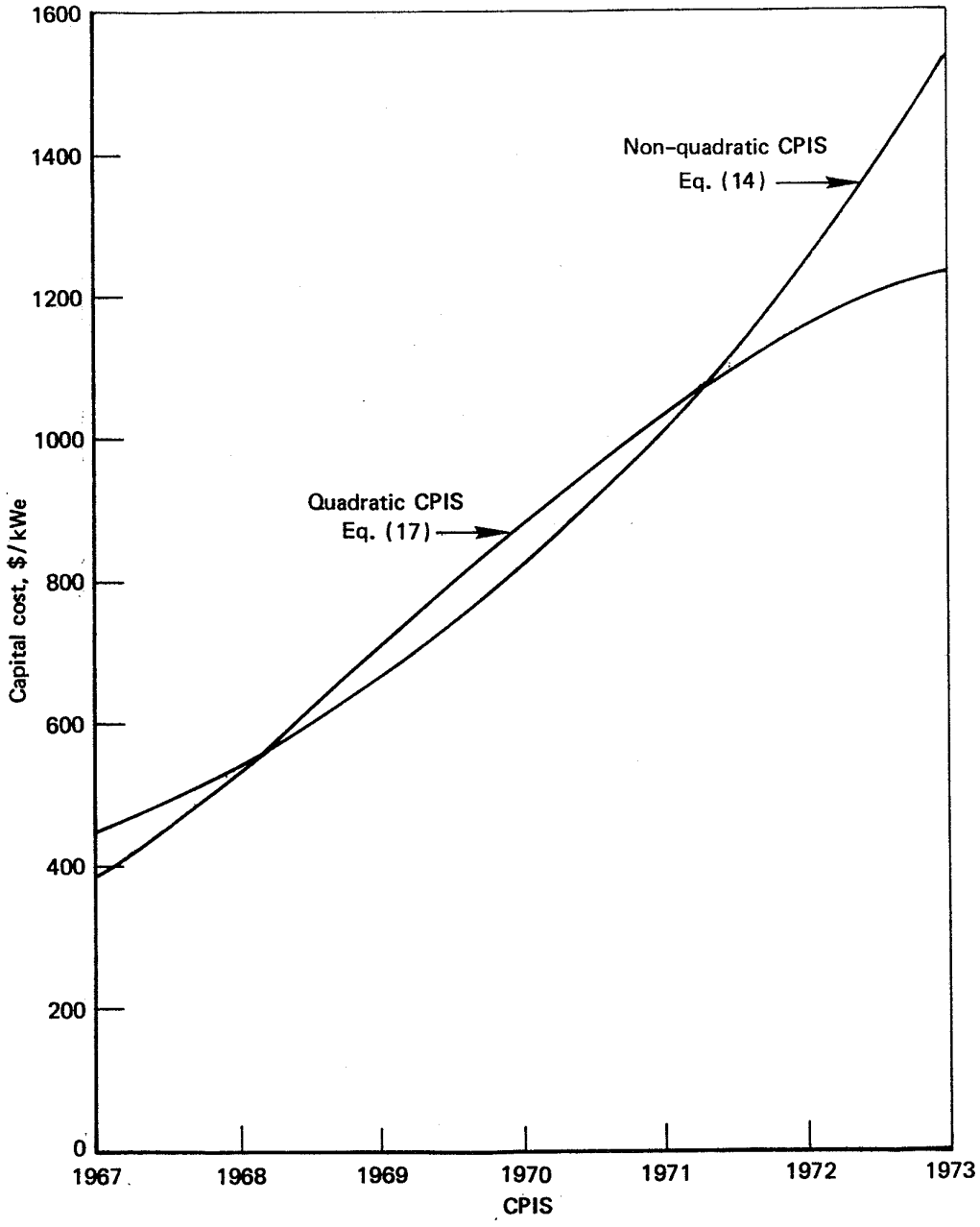


Fig. 11—Comparison of equation forms of the regression analysis plotted at the sample means

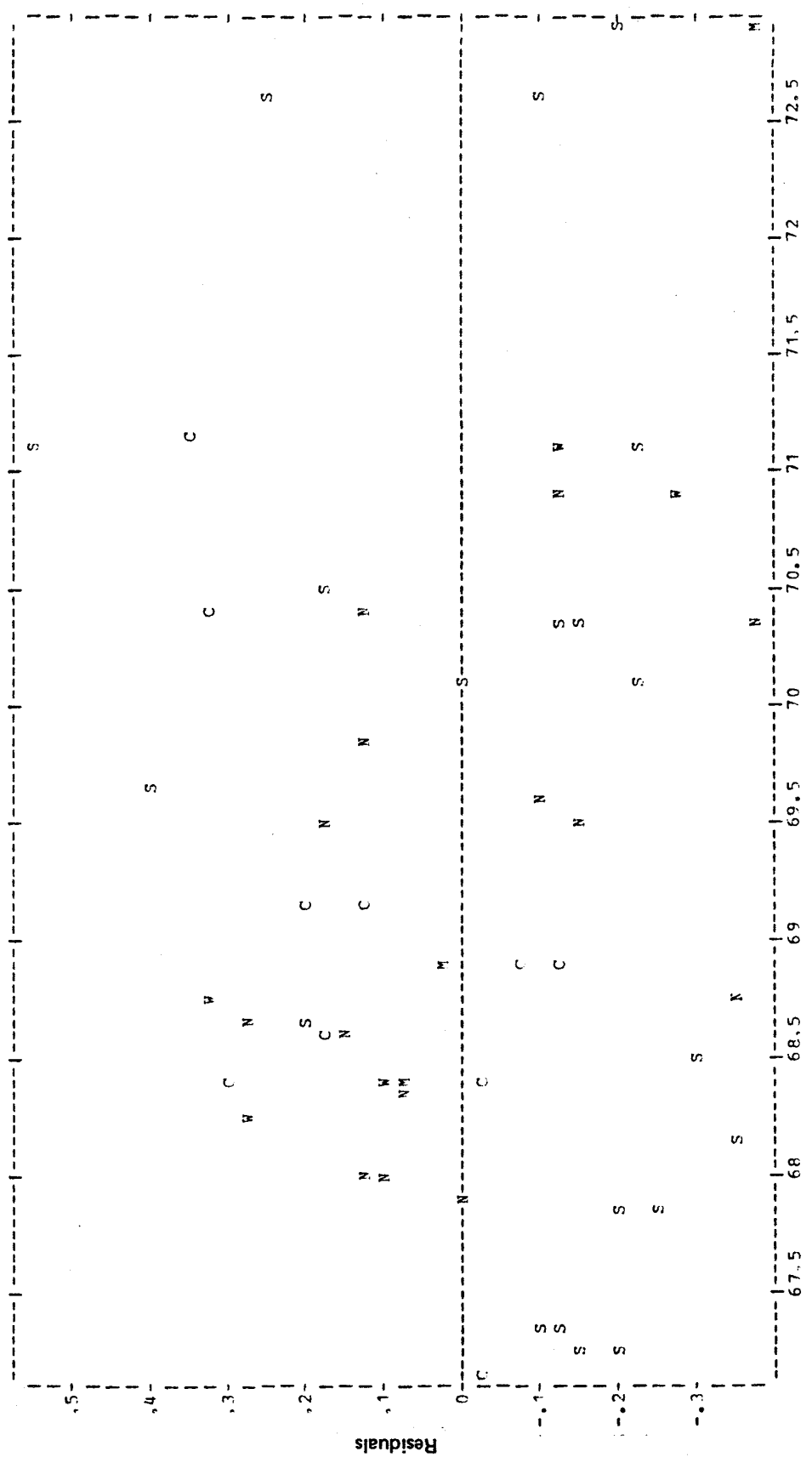


Fig. 12 — Regression equation residuals from Equation (14) plotted against CPIS

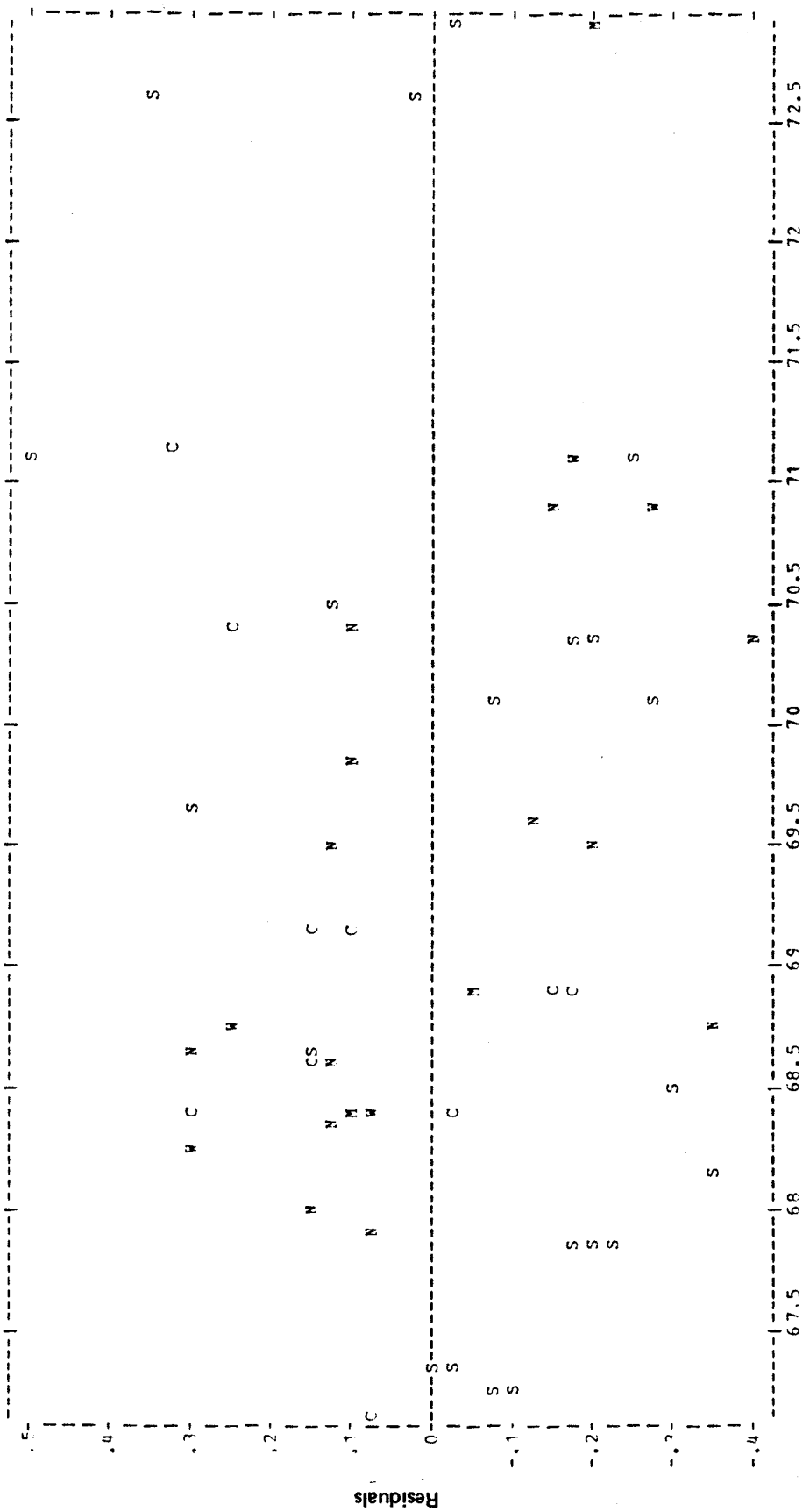


Fig. 13 — Regression equation residuals from Equation (17) plotted against CPIS

residuals, and is slightly more attractive for this reason. But it also shows that there are only four data points in the post 1972 period. These points are for Joseph Farley #1, Edwin Hatch #2, Arkansas Number one, #2, and Joseph Farley #2. Costs of the latter three plants are DOE estimates, and changes in these values may easily alter the conclusion that might otherwise be reached. Caution is the watchword, and the best that may be said is that these are tentative indications that the temporal cost curve is leveling off, but that confirmation of this must wait for the final costs to be tallied on at least the three plants in question.

IV. HOW THESE RESULTS MAY BE USED

The results of the statistical analysis may be described as a mathematical picture of past events, carefully drawn to take into account the effects of several forces operating at the time in different (and sometimes unknown) directions. They are useful in putting into perspective the various factors that affect construction time and capital costs so that more informed inferences can be made about past and future events. However, the equations should not be used to make simple predictions of the future. This would be equivalent to assuming that the future will be straightforward extrapolation of the past. Such an extrapolation is generally not very useful, except to serve as a base case against which the effects of other assumptions may be tested.

Findings of major interest are as follows:

1. Increasing the size of these power plants apparently does not result in significant economies of scale.

2. It was not possible, with the data used, to demonstrate cost economies by duplicating an existing design on the same site.

3. While there is a cost and construction time learning curve, it is fairly flat, and its effects are dwarfed by opposing temporal trends. As long as these temporal trends continue, there is little hope of reducing costs through learning curve effects. Even if the temporal trends cease, cost reductions from learning appear modest.

4. The major driving force behind increased capital costs can only be described as a temporal trend, in the absence of other quantitative measures to describe the various reasons that contribute to longer construction times and higher capital costs. As long as this temporal trend continues, the cost will increase steadily, putting ever greater economic pressure on light water reactors as a means of generating electricity.

All of these findings should be helpful to policy analysts. Scenarios describing future technologies frequently assume LWR capital costs are fixed and low, or are low and declining, as a result of an

assumed learning curve. Commonly seen costs in national and international studies frequently lie in the range of $600-$900/kWe, in 1976, 1977, or 1978 dollars, for plants that will come on line anywhere from five to 25 years in the future. The present report shows that plants coming on line in 1978-1979 averaged over $1200/kWe (1978 dollars), and every indication is that costs are still rising. Ignoring finding No. 4, above, is particularly dangerous. To not only ignore it, but to imply that cost learning will be responsible for continually lower costs, compounds this error. Use of the equations developed in this study can at least provide a defensible estimate of present costs, and perhaps a guide to future costs.

Governmental authorities should note that continued increases in capital costs may dry up the market for LWR power plants. Reasons for the temporal cost increases are unidentified. But to the extent that governmental actions or regulations of any type may contribute to the temporal increases, their possible effects on the market for LWRs must be weighed.

Utilities can profit by understanding that the evidence behind economies of scale is meager, and that the capital cost savings of buying duplicate units may be illusory.

Last, the effects of related events, such as the Three Mile Island incident, can be put into perspective. In the first part of this study we reported that construction permit application times had actually decreased slightly. It would be realistic to believe that Three Mile Island will cause these permits to be reviewed more cautiously, at least for a while. The result may be lengthened permit times. These lead automatically to later construction permits, which in turn imply longer construction times and higher capital costs. But in addition to this effect, Three Mile Island might well result in a series of tighter regulations, more control equipment, and greater quality assurance, all of which contribute to *increasing* the temporal cost coefficient. The combined result of a more cautious approach to issuing construction permits and a larger temporal cost coefficient could be sharply higher capital costs for plants now with construction permits pending.

Appendix
DATA BASE USED FOR ESTIMATING COSTS OF A LIGHT WATER REACTOR POWER PLANT

The cost analysis of light water reactor power plants that was reported in Mooz (1978) relied upon a data base that had its origins with FERC. Utilities file yearly reports with FERC that include information on the capital costs of their generating plants. These data are compiled according to a standard format, and thus there is some assurance that each reporting utility has submitted cost information that is comparable in content to every other utility. The data are in mixed current dollars, and Mooz (1978) designed and utilized a standard system for adjusting the reported values to constant dollars.

The earlier study was performed in 1977, and at that time the available data from FERC covered only 32 LWR power plants.* Of these 32 plants, only 19 had reported cost data for the first year of commercial operation. FERC personnel had cautioned that data for the second year of commercial operation were probably more accurate, since an additional year had passed during which the final accounting procedures for the capital costs could be carried out. This 32 plant data base had been augmented by the inclusion of an additional seven plants that were in commercial operation, but which had not yet reported to the FERC. Estimates of the costs of these plants were taken from DOE publications. Thus, the 39 plant cost data base included seven estimates, and 19 values that were probably subject to some small changes to improve their quality.

By late 1978, this situation had improved in several ways. Second year data were available for most of the plants in the data base, and at least first year data were available for six of the seven plants for which DOE estimates had been used. In addition, first year data were also available for two new plants not previously in commercial operation.

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*This number excluded plants that were partially or wholly subsidized by the government, and turnkey plants, for which true costs are unknown.

This resulted in FERC data for 40 plants. For six other plants,* estimates of capital cost were available from the utility owners. These plants are in commercial operation, and the owner-reported costs should be close to what is reported to the FERC next year. Finally, DOE estimates for nine additional plants are used, to form a data base consisting of 55 plants.

The raw cost data for the 55 plants have been converted to constant 1978 dollars by using the system reported in Mooz (1978). The results were given in Table 3.

Several important caveats accompany these data. As was explained in the earlier report, the FERC reporting system is by plant sites, and the utilities provide information about the total capital investment on the site. For sites that have single plants, the data are clear. For sites containing more than one plant, values for the capital investment on all plants after the first one must be obtained by subtraction. There are uncertainties in this process, since the earlier plants may have had some capital additions in the same year the later plants were added. When this is the case, the cost of the later plant is overstated. Occasionally the reported costs are stated to be the total costs for two or three plants. One cannot know whether they all cost the same, but must assume so. This assumption becomes further distorted by the process of converting the mixed current dollar costs to constant dollars. Because each of the multiple plants almost always has a different date for the beginning and end of construction, the conversion algorithm produces constant dollar costs that appear different, with the later cost being the lower. Since one cannot tell from the data whether the two plants had any differences in costs at all, it is incorrect to draw conclusions from the possible illusion that the later plants always appear to cost less than the earlier ones. This anomaly prevents certain kinds of analysis, such as whether duplicate plants are actually less costly than single plants.

The cost data of Table 3 were also presented in Table 4 in terms of 1978 dollars per kilowatt of installed capacity, where the capacity

*Including the seventh of the seven plants for which DOE estimates had been used.

has been taken from DOE/ET - 0030/7(78). The complete data base used in the study appears in Table 5.

Table 5

COMPLETE DATA BASE

	NO	CPAP	CPIS	OLIS	T1	T2	T3	SIZE	OLLLLL TQQQCQ HCCCCC 112345		COST	TGWCBB OE EW W E R	ND U E 2
1.	2467.	4268.	5872.	42	14	46	6	655	1		M 514.27	1	114
2.	2766.	1767.	2572.	50	13	63	5	693	1		S 231.98	1	1 8
3.	2966.	4267.	1771.	17	9	48	9	805	1		C 322.56	1	1 1 7
4.	3466.	5067.	3373.	42	10	73	141	065	1		S 543.57	11	1
5.	3566.	5067.	3374.	42	10	85	910	651	1		S 531.82	11	11
6.	3666.	8367.	8373.	08	12	63	5	887	1		S 318.24		1111
7.	3766.	8367.	8373.	75	12	71	11	8871	1		S 313.86		11111
8.	3967.	0868.	0073.	58	11	67	111	065	1		M 740.12	11	112
9.	4067.	0868.	0074.	50	11	78	510	651	1		M 728.64	11	1121
10.	4166.	9268.	6776.	58	21	95	101	090	1		M1486.57	1	1
11.	4266.	8367.	9272.	17	13	51	8	514	1		M 385.97	11	3
12.	4367.	2568.	4273.	33	14	59	4	457		1	M 354.27	1	1
13.	4467.	1768.	1772.	33	12	50	7	822	1		S 304.34	1	5
14.	4567.	1768.	4273.	00	15	55	4	8221	1		S 510.63	1	51
15.	4767.	3368.	3374.	25	12	71	5	819	1		M 775.55	1	1 2
16.	4967.	5868.	6776.	92	13	99	3	825	1		S 634.50	1	3
17.	5067.	5868.	5873.	92	12	64	6	535	1		C 393.74	1	3
18.	5167.	6768.	7572.	67	13	47	3	790	1		M 449.78	1	6
19.	5367.	1768.	4273.	58	15	62	4	530	1		C 460.20	1 1	2
20.	5667.	5068.	9273.	25	17	52	31	040	1		C 544.57	1	7
21.	5767.	8368.	9274.	33	13	65	7	850	1		M 451.02		1116
22.	5867.	5068.	4274.	00	11	67	6	778	1		M 516.69	1	3
23.	6066.	1767.	2573.	25	13	72	5	6931	1		S 242.71	1	1 81
24.	6168.	0069.	5074.	50	18	60	10	845	1		M 798.72	1	117
25.	6268.	0069.	5076.	58	18	85	8	8451	1		M 574.48	1	1171
26.	6367.	2567.	8374.	50	7	80	5	887	1		S 302.18		1111
27.	6567.	5068.	5076.	50	12	96	81	065	1		S 516.03	11	2
28.	6667.	1768.	4274.	75	15	76	2	5301	1		C 332.42	1 1	21
29.	6767.	9269.	1774.	75	15	67	101	054	1		C 994.93	1	1
30.	6967.	5868.	9273.	83	16	59	1010	401	1		C 551.98	1	81
31.	7067.	8368.	7574.	58	11	70	8	918		1	M 633.50	1	1115
32.	7169.	0070.	4276.	00	17	67	9	852	1		M1036.63	1 1	8
33.	7568.	3369.	6774.	58	16	59	16	786	1		S 697.99	11	118
34.	7669.	0070.	5076.	17	18	68	3	802	1		S 846.70	1	4
35.	7769.	0870.	9275.	67	22	57	3	8311	1		M 757.82	1	120
36.	7868.	5070.	0876.	67	19	79	6	8211	1		S 534.14	1	41
37.	7968.	5070.	0874.	92	19	58	11	821	1		S 692.10	1	3
38.	8068.	8370.	4274.	08	19	44	11	538	1		C 510.80	11	119
39.	9069.	4271.	0875.	83	20	57	11	130		1	M 764.86	1 1	121
40.	9269.	7572.	5877.	42	34	58	6	829	1		S1106.68	1 1	123
41.	5967.	2569.	5875.	92	28	76	8	965	1		M 975.34	1	2
42.	7469.	1771.	0878.	25	23	86	2	907	1		S1231.63	1	19
43.	8969.	5071.	1777.	25	20	73	7	906	1		C1020.90	1	1122
44.	9168.	9270.	3374.	75	17	53	9	821	1		M 606.45	1	7
45.	10270.	5072.	9278.	42	29	66		7951	1		S 721.28	11	1261
46.	4667.	0068.	25		15	128		1084		1	M 984.76	1	1
47.	8768.	4270.	92		30	83		11061		1	M 910.94	1	21
48.	6867.	9269.	1777.	92	15	105	711	001	1		C 996.35	1	21
49.	10470.	6772.	92		27	66		9121		1	M 696.41	1	1 124
50.	5568.	2569.	8378.	08	19	99		9061	1		M1108.8	1	1 4
51.	8168.	7570.	33		19	104		1148	1		S 911.81	1 1	3
52.	9969.	1771.	08		23	91		9071	1		S 634.75	1	101
53.	8268.	7570.	33		19	92		11481	1		S 879.14	1 1	31
54.	11270.	4272.	58		26	86		8291	1		S 792.08	1 1	1231
55.	6467.	7568.	67		11	123		11151	1		M3523.51	1	21
56.	2165.	2566.	0069.	92	9	47	8	7941		1	C 192.39	1	3
57.	2365.	8366.	2569.	67	5	41	10	490	1		M 192.00	1	1
58.	2565.	8366.	3370.	75	6	53	5	660	1		M 220.73	1	1
59.	2665.	9266.	7571.	75	10	60	22	8731	1		M 439.90	1	1
60.	2866.	0866.	7571.	00	8	51	9	7941		1	C 229.43	1	41
61.	3066.	5067.	2570.	58	9	40	7	700	1		S 184.59	1	2

Table 5--continued

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Table 5--continued

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