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The Effects of Learning by Doing on Nuclear Plant Operating Reliability

Paul L. Joskow and George A. Rozanski*

The importance of "learning by doing" in repetitive production processes is well documented in the literature.[1] All of these studies have focused on the increase in labor productivity in producing particular products that is associated with increases in cumulative output. For example, Searle's study of the wartime shipbuilding program found that labor requirements per ship declined roughly in proportion to the number of ships produced and that the most substantial savings took place during the early years of the program. Along similar lines Alchian estimated "progress curves" in the production of airframes and also found that labor productivity increased with cumulative output, although he did not find evidence of diminishing returns. Finally, Hirsch examined the labor requirements of a machine tool manufacturer and estimated progress functions for seven different machines which were either new products or new models of old products. He too found that labor requirements declined as cumulative output of the new products increased.

Progress functions clearly incorporate a number of types of learning associated with a new production process. Among these are reduced labor

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* MIT and Harvard University respectively. This research was supported by a grant from the Ford Foundation.

[1] See Alchian, Hirsch, Searle and Goody, and Sheshinski. Also see Arrow.

requirements as tasks become routinized through repetition; the effects of learning by management leading to more efficient production and labor scheduling and improved production control; learning by the engineering department of a firm, which redesigns the capital equipment utilized by workers and makes changes in the operation of the plant to improve routing and handling of material; the effects of increased efficiency of suppliers, who themselves experience the kinds of learning mentioned above and are able to provide a speedier and more reliable flow of supplies.

In this paper we propose to examine two aspects of learning by doing by examining the output produced by a sample of U.S. and foreign nuclear plants over time. First, we examine how cumulative plant experience allows a firm to utilize a particular piece of equipment more efficiently; in the case of nuclear power plants how the annual output from a particular piece of equipment increases as experience is gained with it. For a complicated piece of equipment like a nuclear power plant this type of learning includes the identification and correction of particular technical "bugs" as well as increasing ability of workers to use and maintain the equipment more effectively. Second, we examine how the suppliers of nuclear power plants learn to produce plants which require shorter "break-in" or learning periods once introduced as cumulative experience in building plants and learning about problems experienced by purchasers of early plants increases.

The studies by Searle, Alchian and Hirsch related the amount of <u>labor</u> needed to produce a unit of output to the cumulative number of units produced over time. This study is analogous in that the plant capacity factor, and as a result the input of capital to the production of a unit of electricity, is related to the amount of experience that designers, builders, and operators have had with a given plant and technology.[2] Technical progress due to learning by doing increases the utilization of a given plant investment and reduces the capital/output ratio in production. Unlike previous studies, our sample allows us to examine learning by doing across different production technologies and across countries.

Production of Electricity from Nuclear Power Plants

Nuclear power plants are built to have a specified maximum power capacity. For example, a plant may be designed to produce 800 Mw of electric power at any instant in time. If such a plant could run continuously for an entire year, it could produce 7,008,000 megawatt-hours of electricity. Given a specified dollar investment in plant of particular capacity, the more it can be run during the year, that is, the higher its "load factor" or "capacity factor," the lower is the average cost of power produced.

When the first commercial reactors were built, industry suppliers

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[2] Since nuclear power plants are designed to operate as "base load" plants, differences in capacity factors across plants due to "load following" is not a problem. Plant operators generally want to utilize nuclear plants as much as possible since their variable costs are substantially less than those of fossil fueled plants which

and the operating utilities anticipated annual capacity factors of .80.[3/] While many plants operating in the United States consistently achieve capacity factors near this figure, the average capacity factor of commercial nuclear power stations in the United States for the twelve month period ending in November, 1976, was .57. Furthermore, the newer units, which tend to be substantially larger than the older units, have experienced capacity factors of .5 and less. In the same twelve month period considered above, plants of less than 600MW in size had an average capacity factor of .70, whereas plants larger than 600MW had an average capacity factor of .54.

If nuclear power plants must be shut down frequently or operated at less than full capacity, the cost of the electricity they produce will be much higher than has generally been anticipated. However, it has been argued that the aggregate data are misleading for a number of reasons: (1) the industry is moving up a learning curve so that, as the designers, builders, and operators of the plants acquire more experience, overall performance will improve and (2) the apparent effects of reactor size on reliability arise due to the fact that the largest plants are also the newest plants and, once each individual plant passes through a break-in period, its capacity factor will improve.

A Federal Energy Administration study published in 1975 identified a number of factors as contributing to the generally poor operating

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[3/] The annual capacity factor of a plant is defined as the energy generated (in watt-hours) divided by the rated power output of the plant (in watts) times the number of hours in the year (8,760 except in leap years).

performance of nuclear power plants.[4] First, institutional factors, such as the fragmentation of the electric utility industry, mean that most utilities are small and so do not possess engineering and technical capabilities which would allow them meaningful participation in the design, construction, and testing of generating units. They are therefore forced to rely on a small number of firms and suppliers, which typically experience high rates of personnel turnover, and so do not recognize a responsibility for plant performance after plants go on-line.

Second, design and engineering factors contribute to poor operating reliability. These include the escalation of unit size before the industry has had a chance to assimilate its experience with smaller units, a lack of design maturity, the long lead time associated with building new plants and hence the long delay before any feedback experience, the tendency to design plants which have features specific to individual sites and consequent lack of standardization within the industry, and the failure to design plants which are easily maintainable.

Third, once plants have been built, performance suffers due to the lack of preparation and experience of maintenance crews and plant operators. A survey made in 1972 indicated that plant equipment failures were responsible for 96 percent of all forced outages (during a forced outage,

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[4] See Federal Energy Administration, A Report on Improving the Productivity of Electric Power Plants (1975).

a plant is completely shut down). Only four percent were directly attributable to operator errors. However, operator and constructor errors such as faulty maintenance or improper assembly of components often leads to equipment failure.

A study of power plant performance by Komanoff[5] gives further insight into the reasons for the low capacity factors of nuclear plants. Komanoff studied a sample of reactors having an average capacity factor of 59.3. The "lost" capacity factor he assigned to four categories. Of the total, 44 percent was attributable to scheduled outages, 43 percent was due to equipment failures causing partial or total reduction in power output, ten percent was due to regulatory inspections, and one percent resulted from load-following and the time to come to full power following any sort of a shutdown.

Scheduled outages, which are necessary to maintain, refuel, test and repair equipment, are seen to account for a substantial portion of the total. Scheduled outages cannot be entirely eliminated, yet the time they require could be significantly reduced. In addition to the possibility of designing plants which are easier to maintain, operating crews can be expected to learn to perform maintenance tasks more quickly and efficiently over time. For example, nuclear reactors need to be refueled at intervals of twelve to eighteen months, depending upon the level at which the plant has been operating. The average time now required for refueling is ten to twelve weeks, yet the industry anticipates that this time can be reduced to between four and six weeks. Komanoff reports that:

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[5] Komanoff (1976).

> Due to increased plant operator proficiency and a decrease in inspection and maintenance requirements as plants are "broken in," nuclear engineers generally anticipate duration of refueling outage to diminish as plants mature. This expectation is reflected in GE's estimate that BWR [boiling water reactor] refueling will drop from eight to ten weeks for the first two refuelings to five to seven weeks for subsequent refuelings. Westinghouse had also asserted that a refueling "learning curve" (reduced outage durations) has been shown by individual plants. The data presented, however, is scarce beyond the second refueling.[6]

Of the 43 percent of the lost capacity factor caused by equipment failure, 26 percent was due to failure causing complete shutdowns of the plants, and 17 percent was due to fuel failures and equipment failures causing only partial outages. Of the 26 percent leading to complete shutdowns, roughly half of the complete shutdowns were caused by 70 major failures requiring 500 or more hours of down time. The remainder were caused by thousands of smaller incidents. The incidence of equipment failure is widely dispersed over the thousands upon thousands of power plant components, both small and large.

There are several ways in which learning by doing could operate to improve plant performance. Generally speaking, the possibilities for learning by doing occur among plant designers and engineers in the construction of new plants and among plant operators and engineers in the operation and maintenance of an already existing plant. In this study, learning by doing on the part of plant designers and engineers is

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[6] Ibid., p. 42.

studied through its effects on the quality of the plants supplied, that is, whether the new plants which they produce are more reliable. On the other hand, learning by doing on the part of plant operators is studied through its effects on the quantity of the product outputted from a particular plant as more experience is gained with it, that is, whether a plant of given capacity can be made to produce more units of electricity in a given year.

The Model

The general form of the "progress functions" estimated is:

(1) $y = A * g(x) * e^{u}$,

where y is equal to the annual plant capacity factor; A is equal to the asymptotic value of the capacity factor, which the plant would hypothetically attain, once all technical progress due to learning by doing ceased; x is an increasing measure of experience, taking on strictly positive values, and g(x) is the function which describes the operators' learning process, such that g'(x) is positive, g(0) = 0, and the limiting value of g(x) as x approaches infinity is 1. The restriction g(0) = 0 follows from the definition of the capacity factor -- if no electricity has been generated, y is necessarily 0. u is an error term assumed to have a mean of zero and variance-covariance matrix $\sigma^2 I$. Figure (1) depicts the general power plant learning process under consideration.

The general model may be expanded to account for "supplier learning" in addition to "operator learning" as well as to account for differences associated with different nuclear generating technologies and their use in different countries. To account for all of these phenomena, the basic model utilized in this analysis is given by

$$\text{(2)} \qquad y = a_o * a_1^{d_1} * \ldots * a_n^{d_n} * s^b * h(t) * g(x) * e^u$$

where $d_1, \ldots, d_n$ are dummy variables representing plant type and location in different countries, s is equal to a measure of power plant capacity, t characterizes plant vintage, and h(t) describes "producer learning."

For example, for a plant of particular size and particular vintage g(x) gives us the progress or learning function by power plant operators. As cumulative output increases we expect capacity factors to increase due to learning by doing on the part of the plant's operators. This is depicted as the function $g_1(x)$ in figure 2 which approaches an assymptote A_1. The effects of learning by doing by the designers and engineers responsible for building the plant is modeled as a shift in the assymptotic capacity factor. Other things equal, we would expect that the assymptotic capacity factor would shift upward over time, as more plants are built by manufacturers and they learn to build more reliable products. This is shown in figure 2 as a shift in the assymptote from A_1 to A_2. The effect of increasing the size of plants is also modeled as a shift in the assymptotic capacity factor, although the direction of the shift cannot

Figure 1

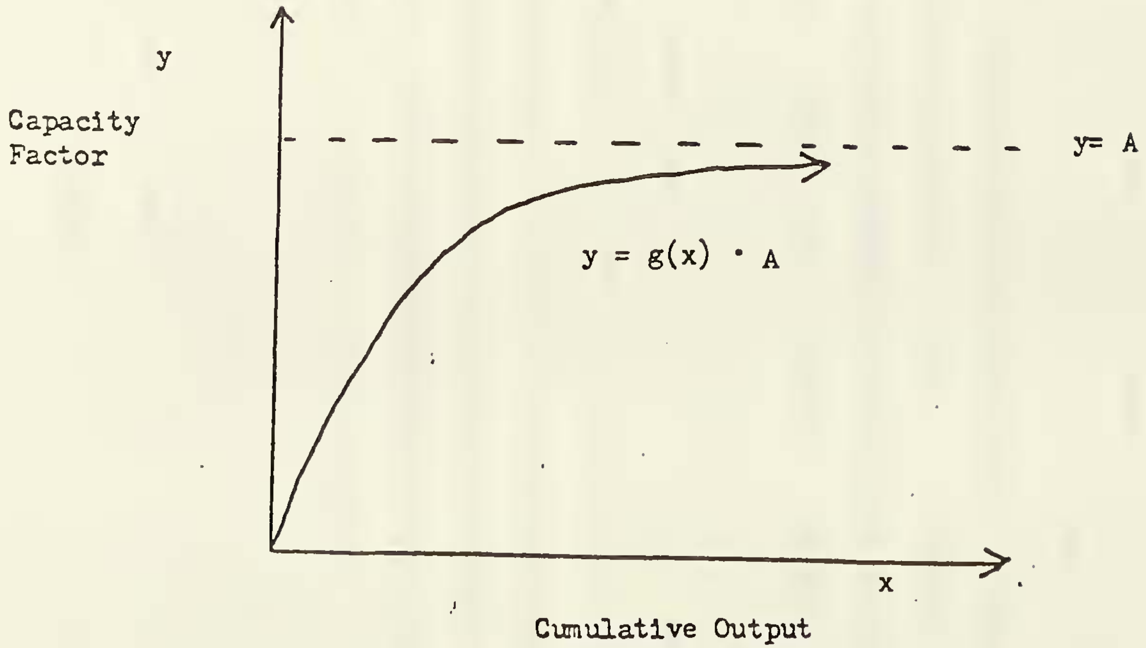
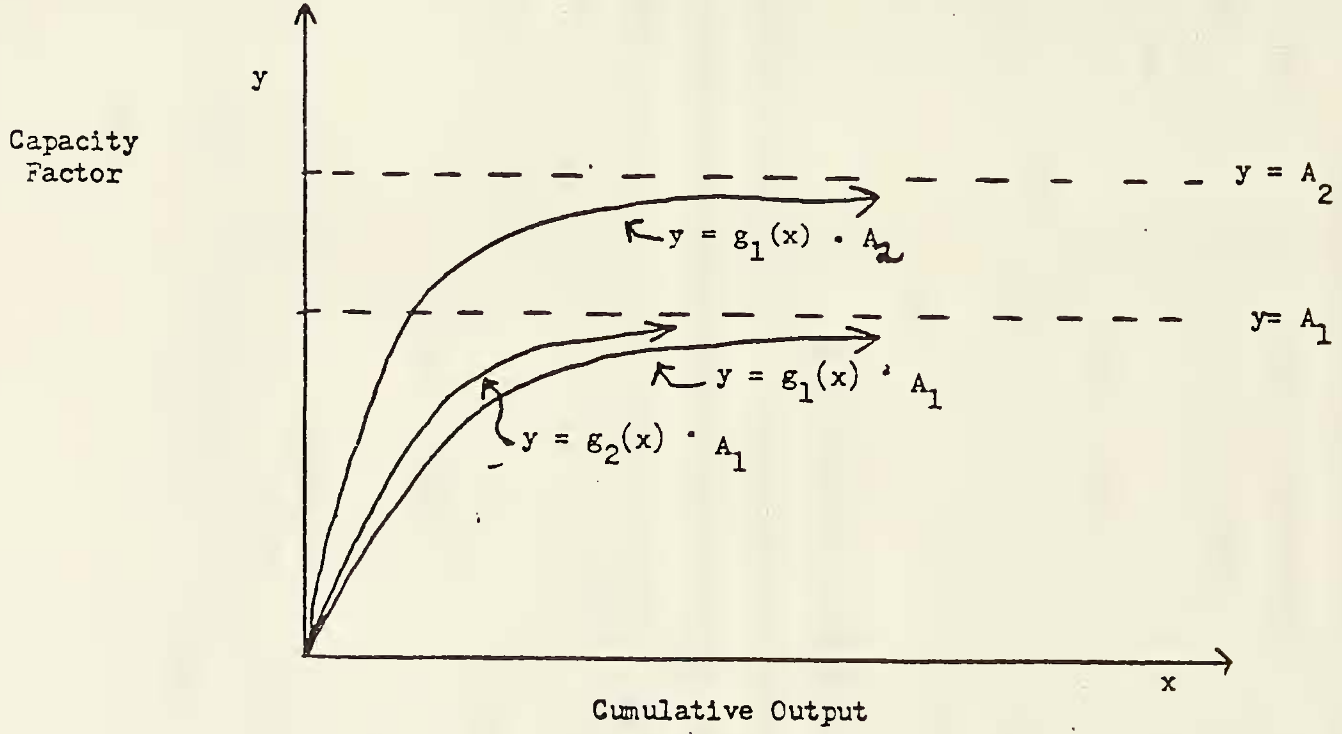


Figure 2


y
Capacity Factor
$y = A_2$
$y = g_1(x) \cdot A_2$
$y = A_1$
$y = g_1(x) \cdot A_1$
$y = g_2(x) \cdot A_1$
x
Cumulative Output

be predicted a priori.[7/]

It is also possible that different reactor types as well as different vintage plants will have operator learning curves with different speeds of adjustment. For example, learning by doing on the part of the suppliers of plants may not effect the assymptotic capacity factor, but may allow plant operators to utilize the plant to produce its maximum output more quickly. In our discussion below, we evaluate this possible learning phenomenon by allowing $g(x)$ to vary for different vintages and plant types. The learning effect is depicted as $g_2(x)$ in figure 2. Finally, we shall examine whether there are differences across countries in the progress functions estimated.

Data, Model Specification and Empirical Results

Data were obtained for a cross section of nuclear power stations operating in the U.S. and several foreign countries for each of the variables in Table 1. Only stations having a gross capacity greater than 300MW (e) were included in the sample. Most reactors smaller than this were built and operated in order to provide the industry with experience in design and development. Such reactors had special features built into them for the purpose of

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[7/] It has been suggested that the nuclear power plant suppliers built larger plants "too quickly" and that as a result they have been less reliable. However the construction of larger less reliable plants may not be a "mistake," but a conscious effort to tradeoff economies of scale in construction against operating reliability.

obtaining information, and do not fairly represent commercial designs.[8/]

Generating units require regular maintenance operations which result in their being offline several weeks each year. These outages are scheduled according to the pattern of seasonal demand fluctuations which the utility faces, and the maintenance requirements of other units in the system. For this reason, statistics based on a twelve-month period were used. Monthly data are published in several trade publications. The latest data available at the time when this work began were for November, 1976, so the sample period was taken to be December, 1975, through November, 1976. Only reactors which began commercial operation before December 1, 1975, were included in the sample.

Currently operating commercial reactors incorporate one of seven designs: pressurized water reactors (PWR), boiling water reactors (BWR), graphite-H_2O reactors (GWR), pressurized heavy water reactors (PHWR), Candu reactors (CNDU), magnox reactors (MAG), and gas-graphite reactors (GG). For reactors of greater than 300MW gross capacity which began commercial operation prior to December 1, 1975, the distribution of reactor types is:[9/]

PWR	42
BWR	31
GWR	1
PHWR	1
CNDU	4
MAG	8
GG	6

For the purposes of this study, only two reactor types were included in the sample: BWRs and PWRs. Confining the sample to BWRs and PWRs

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[8/] See Howles (1976).

[9/] *Ibid.*

Table I

List of Variables *

C	a constant term
CAPFK	plant capacity factor over the period 12-75 to 11-76
CUMOUT	lifetime cumulative output, divided by gross plant capacity
CUMIV	the inverse of lifetime cumulative output, divided by gross plant capacity
CUMIVU	equal to CUMIV for PWRs, zero otherwise
CUMIV2	equal to CUMIV for 'new' BWRs, zero otherwise
CUMIV3	equal to CUMIV for 'new' PWRs, zero otherwise
DPWR	equal to 1.0 for PWRs, zero otherwise
DUS	equal to 1.0 for plants operating in the United States, zero otherwise
GSCAP	gross plant capacity, in MW(e)
LCAPFK	the natural logarithm of CAPFK
LGSCAP	the natural logarithm of GSCAP
LGSCPU	equal to LGSCAP for PWRs, zero otherwise
VINTGE	the month during which each plant began commercial operation, with November, 1962 equal to 1
VINTGU	equal to VINTGE for PWRs, zero otherwise
X1976	cumulative output during the period 12-75 to 11-76, in mwh

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* The data sources are discussed in more detail in the Appendix.

was done in order to make possible the extensive use of analysis of covariance between reactor types.[10] In addition the BWR and PWR's technologies have diffused to a large number of countries, whereas the other technologies have been concentrated in one or two countries only.

All of the equations were estimated with g(x), the operators' learning curve, specified to be of the form g(x) = exp(k/CUMOUT) = exp (k* CUMIV). This form has the advantage that it can be easily linearized and so simplifies estimation.[11] The effects of learning by doing by suppliers -- (h)t in equation (2) -- were modeled by an exponential, exp (d* VINTGE). The basic form of the model (2), to be estimated is therefore:

$$\text{(3)} \qquad CAPFK = C * GSCAP^{b} * \exp(d * VINTGE) * \exp(k * CUMIV)$$

Equation (3) was first estimated pooling the entire sample. These OLS results appear as equation I in Table II.

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[10] During the sample period, one PWR located in Belgium experienced shutdowns due to labor problems. Eliminating this reactor left 72 observations in the sample.

[11] A set of preliminary regressions was estimated using other functional forms for g(x), on an expanded sample which included other reactor types besides BWRs and PWRs. Non-linear least squares was used. Single standard deviation confidence intervals constructed around the derived learning process adjustment multipliers based on different functional forms for g(x) were found to coincide closely. In view of this finding, and the differences and expense which attend the use of non-linear methods, it was decided to limit g(x) to be of the form specified above.

Table II

	C	DUS	DPWR	LGSCAP	LGSCPU	VINTGE	VINTGU	CUMIV	CUMIVU	CUMIV2	CUMIV3	S. E.	R^2
I	2.124** (.775)			-.4306** (.132)		.0027 (.0019)		-2459** (455)				.3214	.47
II	2.461** (.933)	.065 (.100)		-.4958** (.166)		.0031 (.0020)		-2441** (457)				.3227	.47
III	2.010 (1.267)		-.424 (1.553)	-.4694** (.199)	.1239 (.254)	.0070** (.0033)	-.0041 (.0040)	-5509** (1208)	3517** (1289)			.2958	.58
IV	1.912** (.709)			-.4130** (.121)		.0040** (.0017)		-4477** (669)	2367** (616)			.2930	.57
V	1.276** (.612)			-.2858** (.105)		.0040** (.0016)		-7954** (863)	1893* (997)	3958** (851)	-232 (1327)	.2475	.70
VI	1.269** (.606)			-.2855** (.104)		.0040** (.0015)		-7966** (854)	1745** (529)	3879** (717)		.2457	.70

Numbers in parentheses are the standard errors of each coefficient

* Two-tailed t-test indicates significance at a 10% level.

** Two-tailed t-test indicates significance at a 5% level.

All coefficients in I are of the expected sign and all, except for the coefficient on VINTGE, are statistically significant. In addition, the high value for R^2 is surprisingly good for cross sectional data.

The effects of learning by doing by operators of plants, measured by the coefficient on CUMIV, are both significant and substantial. The values computed for g(x) in line I of Table III indicate that the learning process continues for a long time. — Regression equation I implies that even after two full calendar years of operation, a nuclear plant will be operating at less than 80 percent of its eventual capacity factor. As expected, learning by doing is observed to be subject to sharply diminished returns. Figure 3 is a graph of the learning curve estimated by regression equation I, showing the fraction of its potential performance level that a plant will achieve as a function of cumulative output.

The effects of learning by the suppliers of nuclear power plants on the assymptotic capacity factor is given by the coefficient of VINTGE. It has the correct sign in the pooled regression (I), but is not quite significant at the ten percent level. The estimated value does indicate that an additional year of design and construction experience increases the assymptotic capacity factor by about three percentage points or about five percent of the mean capacity factor for the sample. Given the log-linear form of the regression, the coefficient on LGSCAP conveniently turns out to be an estimate of the elasticity of the annual capacity factor with respect to plant size. The effect of increasing unit

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TABLE III

LEARNING CURVE ADJUSTMENT MULTIPLIERS: Actual Output/Assymptotic Output

	Cumulative Output	.25	.50	1.00	1.50	2.00	3.00
	Calender Years	.41	.82	1.64	2.46	3.28	4.92
I:*	Pooled Sample	.33	.57	.76	.83	.87	.91
II:**	Ave. PWR	.38	.62	.79	.85	.89	.92
	Ave. BWR	.13	.36	.60	.71	.78	.85
III:***	Ave. PWR	.06	.24	.49	.62	.70	.79
	Ave. BWR	.03	.16	.40	.55	.64	.74
	New BWR	.16	.39	.63	.73	.79	.86

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* Calculated from Equation I in Table II.

** Calculated from equation IV in Table II.

*** Calculated from Equation VI in Table II.

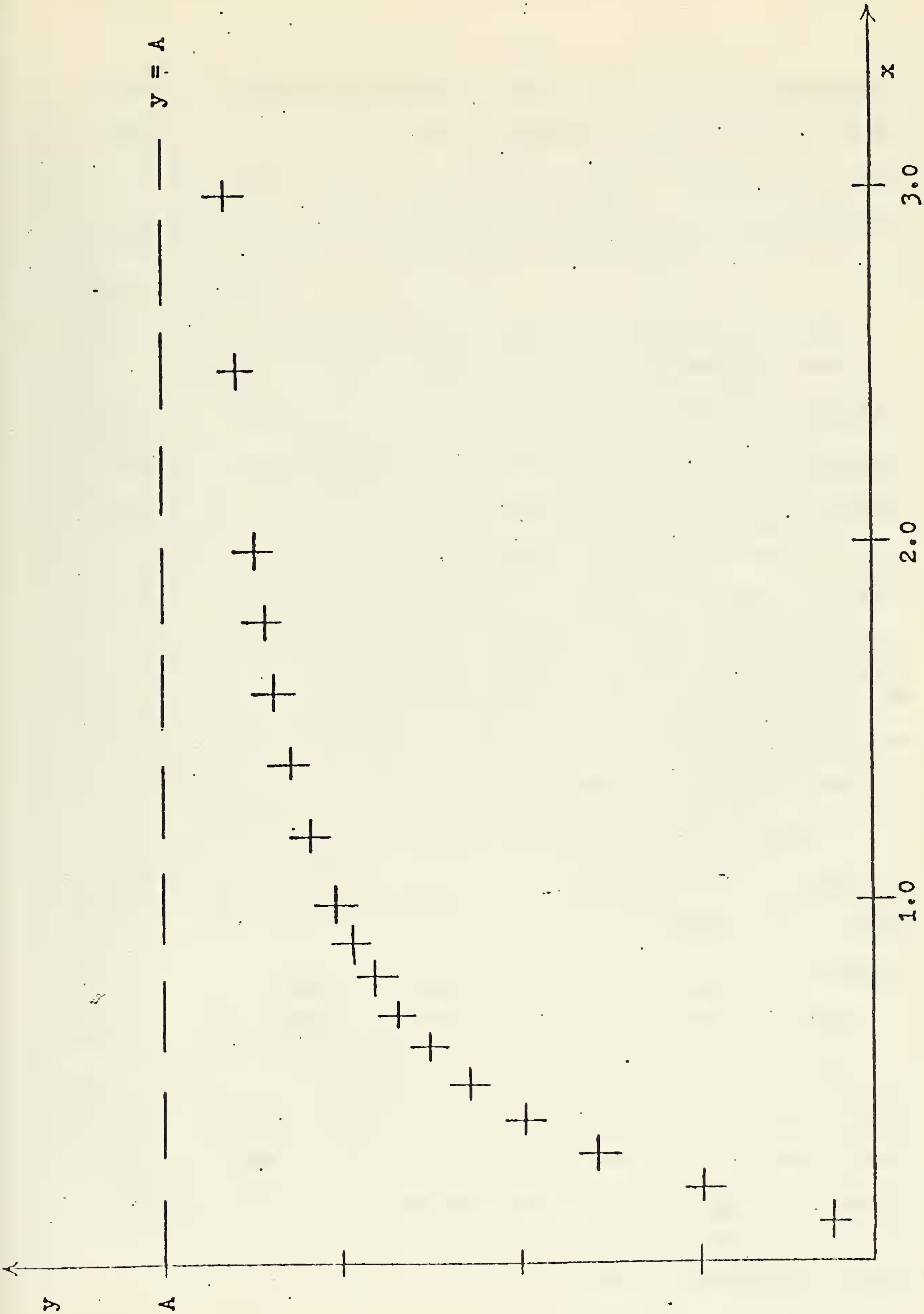

Figure 3

size is seen to be relatively large -- increasing the unit size from 600MW to 1000MW reduces the asymptotic capacity factor by .15 or more, depending on plant vintage. This is in close argreement with the results of a previous study by Komanoff,[12/] which reports an implicit elasticity for U.S. BWRs of .37, compared to the .43 found here.

We next examine whether or not there are differences in power plant performance between the U. S. and foreign countries, in terms of differences in assymptotic capacity factors and differences in operator progress functions. Both the PWR and BWR technologies were developed primarily in the U. S. and have been built abroad either under license by U. S. firms or by foreign subsidiaries of U. S. firms (except for Germany). Since U. S. designs and technical codes are used in almost all countries, we might be surprised to find higher capacity factors abroad or faster learning processes abroad. However, since regulatory requirements and quality control systems, as well as training programs for plant operators vary from country to country, it is conceivable that ultimate power plant performance would be better abroad. On the other hand, difficulties in transferring complex technology from the U. S. could result in poorer power plant performance in other countries, other things being equal.

Equation I was re-estimated after adding the dummy variable DUS. As reported in Table II as equation II, foreign reactors do not have significantly different assymptotic capacity factors. [In addition, we re-estimated equation I separately for U. S. plants and foreign plants. An F-test did not allow us to reject the hypothesis that the learning

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13/ CEP Newsletter, November 1976.

functions were identical between the U.S. and foreign countries.] These results indicate both a successful transfer of technology and that different, regulatory, quality control, and operator training programs in different countries have not affected power plant operating performance significantly.

We were next interested in determining whether the performance of PWR technology differed in any significant way from that of BWR technology. To test this hypothesis, four new variables were constructed: DPWR, LGSCPU, VINTGU, AND CUMIVU. (See Table I.) These variables differ from the variables: C, LGSCAP, VINTGE, AND CUMIV, in that they are zero for all BWRs, and equal to their counterparts for all PWRs.

A series of nested tests was used in order to determine which if any of the four variables C, LGSCAP, VINTGE, AND CUMIV have coefficients which differ significantly between the reactor types. As a first step the fully unconstrained equation III was estimated. Next, a set of four regressions was estimated, constraining each of the variables in turn to be constant across reactor types, while leaving the other three variables unconstrained. The resulting four regressions were compared to equation III, and the one which represented the smallest increase in the sum of squared residuals was selected for further examination. Dropping the variable DPWR out of equation III increased the sum of squared residuals least. We then tested whether the difference was statistically significant. When testing a multiple hypothesis, the appropriate test statistic is an F statistic. In this case, where the test is of a single linear hypothesis (DPWR = 0), a t-test is the uniformly most powerful unbiased test. The t-statistic on DPWR is approximately .3, so the hypothesis that the assymptotic capacity factor is the same for the two reactor types cannot be rejected at any reasonable level of significance.

This procedure was repeated for the other independent variables. The variables LGSCAP, CUMIV, and VINTGE were each constrained in turn to be equal across reactor types and the regressions so obtained were compared to the regression in which all three were left unconstrained to be equal for both reactor types, but C was constrained, in accord with the first test. The result was that the hypotheses that the coefficients VINTGE and LGSCAP were the same for PWRs as for BWRs could not be rejected at a reasonable level of significance.

This was not true with regard to the variable CUMIV, the coefficient of which characterizes the speed of learning by operators. Recall that the operator learning process is described by the equation $g(x) = \exp(-k/x) = \exp(-k*CUMIV)$. The relevant regression results are reported in Table II as regression equation IV. Equation IV gives a value for -k of -4477 for BWRs, and -2110 (-4477 + 2367) for PWRs. The difference is significant at the five percent level. The implication of this result is that PWRs appear to have significantly faster operator learning speeds than do BWRs with the same assymptotic capacity factor. The adjustment multipliers for BWRs and PWRs are reported for equation IV on line II of Table III. The difference is seen to be greatest during the early operation of the plants, and subsequently declines in both absolute and relative terms.

Now that we have properly accounted for differences between BWRs and PWRs, we see that the coefficient of VINTGE in equation IV is also significant at the five percent level and is larger than in regression equation I. This indicates that statistically significant improvements in assymptotic capacity factors are associated with supplier learning incorporated in the design and construction of newer plants. In addition, reduction in power plant performance associated with increasing plant size continues to be observed (LGSCAP).

Finally, we examined whether the learning curve shifted over time. It seems reasonable that as more reactors come on-line, operators become more experienced in handling the sort of problems that commonly arise during the plant break-in period. Plant operators can also draw on the accumulated experience of the industry while learning their trade. Finally, design and construction engineers supplying plants should be able to correct problems found in earlier plants during the design and construction period, reducing "break-in" problems experienced by operators.

The first step of the procedure was to search over time for a suitable breakpoint in the data series. Variables CUMIV2 and CUMIV3 were constructed. These variables are set equal to zero on some subset of the observations, ordered by time, and set equal to CUMIV and CUMIVU on the remainder. In practice, this was done considering only one of the variables at a time. Sixty two regressions were run, with the breakpoint allowed to vary from the date of commencement of commercial operation of the fifth oldest plant to that of the fifth youngest plant. That breakpoint was selected which minimized the sum of squared residuals. This criterion guarantees the strongest test of the hypothesis. After the breakpoint for each series had been selected, regression equation V was estimated, where both the variables CUMIV and CUMIVU were unconstrained across time. The breakpoint for BWRs was at VINTGE = 149, or April 1, 1975. BWRs which began commercial operation on or after this date performed significantly better, as shown on line III of Table III.

Euqation VI which allows for differences between operator learning curves for PWRs and BWRs is the final form of the model. The standard error of the regression has been reduced by almost 25 percent from that of equation I, the crudest form of the model. This implies that allowing for differences of operator learning between PWRs and BWRs, and allowing for the BWR learning curve to shift over time by adding the variables CUMIVU and CUMIV2 reduced the residual variance of equation I by approximately 50 percent. All coefficients are of the predicted sign, and all are significantly different from zero.

The results indicate that we cannot reject the hypothesis that the speed of operator learning for PWRs was constant over time. However, the hypothesis that the learning process for BWRs remained constant over time was rejected at the five percent level. Equation VI clearly indicates that the effects of learning by doing in the operation of a nuclear power plant are substantial, statistically significant and long lasting. The effects of supplier learning are significant but less important, tending to raise the assymptotic capacity factor by a factor of approximately 1.05 each year. Finally, the effect of unit size on performance is found to be negative and significant. That larger plants may perform more poorly than smaller plants may only be a transitory phenomenon that will be eliminated as additional learning, not captured by our sample, takes place. However, even if this is a steady state result, the installation of larger plants with poorer plant performance may not be irrational given what appear to be substantial economies of scale associated with the construction of nuclear power plants.

Conclusions

The results reported here provide further evidence of the importance of "learning by doing" in increasing the efficiency with which output is produced. Technical progress due to learning by doing plays an important role in determining the productivity of nuclear power plants. In particular this study leads us to the following specific conclusions regarding nuclear electric generating technology in the United States and foreign countries.

1. There is evidence of an industry learning curve, with technological improvements increasing the ultimate capacity factors of new plants at a rate of about five percent per year.

2. Larger plants do perform significantly worse than smaller plants, even after controlling for the effects of learning by doing.

3. The performance of BWRs and PWRs differs significantly only in that on average, the learning process is faster for PWRs than for BWRs.

4. The learning curve for BWRs has shifted over time, so that the learning process for new BWRs is significantly faster than that for average BWRs, new PWRs, and average PWRs.

5. There does not appear to be any significant difference in the learning curves in the U.S. and foreign countries. This result indicates that light water reactor technology, even though extremely complicated, has been readily transferred from the U.S. to other countries.

DATA APPENDIX

Data on the date of first commercial operation for each plant were obtained from Nuclear Engineering International (April Supplement, 1976). The variable VINTGE is equal to the number of months after the first commercial plant began commercial operation (November, 1962) that each of the plants in the sample itself began commercial operation. Data on plant type (BWR or PWR) were also obtained from this publication.

Data on electricity generation include the gross electricity generated by each plant during the period December 1975 to November 1976 (X1976) in megawatt-hours. These data were obtained from Nucleonics Week, December 23, 1976, and Nuclear Engineering International, February 1976 and March 1976. Gross cumulative lifetime generation was obtained from Nucleonics Week, December 23, 1976. Gross generation differs from net generation in that it includes "house-load" -- the electricity used by the power station itself. Data on net generation are not available for all plants.

Data on gross plant capacity (GSCAP) were obtained from Nuclear Engineering International, April Supplement, 1976. Gross capacity is an ambiguous concept, and is used in different places to refer to the net design output, or the nameplate capacity, or the licensed capacity (this figure is adjusted as the assessed capability of the plant is changed to reflect age or technical difficulties), or maximum dependable capacity (electrical output under the most restrictive seasonal conditions, as generator output varies during the year according to the temperature of the water used to cool the condensor), to each of what is added an amount representing the house load of the station at full capacity. In this paper we use net design output, corrected for house load as a measure of gross capacity. (GSCAP).

The dependant variable used was the plant capacity factor (CAPFK) defined as:

CAPFK = X1976/(GSCAP * 8784), where

X1976 = gross electrical generation in mwh, over the period 12-75 to 11-76
GSCAP = gross plant capacity, in MW(e)
8784 = the number of hours in the twelve month period (1976 was a leap year)

REFERENCES

1. Alchian, Armen, "Reliability of Progress Curves in Airframe Production." Econometrica. October, 1963.
2. Arrow, Kenneth J. "The Economic Implications of Learning by Doing." Review of Economic Studies. Vol. 29. 1962.
3. Council on Economic Priorities. "Power Plant Performance." CEP Newsletter. November 30, 1976.
4. Federal Energy Administration. A Report on Improving the Productivity of Electric Powerplants. Washington, D. C.: Government Printing Office, 1975.
5. Hirsch, Werner. "Manufacturing Progress Function." Review of Economics and Statistics. May, 1952.
6. Howles, L. R. "Reviewing Nuclear Power Station Achievement." Nuclear Engineering International. April/May, 1976.
7. Komanoff, Charles. Power Plant Performance: Nuclear and Coal Capacity Factors and Economics. New York and San Francisco: Council on Economic Priorities. 1976.
8. Searle, A. D. and C. S. Goody. "Productivity Increases in Selected Wartime Shipbuilding Programs." Monthly Labor Review. Vol. 61, No. 6, 1945.
9. Sheshinski, Eytan. "Tests of the 'Learning by Doing' Hypothesis." Review of Economics and Statistics. November, 1967.