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TRADE-OFFS IN SIZE, QUANTITY AND RELIABILITY OF GENERALIZED NUCLEAR POWER PLANTS: A PRELIMINARY ASSESSMENT

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SUMMARY

An approximate method is used to estimate the effects of system reliability on optimal nuclear plant size, taking into account also scale factors and manufacturing learning curve slopes. The method is used to estimate the additional effective capability gained by adding units of different sizes to an existing electrical system. The number of additional units proves to be sensitive to forced outage rate, estimated here from trends in U.S. light-water reactors from 1971 to 1980. The relative cost of added units ranging in size from 200 to 800 MW is determined as a function of the parameters: scale factor and learning curve slope.

The results generally corroborate the trends found in an earlier study in which the effect of reliability on required installed capacity was not explicitly considered. Optimal plant size decreases with weaker scale effects and stronger learning curve effects. Reliability considerations further reduce the optimal plant size, but the relative reduction is apparently not as great with steeper learning curves. This is a plausible finding inasmuch as the reduction in numbers of additional units due to reliability considerations will affect cost most where the learning curve is steepest.

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INTRODUCTION

In the 1960's and 1970's, there was rapid growth in the size of newly started nuclear power plants because of the anticipated advantages of increasing scale. Any such advantages were overwhelmed by the complications that arose with long construction times, and attention is now being given to a "second generation" of smaller plants of new design. Providing the same production capacity will require larger numbers of plants if they are smaller. Although it seems to have received little attention previously in the electric utility industry, there should be compensating economies due to "learning curve" effects in the manufacture of multiple units (Hill 1983).

In a previous paper (Hill 1984b), a preliminary assessment was made of the effect of manufacturing learning curve economies on optimal nuclear plant size modifying an earlier paper by Lucas (1979). In that analysis it was assumed that there could be a continuous trade-off in size and quantity provided that the total installed capacity remained the same. In fact, however, the use of a larger number of smaller units increases the system reliability. To put it another way, smaller units reduce the total generating capacity that must be installed to provide the same reliability, so fewer are needed.

The fact that reliability considerations favor smaller units suggests that optimal plant size would be smaller than previously estimated. On the other hand, fewer units will reduce the economies due to the learning curve; this also affects optimal plant size. On balance, it is not clear what net effect reliability considerations will have on optimal plant size.

The purpose of this paper is to take into account the additional element of system reliability in the size-quantity trade-off. An estimating formula for the effective load carrying capability of generating units added to an existing power system is used to calculate the number of additional units in the 200 to 800 MW size range to meet the same loss-of-load probability. The relative cost of providing these units, assuming a range of scale factors and

Fig. 1. Additional Effective Capability vs Additional Installed Capacity.

learning curve slopes, is then calculated. The optimal plant size -- the one that provides the same additional effective capability at least cost -- is then shown as a function of scale factor and learning curve slope. This set of optimal plant sizes is then compared to the previous results, in which reliability effects were ignored, to assess the reliability effect.

PROCEDURE

Following the example of Loose and Flaim (1980), the effective load-carrying capability of additional generating units was calculated by the method of Garver (1966). This is an approximate relationship taking into account the size and forced outage rate of the units to be added and the characteristics of the existing system:

$$c^*/m = (c/m) - \ln [(1-r) + re^{e/m}] \quad (1)$$

$$\text{estimate of } m = \sum_{i=1}^n c_i r_i \quad (2)$$

where c^* = effective load carrying capability of a unit with rating "c"

c = rating of a new generating unit in megawatts

$\ln()$ = natural logarithmic function

e = natural logarithm base

r = forced outage rate of a new generating unit (in %)

m = the megawattage of load increase that will give an annual risk increase "e" times greater than before (called the system characteristic "m")

n = total number of generating units in a system.

(Equations (1) and (2) are equations (20) and (22), respectively, of the Garver paper.)

In making these calculations, an initial value of $m = 118$, representing the existing system characteristics, is used following Garver's illustrative example. The additional effective capability as a function of the additional installed capability is shown in Figures 1(a) and 1(b) for two assumptions as to forced outage rate (discussed below) and four plant sizes: 200, 400, 600, and 800 MW. Additional effective capability is defined as the increase in the load carrying capability of the system at the same reliability (i.e., the same loss-of-load probability) as the original system, following Garver (p. 910).

Table 1 Nuclear Light-Water Reactor Operating Characteristics, 1971-1980^a

Size Category ^c	Number of Units ^d	Unit Years	Cumulative Capacity Factor	Equivalent Availability ^e	Cumulative Forced Outage Rate (Percent) ^a				
					Reactors	Turbine Generator	Unit	Equiv. F.O.R.	Scheduled Outage ^b
100-199	2	10	65.0	76.1	2.3	3.8	6.1	7.6	27.0
200-299	1	8	42.1	43.2	4.9	0.7	8.3	41.9	26.6
300-399 ^f	--	--	--	--	--	--	--	--	--
400-599	11	83	72.3	79.7	2.9	2.8	6.8	8.0	13.6
600-799	8	62	68.1	71.0	4.7	1.8	7.5	11.5	23.8
800-999	30	160	56.0	63.5	10.1	3.2	16.8	22.4	19.3
1000+	13	72	56.2	64.9	7.0	4.2	18.3	23.4	17.3

^aThe forced outage rate represents that fraction of total time the unit was unavailable due to unanticipated equipment failure (hours of forced outage divided by the hours the unit was in service plus hours of forced outage x 100), not including scheduled maintenance time.

^bThe scheduled outage rate represents that fraction of time the unit was unavailable due to anticipated downtime for equipment repairs (hours of scheduled outage divided by hours the unit was in service plus hours of scheduled outage times 100), not including the time the unit was available for service but not used.

^cEach size category includes both pressurized and boiling water reactors in megawatts-electric installed capacity.

^dUnits are defined as the total nuclear power plant including the nuclear reactor and steam supply system, turbine generator, and entire balance of plant.

^eThe equivalent availability factor is defined as the fraction of a given operating period (one year) that a unit is available for service less the time the unit is out of service for scheduled or forced (unanticipated) outages.

^fNo units reported in this category.

Source: North American Electric Reliability Council, "National Electric Reliability Council Equipment Availability Composite Unit Summary Report," No. SR-81-42, performed for Energy Information Administration, U.S. Department of Energy (Washington, D.C., July 1982).

Source: Table 1.

Fig. 2. Equivalent Availability and Forced Outage Rates vs Plant Size.

LEARNING CURVE SLOPE							
		Increasing Learning Effect →					
		No Learning Curve	Multiple Nuclear Plants Built At One Site	Typical of Recent Energy Technologies		Traditional 80% Learning Curve	
Scale Factor (s)	Learning Curve exponent (b)	100%	95%	90%	85%	80%	
		0	-0.074	-0.152	-0.234	-0.322	
Increasing Scale Effects ↑	Lucas' "Typical Values" Range	0.5	650	575	500	400	325
		0.6	475	400	375	300	
		0.7	375	325	235		
		0.8	300				
		0.9					
No scale effect		1.0	200 or smaller				

Table 2(a). Optimal plant size (forced outage rate increasing with size) (MW)

NOTE: For justification of the characterization of scale factors and learning curve slopes see Hill (1983).

0.5	800 or larger				500
0.6			600	400	
0.7		450	400		
0.8	400	300			
0.9			200 or smaller		
1.0					

Table 2(b). Optimal plant size (constant forced outage rate) (MW)

2. The assumptions as to forced outage rate were based on the data shown in Table 1 which is reprinted from DOE/EIA-0356/2, using data developed by the North American Electric Reliability Council. These data are plotted in Figure 2 which, except for an anomalous value for one reactor in the 200-299 MW size category, indicates an increase in forced outage rate with increasing plant size. Two linear regression relationships were calculated from the five data points; one using the equivalent forced outage rate and the other its logarithm as the independent variable. The five points were weighed equally, regardless of the number of units they represent, and they were taken at the midpoint of the size category. The results were as follows:

$$\begin{aligned} \text{F.O.R.} &= 0.0183 \text{ MW} + 2.1137 & (3) \\ (\text{correlation coefficient} &= 0.9027) \end{aligned}$$

$$\begin{aligned} \text{F.O.R.} &= e^{(0.001313 \text{ MW} + 1.6691)} & (4) \\ (\text{correlation coefficient} &= 0.9226) \end{aligned}$$

where F.O.R. = equivalent forced outage rate (in %)

MW = unit size in megawatts

The exponential relationship with a correlation coefficient of 0.9226 provides the better fit and is used in these calculations. Inasmuch as the forced outage rate of units in the 100-199 MW and 400-599 MW ranges were virtually the same, a second set of calculations was made with the assumption that the forced outage rate is constant at 8%.

3. A constant level of additional effective capability of 2000 MW was chosen to calculate the total additional installed capability, as shown in Figures 1(a) and 1(b). This gives the number of additional units in the 200 through 800 MW sizes needed to provide this additional effective capability. (Fractional numbers of units were used in the following calculations.)

4. The relative total cost of these units was then calculated with scale factor (s) and learning curve exponent (b) as parameters. (Explanations of scale and learning effects and definitions of scale factor and learning curve exponent are given in Hill (1974). See Tables 2 and 3 for typical values.) The results are shown in Tables 2(a) and 2(b) for the two assumptions as to forced outage rate.

LEARNING CURVE SLOPE

		Increasing Learning Effect →				
Scale Factor (s)		No Learning Curve	Multiple Nuclear Plants Built At One Site	Typical of Recent Energy Technologies		Traditional 80% Learning Curve
		100%	95%	90%	85%	80%
		0	-0.074	-0.152	-0.234	-0.322
Increasing Scale Effects ↑	Lucas' "Typical Values" Range	0.5	807	726	621	508
		0.6	692	595	484	345
		0.7	559	445	315	150
		0.8	403	270	---	---
		0.9	220	---	---	---
	No scale effect	1.0	---	---	---	---

Table 3(a). Optimal plant size (disregarding reliability effects) (MW).

NOTE: For justification of the characterization of scale factors and learning curve slopes, see Hill (1983).

0.5	0.80	0.79	0.80	0.79	0.89
0.6	0.69	0.67	0.77	0.87	----
0.7	0.67	0.73	0.75	----	----
0.8	0.74	----	----	----	----
0.9	----	----	----	----	----
1.0	----	----	----	----	----

Table 3(b). Ratio of optimal plant size, with and without reliability effects.

5. To evaluate the significant of reliability effects, the set of optimal plant sizes was then compared with that obtained in the previous analysis (Table 3(a)) in which reliability effects were ignored, with results as shown in Table 3(b).

RESULTS

Optimal plant size is shown in Table 2(a) for the case where forced outage rate increases with size and in Table 2(b) for the case where forced outage rate is assumed constant. Optimal plant sizes are identified by interpolation between the four sizes calculated. The systematic variation in cost with plant size is illustrated in three carpet plots (Mazzitelli 1984), Figure 3, showing the variation with learning curve slope at scale factors of 0.5, 0.6 and 0.7.

As one would expect, optimal plant sizes are smaller in the case where forced outage rate increases with size. Optimal plant size is reduced as the learning curve slope becomes steeper and as scale effects become weaker.

The results shown in Table 2 are quite sensitive to the assumption made as to the variation of the forced outage rate with plant size. Where forced outage rate increases with size, there is no case where the optimal plant size is larger than 650 MW. If the forced outage rate is assumed constant at a level of 8%, on the other hand, several combinations of flat learning curves and strong scale effects lead to a size of 800 MW or larger. In both cases, the combination of steep learning curves and weak scale effects leads to an optimal size of 200 MW or smaller, more often in the case of varying forced outage rate.

For purposes of comparison, Figure 4 and Table 3(a) show optimal plant size following from the results of the previous analysis (Hill 1984b) in which total installed capacity was invariant with size. The values shown are based on the assumptions in the paper by Lucas (1979). The variation across cases is more precise in this table because optimal size is determined from an analytical solution, whereas the results of the present paper are interpolated (where the results are within 200-800 MW range) from Figure 3.

Fig. 3. Variation in Cost with Scale Factor, Learning Curve Slope, and Plant Size.

Fig. 4. Optimal Plant Size with Reliability Effects Ignored.

Table 3(b) shows an estimate of the reduced optimal size due to the greater reliability of small units. The case where forced outage rate increases with size, shown in Table 2(a), is used for comparison. The values in Table 3(b) are obtained by dividing those in Table 2(a) by those in Table 3(a).

The optimal size, taking reliability into account, is reduced to about two-thirds to four-fifths of the size previously calculated as optimal when there is no learning curve. The steeper the learning curve, the less the reduction in optimal plant size: a plausible result inasmuch as the increase in cost from a reduction in the number of units would be greatest with the steepest learning curve. It should be emphasized that the absolute levels of these results depend in part upon the assumptions made by Lucas.

DISCUSSION

Garver's Method

These results depend entirely upon the validity of the Garver estimating equations. Garver's method is designed to provide graphical means of making preliminary estimates of the effective load carrying capability of generating units without recourse to "digital computer calculation". In an example of adding one generating plant, he finds variations of 5 or 6% in the numerical results as acceptable. He uses the method to show the effects of adding up to five additional units without, in this case, discussing the limits of approximation. As shown in Figures, 1(a) and 1(b), Garver's method is used here in adding up to 13 units.

Garver's method indicates little advantage in additional size when only one unit is added to increase the effective capability. With constant forced outage rate, the gain in effective capability is virtually the same when either a 400 MW unit or a 600 MW unit is added, as can be seen from the lower ends of the curves plotted in Figure 1(b). With forced outage rate assumed to increase with unit capacity, as shown in Figure 1(a), the increase in effective capability is virtually the same for one 400 MW unit and one 600 MW unit, and either actually leads to a greater increase in effective capability than one 800 MW unit.

Forced Outage Rate

These results are quite sensitive to the assumption made as to the variation of forced outage rate with plant size. At the 2000 MW level of additional effective capacity shown in Figure 1, for example, the required additional installed capacity of 800 MW plants goes from 3090 MW in Figure 1(a) to 3620 MW in Figure 1(b), an increase of 17%. Although the correlation coefficient of 0.9226 for the exponential relationship shown in Figure 2 is high, it is predicated on dropping one of six data points -- and that within the range of specific interest -- as anomalous. In the absence of data in the 300-399 MW size category (Table 1), the trend is strongly influenced by only two data points (representing 13 units), one for the 100-199 MW size category and one for the 400-599 MW size category. If the trend were determined by only these two points, one would be justified in assuming a constant forced outage rate with size. It is the higher rates at larger sizes, beginning with one point in the 600-799 MW range, that suggests that the forced outage rate increases with plant size. If the regression analysis were weighted by the number of units each data point represents, the trend toward greater fixed outage rate with increasing size would probably be even stronger. Individual plants, of course, may vary substantially from these generalized trends.

Learning Curve Considerations

In these calculations, it is assumed that the specified learning curve described the reduction in cost with successive units installed in this one system. This would be the case if the units were constructed or manufactured to the individual system specification. However, if standard units manufactured in larger quantities are supplied, the reduction in unit cost for this system is likely to be different from the manufacturing learning curve. How different depends upon what units are supplied to this system. If it were provided with every tenth unit built by the manufacturer, for example, the reduction in cost for this system would be greater than that indicated by the manufacturing learning curve. On the other hand, if these are units manufactured at the tail end of the manufacturing learning curve, the absolute reduction in cost with successive units will be less even though the unit costs are declining at an exponentially steady rate.

Comparative Costs

As shown in the carpet plot, Figure 3, the relative cost curves are quite flat near the minimum cost points. However, the cost variation becomes more pronounced with combinations of strong scale effects and weak learning effects or vice versa. For example, with a weak scale effect ($s = 0.9$) and a strong learning effect (80% curve), the 800 MW plants would cost 65% more than 200 MW plants of equivalent capability, assuming a constant forced outage rate, and 86% more with the varying outage rate.

It should be recognized that the costs here represent the capital cost of the units added to the system. The comparison would hold for life cycle costs only if operating costs were proportional to capital costs or negligible.

CONCLUSION

Allentuck (1977) notes that the erosion of economies of scale in electric power plants may be of three kinds: one mathematical, and two technological (p. 241). First, following strictly from the laws of probability, a system supplied with fewer units of larger size requires a greater amount of reserve capacity than does a system serving the same load with a greater number of smaller units. Second, the forced outage rate experienced in the operation of larger units increases with greater capacity, a consequence of which is decreased availability. Third, larger units require a greater amount of labor effort to restore the unit to service after either a planned or forced outage, further decreasing availability.

Garver's method deals with the first two effects. In this analysis, uncertainty in the second is treated by using two different functions for forced outage rate. Lucas makes use of empirical evidence that availability declines linearly with plant size, presumably taking into account the second and third effects.

Starting from somewhat different premises, therefore, the two methods end with results that reasonably corroborate each other. Subject to further verification, it seems reasonable to conclude that:

1. Learning curve economies reduce the optimal size of nuclear power plants from what might be estimated otherwise, as described in the earlier report (Hill, 1984b).
2. Reliability considerations further reduce this optimal size. This preliminary analysis suggests that the reduction may range up to one-third of the plant size, although this absolute comparison depends in part upon the assumptions of the Lucas paper.
3. Optimal plant size is smaller with steeper learning curves, but this trend is somewhat offset by reliability effects.

These conclusions apply to trends in size, quantity, reliability, and availability of generalized nuclear power plants from which individual plants may depart markedly. To verify these preliminary conclusions, a more detailed representation of the cost of nuclear generated electricity needs to be investigated, taking into account construction times, interest rates, and tax treatment, among other things, as previously outlined (Hill 1984a).

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