

**Standardization, Diversity, and Learning:  
A Model for the Nuclear Power Industry**

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# STANDARDIZATION, DIVERSITY, AND LEARNING: A MODEL FOR THE NUCLEAR POWER INDUSTRY

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## ABSTRACT

This paper discusses the lack of standardization, frequently mentioned as a burden borne by the U.S. nuclear industry. We present a simple model of learning and standardization. We show that when the effects of learning through diversity are strong, the present value of long-run costs can be minimized with either complete standardization or with complete experimentation where no two reactors are similar in the early stages of the industry. The conclusion discusses the relevance of these and other analytical results to the present U.S. nuclear industry regarding standardization policies.

Keywords: standards, standardization, diversity, learning, nuclear power

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## 1. STANDARDIZATION AND THE U.S. NUCLEAR POWER INDUSTRY

In many discussions of industrial progress, the slow achievement or lack of standardization has played a prominent role in the alleged causes of success or failure. This is the case in the U.S. nuclear power industry. Many difficulties facing this industry are attributed to a failure to standardize at the right moment in the development of this technology. Proponents of commercial nuclear power were optimistic during the 1960s. Several reactor prototypes were completed through the U.S. Atomic Energy Commission's (AEC) Power Demonstration Reactor Program under contracts awarded between 1956 and 1965. To encourage reactor orders, turnkey and partial turnkey contracts were negotiated in 1965 (5 units), 1966 (9 units), and 1967 (3 units). These involved two types of light water reactors, Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs). They built by four Nuclear Steam Supply System (NSSS) manufacturers: Westinghouse-PWR (7 units), General Electric-BWR (6 units), Babcock & Wilcox-PWR (3 units), and Combustion Engineering-PWR (1 unit). The first two large (above 200 Megawatt-electric, MWe) nuclear power plants entered commercial service on January 1, 1968: Haddam Neck in Connecticut and San Onofre 1 in California. The AEC foresaw the completion of many hundreds of commercial reactors by the end of the 20th century.

Yet, as reactors were completed and operation began, the electric utilities' honeymoon with nuclear power turned sour. First, the time to complete construction doubled from under 60 months in 1968 to more than 120 months by 1980. Second, the

real cost per kilowatt of capacity tripled from \$400 to \$1200 (1980 dollars). Third, productivity was far lower than expected, averaging 63% of potential output between 1976 and 1985 (see Rothwell 1990).

Nuclear power's proponents blamed construction and operation problems on two related causes: regulation and the lack of standardization. Reactor promotion and regulation were the responsibility of the AEC until 1974. In the mid-1970s reactor promotion, primarily through research and development support, was assigned to the U.S. Department of Energy (DOE). Reactor regulation was assigned to the U.S. Nuclear Regulatory Commission (NRC). The NRC was forced to regulate a fast-changing industry. The number of findings related to reactor problems issued by the NRC's Inspection and Enforcement branch increased from less than 50 in 1976 to more than 850 in 1985. One problem was the diversity of nuclear power plants.

In the U.S. there have been four major reactor vendors, 16 architect-engineers, 20 general contractors, and over 50 nuclear-electric utilities. Because of the large number of responsible parties and changing reactor regulations, each plant is, in some purely technical sense, unique. If there are benefits to standardization, are there drawbacks? What determines the best balance between gains and losses? Is it possible that the critics could be wrong? Could a low degree of standardization throughout the initial phase of a technology's commercial application be the economically most efficient strategy for society to pursue?

## 2. LEARNING AND STANDARDIZATION

Much of the literature addressing the economic benefits of nuclear power plant standardization has addressed four problems: construction costs, operator training, safety, and operating reliability (see, e.g., Thomas, 1989). In each of these areas, there are strong grounds for believing that less diversity would be beneficial.

The evidence regarding construction costs is compelling (see Rothwell, 1986). Costs of design preparation and construction licensing are fixed. Amortizing these over many identical plants naturally reduces these average capital charges per plant. Further, construction lead times are important in determining the fixed capital charge, because the amount of finance capital tied up in these long gestation-period projects is substantial. Strictly speaking, these are arguments for scale in plant production, i.e., for building many plants of a single type, rather than for standardizing all plants in the industry. But, if only a few plants are to be built, it is equivalent in practice.

The points regarding operator training and safety are different. Of course, there are fixed costs in designing a training program with simulation routines for each plant type. These can be lower per trainee if there are more operators training for each plant type. The main issue is interchangeability of operators and supervisory personnel across plants. Standardization enlarges the pool of potential operators that might staff new plants or compensate for unanticipated turnover at existing plants. Experience-based training might be as important as, or more important than, initial training for certification in reducing the probability of operator error. Responses to crises are harder to plan when the range of experience is narrow. The pooling of operator

experience, more feasible with similar plants, would help in preparation for safety problems. Also, distributing experienced operators throughout the industry would likely raise the quality of crew response.

Beyond these generally acknowledged considerations, lies a further range of learning effects to which standardization can be expected to contribute. During plant operation, there will be breakdowns, which, when their cause is diagnosed and remedied, provide opportunities to enhance the performance of other plants of the same kind. Contractors who undertake retrofitting could do these tasks more cheaply and more quickly if they could acquire more experience and spread their costs over a larger or longer run of jobs. Since downtime for refueling and maintenance is a major source of reduced plant availability, the opportunity to optimize the sequence of refuel and maintenance activities will be greater if the plant is not unique. Most plants subcontract some maintenance tasks, bringing many workers into the plant for this purpose while refueling is in progress. The same arguments made for the benefits of uniformity through reduction of retrofitting costs, therefore, can be made for the costs of specialized maintenance contractors.

The opportunity to derive economic benefits from learning, whether from one's own experience or from the experience of others, argues for greater uniformity in the production facility. Standardization, like other forms of "experimental control," makes it easier to identify empirical irregularities that point to underlying structural conditions deserving further investigation. Therefore, it promotes the learning process directly and widens the sphere of application for what has been learned.

However, we must observe that there is one respect in which standardization is learning's enemy. The point is obvious when one considers evolutionary adaptive processes as a mode of learning. Selection, whether natural, or in designed experiments, can only work when there is diversity. Operating nuclear power stations based on diverse engineering solutions to the same set of fundamental problems presents an opportunity to discover what will perform best under actual field conditions. After a period of experimentation, during which information can be collected, it is desirable to choose the most efficient design (assuming the conditions prevailing during the experimental phase are expected to persist) and standardize practice on that one. (On the value of diversity, see Weitzman 1992).

Indeed, there is a large body of theoretical work on the problem of how to play "multiple-arm bandits" that shows the optimality of the general form of strategy just described: gather information sequentially about the performance of the various (stochastic) processes, but eventually pick one of them. See Cowan (1987). For two- or n-armed slot machines, the standard analysis treats each "arm" as characterized by a stationary (albeit unknown) probability distribution over the payoffs. Experimentation is therefore non-intrusive in the sense that trying the alternative arms will in no way alter the underlying odds of hitting the jackpot on any of them. But non-intrusive experimentation is not a condition that is likely to be satisfied when operating variant designs for durable industrial facilities.

Even if information acquisition is a valuable by-product of running nuclear power plants, the utility's goal is to keep them running (consistent with safety) and make

feasible improvements to enhance performance. So the experimentation stage does not make controlled experiments possible: plants that can be successfully operated under field conditions are likely to be one's about which more is learned. This positive feedback makes it more likely that these plant designs will be favored as a basis for future modifications, optimization of maintenance procedures, and operator training programs. In this fashion, design types favored by early circumstances that were possibly adventitious could emerge as the ones on which individual practice should become standardized. Cowan (1990) has argued that such a process led to the emergence of light water reactors as the dominant technology for NSSS, despite the initial technical advantages offered by gas-graphite and heavy-water reactor designs.

Therefore, although standardization might ease the improvement of technical performance in an industry through learning processes, incremental learning creates positive feedback that can lead to defacto standardization. Also, the designs selected by decentralized sequential choice need not be globally optimal either from the view point of present operating performance or their susceptibility to future improvement. Consequently, it is important to avoid endowing standardization with normative content, because it cannot be presupposed to be "a good thing" ipso-facto. It is only an instrumentality that in some circumstances promotes the acquisition and diffusion of technical knowledge.

### 3. THE STANDARDIZATION-DIVERSITY TRADE OFF: A MODEL

To specify the ideas put forward in the previous section, we consider a highly stylized model of the way standardization decisions could affect the structure of cost during the evolution of a complex technical system operated by a central authority. We will simplify the problem by positing a three-stage evolution: In Stage I, a set of plants is built; the decision is whether to standardize on one or a few designs, or experiment by building many designs. In Stage II, these plants are operated and undergo incremental improvements at rates that are positively influenced by the degree of standardization achieved in Stage I, so that their operating costs are reduced. For example, Stage II corresponds to the period from 1974 to the present in the U.S. In Stage III, the original complement of plants is replaced with an equal number of new ones that can be built to take advantage of what was learned during Stages I and II.

We will suppose, following the discussion in Section 2, that standardization abets some forms of learning, while diversity promotes others. Is there an optimal degree of standardization for a central manager to adopt at the outset (before the start of Stage I) that would balance the opposing effects on the present value of expected production costs in the industry? We can find the answer to this by formally representing the expected costs of each Stage as they appear *ex ante* from the perspective of Stage I.

#### 3.1. Stage I: Construction

The central manager's goal is to build  $N$  plants of types  $j = 1, \dots, m, \dots, M$ . For simplicity we assume symmetry: there are to be  $n$  plants of each type, i.e.,  $n_j = n$ .

Therefore, we can write  $N = n \cdot m$ . Of course, this presupposes  $M \geq N$ , i.e., there are enough variants to build the entire complement of plants on a one-of-a kind basis. (Of course, the symmetry assumption is a restrictive, special case that we address in our conclusions.)

Next, we assume that construction costs are identical for the first plant of each type:  $k_{0j} = k_0$ . There is learning in construction activity. Because we assume all plants are built instantaneously at the end of Stage I, where the duration of Stage I is  $\tau_1$ , learning is equivalent to economies of scale in the number of plants of a given type:

$$k_j(n) = k_0 n^{-\gamma}, \quad 0 < \gamma \leq 1, \quad (1)$$

where  $\gamma$  is a measure of learning. The total cost of each group of plants is  $n \cdot k_j = n (k_0 \cdot n^{-\gamma}) = k_0 \cdot n^{1-\gamma}$ . The total cost of building all  $N$  plants is

$$K(N|m) = m (k_0 n^{1-\gamma}) = m k_0 \left(\frac{N}{m}\right)^{1-\gamma} = N k_0 \left(\frac{m}{N}\right)^{\gamma}. \quad (2)$$

Therefore, total cost is an increasing function of  $m/N$ , a measure of relative diversity.

### 3.2. Stage II: Operations and Incremental Learning

Stage II costs are composed of two parts: a fixed charge and a variable charge. Because Stage II begins with all plants complete and all plants are depreciated by the end of Stage II, we assign the construction cost of all plants to the beginning of Stage II. The fixed charge per plant is  $k_0 (m/N)^{\gamma}$ . The variable charge reflects the initial variable cost (with full capacity utilization) minus the realized cost savings. We abstract from the dynamics of the learning process, assuming instead that cost savings

are realized instantaneously at the beginning of Stage II. This abstraction depends on the assumption of full capacity utilization. To simplify, we assume that initial variable cost,  $C_{0j}$ , are equal to  $C_0$  for all  $j$ . All plants start with the same initial cost. All differences arise only from differential learning-by-using.

Because of incremental adaptations in design, retrofitting, and operating procedures, operation results in learning opportunities that generate a distribution of attainable cost savings. We are interested in only the largest of these cost savings. If cost savings,  $v_j$  for plants of type  $j$ , are distributed with mean  $\mu_j$  and variance  $\sigma_j^2$ , the expected *maximum* cost improvement for a single plant of type  $j$  is the mean of the cost-savings distribution:  $E(v_j^{\max} \mid n_j = 1)$ .

But suppose by replicating the number of plants of type  $j$  that the size of the sample drawn from the distribution  $V_j(\mu_j, \sigma_j^2)$  is increased to  $n_j > 1$ . How will  $E(v_j^{\max})$  be affected? Here, we make use of a general result on extreme value distributions: When such samples are drawn from unimodal distributions, the expected extreme value is a positive function of the mean and the standard deviation. Also, it is a positive concave function of the sample size. The effect of increasing sample size interacts positively with the standard deviation of the underlying distribution. Allowing for one or more plants of each type, the behavior of the expected maximum improvement from experienced-based learning for type  $j$  can be described by

$$E(v_j^{\max} \mid n) = \mu_j + B \sigma_j (\log n)^\beta, \quad 0 < \beta < 1, \quad \text{for } n \geq 1. \quad (3)$$

See Gumbel (1958). See David (1974) for other applications of this parameterization and its relationship to the extreme value distribution of normal variates.

In the following, we assume that  $\sigma_j = \sigma$  for all  $j$  and that  $\mu_j$  has a  $\Lambda(\bar{\mu}, \theta)$  distribution. The mean across plant types of expected cost improvements for any given plant type is  $\bar{\mu}$  and its variance is  $\theta$ . (The first of these assumptions will be relaxed subsequently.) The expected total cost improvement for each group of  $n$  plants is

$$g(n) = n \mu_j + B \sigma n (\log n)^\beta. \quad (4)$$

The expected cost improvement for  $N$  plants for  $m$  types is

$$G(N|n) = N [\bar{\mu} + B \sigma (\log n)^\beta]. \quad (5)$$

Because we have assumed that  $n_j = n$  and  $\sigma_j = \sigma$ , expected improvements in variable cost are identical. It is the distribution of  $\mu_j$  that is responsible for differences in variable costs developing during Stage II. Therefore, the variable cost per period is  $N [C_0 - \bar{\mu} - B \sigma (\log \frac{N}{m})^\beta]$ , where Stage II has a duration of  $\tau_2$  periods. These costs are discounted to the beginning of Stage II by  $\delta_2(i, \tau_2)$ ;  $\delta_2$  is a uniform series, present value factor that depends on the interest rate,  $i$ , and  $\tau_2$ . The expected cost in Stage II ( $EC_{II}$ ) for the  $N$  plants is

$$EC_{II} = N k_0 \left(\frac{m}{N}\right)^\gamma + \delta_2 N [C_0 - \bar{\mu} - B \sigma (\log \frac{N}{m})^\beta]. \quad (6)$$

Greater (relative) diversity ( $m/N$ ) drives up expected costs during Stage II. This can be seen from the unambiguously positive sign of the first and third terms' derivatives with respect to  $(m/N)$  in equation (6).

### 3.3. Stage III: Second Generation Plants -- Construction and Operation

In the third stage we suppose that the knowledge gained during Stages I and II can be transferred to another generation of plant constructors, who in Stage III will select one design on which to standardize. We make the following assumptions:

- (1) Cost of building a *single* one of the  $N$  replacement plants built in Stage III will be the average achieved in Stage I:  $k_{j0}^{III} = k_0 \cdot n^{-\gamma}$ , where the rate of learning is the same as in Stage I.
- (2) Opportunities to observe different plants with different  $\mu_j$ 's make it possible to select the best design, i.e., the maximal draw from the  $\Lambda(\bar{\mu}, \theta)$  distribution.
- (3) Operation of the type of plant selected for standardization in Stage II yields the same distribution of potential cost reductions, with the expected maximum improvement exceeding that available in Stage II if and only if  $m > 1$  in Stages I and II. (If complete standardization was not achieved initially, there will be additional anticipated operating gains from moving to complete standardization in Stage III.)

Corresponding to assumption (1), the construction costs for  $N$  plants of a single type built instantaneously at the beginning of Stage III will be

$$k^{III}(N | m) = N [k_0 (\frac{m}{N})^\gamma] N^{-\gamma} , \quad (7)$$

where  $N^{-\gamma}$  represents learning in replacing all Stage I plants with a single type.

Corresponding to assumption (2), the selection of the type of plant with the largest expected (single plant) cost reduction can be represented as a draw from the extreme

value distribution generated by  $\Lambda(\bar{\mu}, \theta)$ . The expected mean improvement is

$$E(\mu_j^{III} | m) = \bar{\mu} + A \theta m^\alpha, \quad 0 < \alpha < 1. \quad (8)$$

This is where diversity during Stages I and II will have its pay-off by permitting more scope for design learning, reducing operating costs during Stage III. Variable cost per period is  $N [C_0 - \bar{\mu} - A \theta m^\alpha]$ , where Stage III has a duration of  $\tau_3$  periods. These are discounted to the beginning of Stage III by the factor  $\delta_3(i, \tau_3)$ . The expected cost in Stage III ( $EC_{III}$ ) for the  $N$  plants is

$$EC_{III} = N k_0 \left(\frac{m}{N}\right)^\gamma N^{-\gamma} + \delta_3 N [C_0 - \bar{\mu} - A \theta m^\alpha]. \quad (9)$$

Stage III contains, or represents, many later stages in which further design improvements might be possible if complete standardization was not chosen in earlier stages. From an analytical viewpoint there will be some point beyond which it will be optimal to suppress diversity, as we pointed out in the discussion of the multiple-armed bandit problems in Section 2. We simplify our model by identifying that point with Stage III. We assume that the service life of first generation plants has been suitably adjusted so they do not require replacement before the point at which there is enough information to justify selecting a standard design.

#### 4. OPTIMAL DIVERSITY

What is the cost-minimizing value of  $m$ , the number of different plant types to build in Stage I? To answer this question, we introduce discount factors,  $\delta_2'(i, \tau_1)$ ,

which translates Stage II costs into Stage I present value equivalents, and  $\delta_3'(i, \tau_1 + \tau_2)$ , which translates Stage III costs into Stage I present value equivalents. Expressing all costs (see equations 6 and 9), we write the present value expected costs at the beginning of Stage I,  $C^*(N|m)$

$$\begin{aligned} &= \delta_2' N^{1-\gamma} k_0 m^\gamma + \delta_2' \delta_2 N [C_0 - \bar{\mu} - B \sigma (\log \frac{N}{m})^\beta] \\ &+ \delta_3' N^{1-2\gamma} k_0 m^\gamma + \delta_3' \delta_3 N [C_0 - \bar{\mu} - A \theta m^\alpha] . \end{aligned} \quad (10)$$

The first order condition for a minimum (or maximum) is given by  $\partial C^*/\partial m = 0$ .

The first derivative,  $\partial C^*/\partial m$  equals

$$q_1 \gamma m^{\gamma-1} + \delta_2' \delta_2 q_2 \beta (\log \frac{N}{m})^\beta m^{-1} - \delta_3' \delta_3 q_3 \alpha m^{\alpha-1} = 0 , \quad (11)$$

$$\text{where } q_1 \equiv \delta_2' N^{1-\gamma} k_0 + \delta_3' N^{1-2\gamma} k_0$$

$$q_2 \equiv N B \sigma ,$$

$$q_3 \equiv N A \theta .$$

Note that  $q_1$ ,  $q_2$ , and  $q_3$  are all positive. Next, we check the second order condition for a minimum, i.e., that  $\partial^2 C^*/\partial m^2 \equiv \Delta > 0$ . The second derivative is

$$\begin{aligned} \Delta &= -q_1 (1 - \gamma) \gamma m^{\gamma-2} \\ &- \delta_2' \delta_2 q_2 \beta m^{-2} (\log \frac{N}{m})^\beta [1 + \beta (\log \frac{N}{m})^{-1}] . \\ &+ \delta_3' \delta_3 q_3 m^{\alpha-2} (1 - \alpha) \alpha \end{aligned} \quad (12)$$

The first two terms on the right hand side are negative, but the third term is positive. Therefore, whether  $\Delta$  is greater than, equal to, or less than zero depends on where the second order partial is evaluated. To evaluate the expression for  $\Delta$  where  $\partial C/\partial m = 0$ , we find from equation (11), multiplying both sides by  $(1 - \alpha) m^{-1}$ :

$$\begin{aligned} & \delta_3' \delta_3 q_3 \alpha (1 - \alpha) m^{\alpha-2} \\ & = q_1 (1 - \alpha) \gamma m^{\gamma-2} + \delta_2' \delta_2 q_2 (1 - \alpha) \beta \left(\log \frac{N}{m}\right)^\beta m^{-2}. \end{aligned} \quad (11a)$$

Substituting this into equation (12) yields

$$\begin{aligned} \Delta & = q_1 (\gamma - \alpha) \gamma m^{\gamma-2} \\ & - \delta_2' \delta_2 q_2 \beta m^{-2} \left(\log \frac{N}{m}\right)^\beta \left[ \alpha + \beta \left(\log \frac{N}{m}\right)^{-1} \right]. \end{aligned} \quad (13)$$

There are two main cases:

Case I, where  $(\gamma - \alpha) \leq 0$ , which implies that both terms in equation (13) are negative and is thus sufficient to establish that *no interior cost-minimizing value for  $m$  exists*; and

Case II, where  $(\gamma - \alpha) > 0$ , which is necessary, but not sufficient, for the existence of an interior optimum for the value of  $m$ .

The interpretation of the results for Case I is straightforward and conforms to our intuition. Given the implications of increasing returns (where the elasticity ( $\gamma$ ) of Stage III construction costs with respect to the number of plant types,  $m$ , built in Stage I is equal to or less than the elasticity ( $\alpha$ ) of expected Stage III cost reductions with respect to  $m$ ),  $C^*(m)$  rises to an interior *maximum*. Under these conditions there are two sub-cases of interest: Case I-A in which the lowest costs are achieved at one extreme, where only one type of plant is built *from the outset* ( $m = 1$ ), and the degree of relative standardization is  $1 - (m/N) = 1 - (1/N) \rightarrow 1$ . In the other case, Case I-B, maximal diversity is superior from the viewpoint of cost minimization and  $m^* = N$ , so the degree of relative standardization is  $1 - (N/N) = 0$ .

Intuition suggests that when the benefits of learning how to operate plants more efficiently in Stage II are not very heavily discounted (when  $\delta_2'$  is not a small number)

and where the learning opportunities that depend on initial diversity are more constricted ( $\alpha$  is closer to zero than to one, but not less than  $\gamma$ , and  $\theta$  is small), Case I-A would emerge. Standardization from the outset would then be the optimal strategy.

These intuitions are readily confirmed. We can simply evaluate  $C^*(N|m)$  at the two extremes,  $m = 1$  and  $m = N$ , and examine the difference:

$$\begin{aligned} C^*(N|m = 1) - C^*(N|m = N) \\ = \delta_2' k_0 N (N^{-\gamma} - 1) - \delta_2' \delta_2 N B \sigma (\log N)^\beta \\ + \delta_3' k_0 N^{1-\gamma} (N^{-\gamma} - 1) + \delta_3' \delta_3 N A \theta (N^\alpha - 1) . \end{aligned} \quad (14)$$

Since  $N > 1$ , the first three terms of this expression are negative. Therefore, the only way for the expression to be positive (implying that the level of costs is lower under maximal diversity), is for  $A$ ,  $\theta$ ,  $\alpha$ , and  $\delta_3' \delta_3$  to be large.

Next, we examine Case II in which  $(\gamma - \alpha) > 0$  satisfies the *necessary* condition for the present value of expected costs to be strictly minimized by selecting some initial level of design diversity, i.e.,  $m > 1$ . For a strict minimum,  $(\gamma - \alpha) > 0$  is not sufficient. The second order condition must be satisfied where  $\partial C^*/\partial m = 0$ , i.e.,  $\Delta > 0$ . From equation (13), the second order condition is satisfied when

$$q_1 (\gamma - \alpha) \gamma m^\gamma = \delta_2' \delta_2 q_2 \beta \left( \log \frac{N}{m} \right)^\beta \left[ \alpha + \beta \left( \log \frac{N}{m} \right)^{-1} \right] . \quad (15)$$

Solving the first order conditions for  $m^\gamma$  from equation (11) and substituting into equation (15), the condition for a strict minimum of  $C^*$  is

$$(\gamma - \alpha) \frac{\delta_3'}{\delta_2'} \frac{\delta_3}{\delta_2} \frac{q_3}{q_2} \frac{\alpha}{\beta} m^\alpha > \left( \log \frac{N}{m} \right)^\beta \left[ \gamma + \beta \left( \log \frac{N}{m} \right)^{-1} \right] , \quad (16)$$

with  $(\gamma - \alpha) > 0$ .

Can a strict minimization of the present value of expected costs be accomplished by following an initial policy of "experimentation" with  $m = N$ , i.e., no duplication of plant designs in Stage I? We have found that in Case I such a policy will be better (than initial standardization) when  $A$ ,  $\theta$ ,  $\alpha$ , and  $\delta_3' \delta_3$  are large. For Case II, however, the inequality in equation (16) can never be satisfied at  $m = N$ , because with  $m = N$  the logarithm of  $N/m$  is equal to zero and its inverse is undefined.

Not too surprisingly, a policy of complete standardization, i.e.,  $m = 1$ , could be optimal for Case II. The second order condition in this special case is

$$(\gamma - \alpha) \frac{\delta_3'}{\delta_2'} \frac{\delta_3}{\delta_2} \frac{\alpha}{\beta} \frac{A}{B} \frac{\theta}{\sigma} > (\log N)^\beta [\gamma + \beta (\log N)^{-1}] , \quad (16a)$$

which, given  $(\gamma - \alpha)$ , could be satisfied for moderate values of  $N$  if  $(\alpha A \theta) > (\beta B \sigma)$  and  $(\delta_3' \delta_3) > (\delta_2' \delta_2)$ . Also, the first order condition at  $m = 1$  can be represented as

$$(\log N)^\beta = \frac{\delta_3'}{\delta_2'} \frac{\delta_3}{\delta_2} \frac{\alpha}{\beta} \frac{A}{B} \frac{\theta}{\sigma} > \frac{\gamma k_0 N^{-\gamma}}{\beta B \sigma} \cdot \frac{\delta_2' + \delta_3' N^{-\gamma}}{\delta_2' \delta_2} \quad (17)$$

Therefore, if  $(A \cdot \theta)$  is large in relationship to  $(B \cdot \sigma)$ , equation (17) could be satisfied if  $N$  is large enough to make the negative term on the right hand side negligibly small.

This implies that if the number of plants to be built is large enough, a policy of initial standardization would be strictly optimal -- under Case II conditions -- because the benefits gained in construction, and from incremental improvements learned in operations, outweigh the foregone gains from initial experimentation with alternative plant designs.

## 5. CONCLUSIONS

Our analysis serves to emphasize the point that the issue surrounding the question of technical standardization in the design of nuclear power plants is fundamentally a matter of timing: *eventually* complete standardization will be desirable. The problem is how soon one should move toward achieving this. Without establishing the empirical facts concerning the strength of learning effects in construction, operation, and redesign, we cannot justifiably assert that U.S. policy erred initially in encouraging and later in tolerating diversity in the nuclear power industry. The accidents of history that brought a halt to construction of nuclear power stations in the U.S. during the 1970s, and the persistence of political and economic conditions that are likely to continue to block construction of new nuclear capacity until the end of this century, have made more salient the costs of extreme diversity and have deferred realization of whatever benefits it might have yielded in the redesign process. In this respect the U.S. is suffering from a lack of standardization.

Our analysis of Case I suggests that when the effects of learning through diversity are strong, standardization can be an all-or-nothing proposition and the best course could turn out to be a total initial eschewal of standardization. That particular conclusion is shaped by the special assumptions of our model, notably, by the symmetry assumption. The latter assumption excludes the possibility of getting the benefits of standardization in construction and operational learning without having to sacrifice the opportunity to learn about the ability to improve variant plant types through some degree of diversity. The results might be different were we to relax the symmetry

conditions, for example, by allowing  $n$  of one plant type and one of each of the other plant types, i.e.,  $N = n + (m - 1)$ . It seems, then, that even if learning for redesign were considered, the extreme heterogeneity of the U.S. nuclear power plant population represented a needless sacrifice of the benefits of standardization. This illustrative restriction is only one of many that should in principle be considered. The general combinatorial problem of optimally distributing  $N$  plants across  $m > N$  types is an analytically difficult one that lies beyond the scope of the present work.

We have shown that if we could properly gauge the degree of similarity or diversity among complex, multi-component production facilities, we could address the economic optimization issues associated with the degree of standardization in an industry. While this paper has focused on nuclear power plants, the same conceptual framework is applicable to other large, technical systems. One could follow essentially the same approach in examining the operating characteristics of airline fleets, for the same economic benefits to standardization are relevant for airplanes: manufacturing costs, operator training, safety, and operating reliability. However, in the airline example, we would be forced to consider the influence of competing fleets in our model. We have ignored this issue for nuclear power plants, i.e., the role of international technology transfer and competition in determining the optimal number of plant designs. Because of this, and other simplifications, this paper should be considered as a first step in our understanding of the importance of standards in the dynamics of large technical systems.

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