INDUSTRIAL STRUCTURE AND TECHNOLOGICAL CHANGE
IN THE NUCLEAR POWER INDUSTRY

by

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Mark J. McCabe

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ABSTRACT

1. Adoption of Technologies with Uncertain Costs: The Case of
Nuclear Power

The adoption pattern for nuclear reactors in the U.S.
suggests that many electric utilities pursued investment
strategies involving diversification despite the existence of
substantial switching costs and network externalities. The
relevant theoretical literature is divided in this area,
either focusing on diversification as a response to
uncertainty or on the behavior of markets with switching costs
and network effects. The model presented here attempts to
remedy this situation by integrating these two theoretical
strands.

In the model, this tradeoff between diversification and
specialization on the demand side is modelled with both
competitive and oligopolistic supply sectors. In the latter
case, when technologies have single sponsors, I show that the
collusive price can be supported in equilibrium even in a
single period model. This occurs when utilities value
diversification more than specialization. Results for the two
period version of this game are also discussed.

2. Principals, Agents and the Learning Curve: The Case of
Nuclear Power Plant Construction

The econometric evidence for learning in nuclear
powerplant construction is mixed. Although the results from
some early papers indicated that costs decrease as experience
accumulates, recent studies contradict this conclusion. They
find that learning is observed only when construction is
performed in-house by the utility; when construction is
performed by outside contractors (the majority of cases) costs
do not decline with additional experience.

Implicit in the existing literature is the assumption
that the incentives and potential for learning in the nuclear
industry are similar to those observed in the standard
manufacturing context: given a product's market-determined
price, a firm will always reduce costs when learning is
possible. Given the dichotomous evidence for learning in nuclear construction, it is clear that this manufacturing analogy is not entirely correct. In particular, since the projects involving outside firms were subject to cost-plus contracting, one must ask whether these agents had any incentive to reduce costs over time. Furthermore, even if these incentives existed, was agent learning possible? An agent was hired by a variety of utilities, each with different design needs. Thus, the transferability of learning from utility to utility may have been minimal.

This paper responds to these questions by first, proposing a model of learning that is appropriate for nuclear power construction and second, specifying a suitable empirical model. The model of learning is based on the theory of supergames. The basic conclusion is that effort can be elicited from contractors subject to cost-plus contracts if their interactions with utilities are repeated over time. The econometric evidence provides support for this mechanism. Learning by agents is observed when factors such as design heterogeneity and construction organization are properly incorporated into the empirical analysis.

3. The Effect of Industrial Structure on Learning by Doing in Nuclear Power Plant Operation

Recent studies of technological innovation have drawn attention to the cumulative economic importance of secondary technical refinements, improvements and adaptations to products or processes after their introduction to the market (Rosenberg, 1982; Freeman, 1982). Secondary improvements may occur as a result of 'exogenous' scientific or engineering advances, or alternatively may emerge from the experience accumulated with the technology following its initial introduction. The role of experience in bringing about technological change has been extensively analysed in the literature on learning by doing.

In this paper we investigate the impact of learning on the operating performance of nuclear power plants of the light water reactor (LWR) type in the United States and France. Of particular interest is the effect of industry structure on the relationship between learning and operating performance. We find that two structural factors prevent the benefits of operating experience from being uniformly distributed throughout national industries. First, differences in reactor technology limit the potential for information sharing. Second, even when reactors exhibit similar technology, the additional costs associated with sharing information between plant sites and across corporate boundaries discourage this activity. These results have important implications for decisions affecting the choice of technological standards, siting policy and firm size in the nuclear industry.
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Table of Contents

Chapter One: Introduction .......................................................... 7

Chapter Two
Adoption of Technologies with Uncertain Costs: The Case of Nuclear Power ................................. 19

Chapter Three
Principals, Agents and the Learning Curve:
The Case of Nuclear Power Plant Construction ........................................... 56

Chapter Four
The Effect of Industrial Structure on Learning by Doing in Nuclear Power Plant Operation ................ 122
Chapter One: Introduction
In the past decade the field of industrial organization has experienced a theoretical revolution of sorts. Advances in game theory and the theory of the firm have transformed the study of market behavior and regulation. The static, often descriptive analyses of strategic behavior so common in the IO literature of the 1950s and 60s have been replaced by dynamic, formal models.

This upheaval in the field has affected empirical work in at least two ways. First, since predictions based on the new models are very sensitive to the assumptions made, studies combining data from several industries have been largely supplanted by analyses of individual industries. Second, because the data required to test these models is not typically available from public sources, access to proprietary information is of paramount concern in selecting research topics.

This dissertation is written with these considerations in mind. Consisting of both theoretical and empirical elements, the three essays that follow address different aspects of one industry, the nuclear power industry. And although the problem of data acquisition is not entirely solved, the fact that users of nuclear technology - electric utility firms - are regulated does ease this burden.¹

¹ As an aside, one negative consequence of deregulation in the US that is often ignored by economists in their welfare calculations is the dwindling amount of information reported to regulators and then published for public consumption.
This choice of industry was also influenced by other factors. Good empirical work in IO normally requires detailed knowledge of the institutions and technology specific to a given industry. Master's level work on the nuclear industry provided me with this background. Also, the new theoretical tools alluded to above had not yet been applied in studies of this industry. Together, these factors suggested to me that nuclear power was good "fodder" for an IO dissertation.

*Industrial Structure and Technological Change in the Nuclear Power Industry* examines three activities commonly observed in the electric power industry. The first essay considers *adoption* of steam-generating nuclear technology by electric utilities. The next paper addresses questions related to nuclear power plant *construction*. The final essay, written jointly with Richard K. Lester, discusses *operation* of completed facilities.

During the past decade, each of these activities has been the subject of papers in the IO literature. Generally, these three topics are addressed separately. Nonetheless, one recurrent theme in most studies of nuclear power is the importance of learning processes. In the case of adoption, several papers on lock-in have cited nuclear power as an example of how a single technology can gain market dominance due to the interaction of early adoption and dynamic
increasing returns. From this perspective, the commercial success of light water reactor technology was not foreordained. Rather, the choice of LWR technology for naval ship propulsion in the 1950s granted an early experience advantage that other reactor technologies could not overcome during the later, commercial phase of competition.

Studies of learning-by-doing in powerplant construction and operation are primarily empirical in nature, attempting to determine whether construction costs and operating performance improved with experience. A shared element in these papers' approach to the question of learning is a tendency to focus upon individual firm behavior. For example, past studies of learning in power plant operations assume that reactor performance is a function of experience gained at the same reactor.

The essays that follow advance this literature in a number of ways. First, each essay is motivated by an important empirical question that was either overlooked or unresolved in earlier papers. Second, constructing answers to these questions requires additional conceptual and theoretical machinery. In large part, this "machinery" is inspired by recent theoretical developments in IO. Third, unlike past work, connections are made between adoption decisions on the one hand and construction/operation on the other.

The point of departure for the essay on adoption is the
failure of the lock-in story to account for the "fine-
structure" of reactor adoption in the U.S. If the LWR enjoyed
such a large lead over its competitors, why did some utilities
order alternative reactor designs well into the first nuclear
era? Furthermore, LWR technology was not homogeneous. Two
distinct types were sold in the U.S. market: Boiling Water
Reactors (BWRs) and Pressurized Water Reactors (PWRs). Why did
both types succeed? Why did many utilities adopt more than
one technology?

The answer to the last question forms the central
argument for the first essay: faced with an assortment of
technologies, each with uncertain costs, risk averse utility
managers chose to diversify their portfolio of reactors,
despite the existence of substantial switching costs and
operational network effects. This diversification strategy
contributed to the success of both the PWR and BWR and helps
explain why utilities pursued alternatives to the LWR.

In the paper, this tradeoff between diversification and
specialization on the demand side is modelled with both
competitive and oligopolistic supply sectors. In the latter
case, when technologies have single sponsors, I show that the
collusive price can be supported in equilibrium even in a
single period model. This occurs when utilities value
diversification more than specialization. Results for the two

Evidence of network effects is provided in the essay on
plant operations. The link between adoption decisions and
operational performance is addressed in both essays.
period version of this game are also discussed.

The second and third essays both take a second look at the question of learning. Past studies of learning in construction and operation focus upon individual firm behavior and ignore the important relationships, cooperative or otherwise, that exist between firms in the nuclear industry. As a consequence, efforts at estimating the effects of learning in these two activities have suffered from model misspecification. The objectives of both essays is to consider how these previously neglected relationships affect the learning process and specify appropriate empirical models.

The econometric evidence for learning in nuclear powerplant construction is mixed. Although the results from some early papers indicated that costs decrease as experience accumulates, recent studies contradict this conclusion. They find that learning is observed only when construction is performed in-house by the utility; when construction is performed by outside contractors (the majority of cases) costs do not decline with additional experience.

Implicit in the existing literature is the assumption that the incentives and potential for learning in the nuclear industry are similar to those observed in the standard manufacturing context: given a product's market-determined price, a firm will always reduce costs when learning is
possible. Given the dichotomous evidence for learning in nuclear construction, it is clear that this manufacturing analogy is not entirely correct. In particular, since the projects involving outside firms were subject to cost-plus contracting, one must ask whether these agents had any incentive to reduce costs over time. Furthermore, even if these incentives existed, was agent learning possible? An agent was hired by a variety of utilities, each with different design needs. Thus, the transferability of learning from utility to utility may have been minimal.

The essay on construction responds to these questions by first, proposing a model of learning that is appropriate for nuclear power construction and second, specifying a suitable empirical model. The model of learning is based on the theory of supergames. The basic conclusion is that effort can be elicited from contractors subject to cost-plus contracts if their interactions with utilities are repeated over time. The econometric evidence provides support for this mechanism. Learning by agents is observed when factors such as design heterogeneity and construction organization are properly incorporated into the empirical analysis.

Past studies of learning in power plant operations assume that reactor performance is a function of experience gained at the same reactor. The possibility that information-sharing occurs between electric utilities (or between operators of
different reactors owned by the same firm) is overlooked. The third essay examines inter-reactor learning using data from the U.S. and France.

Of particular interest is the effect of industry structure on the relationship between learning and operating performance. Two basic questions are posed. First, do differences in reactor technology limit the potential for information sharing? If so, the existence of two distinct reactor networks in the U.S., one consisting of BWRs, and the other, PWRs, may have handicapped industry-wide performance. This contrasts with the French industry which is based entirely on the PWR design.

Second, even when reactors exhibit similar technology, how is inter-reactor learning affected by physical proximity and corporate boundaries? The idea here is that greater proximity or common ownership reduces the costs associated with inter-reactor learning. Again, the U.S. and French industries offer a stark contrast. All French reactors are located at multi-unit sites and are operated by a single utility; in the U.S. ownership of reactors is spread over many firms, resulting in many single-unit sites.

The econometric evidence presented in the third essay provides strong support for these structure/performance hypotheses. In the U.S., inter-reactor learning does not occur across networks. In both nations, intra-site inter-reactor learning is far more pronounced than learning between reactors
located at different sites or operated by different firms.

The existence of operational network effects, of course, raises questions about the wisdom of technological diversity. In an ex post sense, industry-wide performance in the U.S. suffers from this coordination failure. However, as explained above, this outcome can be seen as rational once the risk aversion of utility decisionmakers and the initial uncertainty associated with various technologies is considered.

Although the French industry's adoption of a single technology is not addressed in the first essay, it should be noted that this choice was made a decade after the initial reactor orders were made in the U.S. By that time adoption of a single standard was less risky since more was known about the costs and performance of various alternative technologies.

The other significant result from this essay - that siting policy and firm size are important determinants of reactor performance - also points to shortcomings in the U.S. industry. Fragmentation in the U.S. utility sector inhibits inter-reactor learning; in contrast, the performance of reactors in France is enhanced by greater concentration in the utility sector.³

³ This issue of concentration also arises in construction. As the second essay demonstrates, learning during plant construction was greater for utilities building several reactors. The explanation offered for this result relies on the fact that utility design preferences are held constant when the same agent is hired for each project. This improves the transferability of experience from project to
Finally, the essays contained in *Industrial Structure and Technological Change in the Nuclear Power Industry* are by no means the last word on the issues summarized in this introductory chapter. Each essay offers a number of opportunities for future research. The most obvious tasks are empirical in scope. As mentioned earlier, regulated electric utilities are the source of much of the data used in this dissertation. Although such information is necessary for answering the questions posed in these essays, additional data is required to properly test various hypotheses. The best example is the essay on adoption. To verify that suppliers enjoyed market power when utilities preferred diversification, data on reactor choices must be supplemented by pricing data of some sort.

Another empirical challenge involves examining the role of regulation in the U.S. In the case of electric utilities operating nuclear facilities, regulation has both economic and safety dimensions. State public utility commissions impose various forms of revenue constraints on utilities; The U.S. Nuclear Regulatory Commission ensures safety via its extensive rulemaking and enforcement powers.

To a large extent regulatory issues are ignored in the economic literature cited here. In the three essays that follow we assume that economic regulation involves lags, project and thus leads to greater cost reduction.
providing utilities with an incentive to reduce costs during adoption, construction and operation of power plants. At the same time, it is assumed that supplier firms and utilities satisfy safety requirements.

Obviously, future work should explicitly model these processes. In particular, regulation of nuclear operations offers several interesting research opportunities. In recent years, many state PUCs have supplemented their standard rate of return regulations with plant-specific incentive schemes. These schemes offer rewards and penalties based on plant performance. Little is known about their effectiveness, nor about how industry structure influences their effects. Similarly, the effects of industry structure and economic incentives on safety outcomes is essentially unexplored territory.
Chapter Two

Adoption of Technologies with Uncertain Costs:

The Case of Nuclear Power
Introduction

Recent papers on technological lock-in have cited nuclear power as an example of how inferior technologies can gain market dominance due to the interaction of early adoption and dynamic increasing returns. Although the concept of lock-in is useful for understanding the eventual success of light water reactors (LWRs) in the U.S. and abroad it fails to acknowledge or explain some important aspects of the adoption pattern in the U.S.

The empirical record suggests that many U.S. electric utilities pursued investment strategies involving diversification despite the existence of substantial switching costs and network externalities. The relevant theoretical literature is divided in this area, either focusing on diversification as a response to uncertainty or on the behavior of markets with switching costs and network effects. The model presented here attempts to remedy this situation by integrating these two theoretical strands.

The paper is organized in four sections. First, a brief review of the lock-in literature is presented. This is followed by an analysis and interpretation of reactor adoption in the U.S. The third section uses this discussion to construct a model of adoption that incorporates cost uncertainty. We conclude by considering some extensions of the model that bear upon additional aspects of the historical record.
1. The Lock-In Literature

The theoretical literature on lock-in (Arthur (1989), Habermeier (1989)) makes explicit reference to the case of nuclear power. The market dominance of light water reactor (LWR) technology in the U.S. and elsewhere is cited as an example of how an arguably inferior technology can be locked-in due to the interaction of early adoption and dynamic increasing returns. In both Arthur and Habermeier lock-in occurs when a random sequence of buyers contains a sufficient number of firms that prefer one technology over its competitors. Given the appropriate adoption pattern, the cost of this technology is lowered enough to attract even buyers who initially preferred the alternatives. In these models, the supply sector is assumed to be competitive.

Although these models demonstrate how lock-in might occur some of the underlying demand- and supply-side assumptions do not correspond well to the U.S. nuclear experience. In the U.S. competition between two technologies - LWRs and High Temperature Gas Reactors (HTGRs) - was observed. Since these two reactor types were potentially excellent substitutes with respect to baseload electricity production it is not obvious why the buyers (electric utilities) would exhibit heterogeneous preferences given similar priors about the costs of the two choices. If buyers are of a single type, the lock-in story becomes trivial: everything else equal, the
technology preferred by all buyers always dominates. How then did the LWR achieve dominance if, as some have argued, the LWR was the inferior technology?\(^1\)

A better story can be constructed if one includes the role of the U.S. military/industrial complex. The choice of LWR technology for naval ship propulsion in the 1950s granted an early experience advantage that the industrial parties (General Electric and Westinghouse) could exploit commercially. The success of the naval program demonstrated the viability of LWR technology and lent credibility to GE and Westinghouse's claims of commercial competitiveness. Between 1963 and 1970 U.S. utilities ordered 98 LWRs and only one HTGR (Atomic Industrial Forum (1986)). Thus, even if all buyers, ex ante, would have preferred the HTGR for commercial power production, this first-mover advantage enabled LWR suppliers to lock-out the competitor. A number of writers, most notably Cowan, have emphasized this aspect of the industry's history in explaining LWR dominance.

Another factor ignored by the basic lock-in story is the potential for strategic pricing. The small number of firms selling reactors suggests that they enjoyed a degree of market power. HTGR technology was sponsored by a single firm; four firms sold variants of the LWR. Several authors, including Hertsgaard (1983) and Bupp & Derian (1978), provide evidence

\(^{1}\) See Cowan (1990) for a discussion of the relative merits of the HTGR and LWR designs.
that GE and Westinghouse set prices below costs on early sales (the turnkey projects) and then recouped these losses on subsequent projects. Since the HTGR sponsor, General Atomic (GA), should also have been able to set prices in this fashion, the failure of this supposedly superior technology to dominate the market is probably due to the LWR's first mover advantage.²

2. The "Fine Structure" of Reactor Adoption in the U.S.

Although we can account for the general success of LWR technology in this manner several related empirical and theoretical questions remain. First, the history of U.S. Nuclear Steam Supply System (NSSS) orders indicates that a small, but significant number of HTGRs were ordered by American utilities in the early 1970s (eight orders were placed during the period 1971-74; see AIF (1986)). Although these eight orders were later cancelled³ along with dozens of LWRs during the 1970s, the fact that they were placed at all

² If we allow for capital market imperfections it is likely that the relatively large size of the GE and Westinghouse conglomerates enabled them to absorb early losses more easily than the smaller and undiversified GA. This asymmetry would have diminished any strategic advantage enjoyed by GA.

³ In the case of the eight HTGR reactors, 4 were cancelled by utilities due to a combination of financial constraints and regulatory uncertainty; GA reneged on its obligations for the other units. More on this latter point below. See DOE (1983), and three issues of Nuclear News, 10/75-12/75.
suggests that the LWR advantage was not absolute for all buyers.

Second, LWR technology was not homogeneous. Two distinct types were sold in the U.S. market: Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs). (Only the latter was adopted by the U.S. Navy for its ships and submarines.) Furthermore, three PWR vendors - Babcock & Wilcox, Combustion Engineering and Westinghouse - sold different versions of this technology. What pattern of NSSS orders did this technological competition - HTGRs vs. LWRs, BWRs vs. PWRs, etc. - produce? And, most importantly, what factors influenced utility decisions?

Before examining the historical record in detail it is useful to consider the latter question. Aside from traditional factors such as expected capital and operating costs, the technology adoption literature suggests that investment decisions may be a function of technology-specific fixed costs ("switching costs") and potential network effects. Recent theoretical work argues that switching costs may dampen competition and discourage switching by buyers (see papers by Klemperer (1987), Farrell and Shapiro (1988)). The existence of network externalities typically results in market dominance (in a given period) by a single (possibly inferior) technology (Katz and Shapiro (1986)). Thus, the presence of switching costs implies technological specialization by individual buyers; with network externalities this specialization should
occur not only at the firm level but also industry-wide.

In the U.S. nuclear industry there is evidence for both switching costs and network effects. Even though the various reactor types are functionally equivalent, utilities acknowledge that switching costs are incurred when both BWRs and PWRs are operated by the same firm. These additional costs include the retraining of operating and maintenance personnel (see Business Week, 1991). Lester and McCabe (1991) have shown that information exchange (operational learning-by-doing) is effective only among operators of the same type of reactor (BWR or PWR), thus producing network effects (at the firm and industry level). In that study there was insufficient data to test for similar effects among the several versions of PWR.

Assuming that these network effects were anticipated by the industry, the diffusion of several types of LWRs clearly refutes the prediction of industry-wide specialization.\(^4\) Presumably, similar network effects were expected and would have arisen with the diffusion of HTGRs. Why then were nine HTGR units ordered concurrently with LWRs? At the firm level, the evidence for buyer specialization is not strong either. Table 1 shows that slightly more than half of all firms

\(^4\) Although little is known about buyer expectations regarding network effects the existence of formal information-sharing networks is not in doubt. Vendor-sponsored "Users Groups" served this purpose; in addition, the U.S. Nuclear Regulatory Commission (NRC) issued design specific summaries of industry-wide operating experience. For a description of these mechanisms see the Staff Report to the President's Commission on the Accident at Three Mile Island (1979), and Phung (1984).
ordered NSSSs from two or more vendors (row C, column 1). When utilities are divided according to the number of plant sites that were planned, we see that most single site firms specialized whereas multi-site companies typically diversified (see rows B and C, columns 2 and 3).\(^5\) Ignoring the differences between PWR vendors, two-thirds of multi-site firms planned to diversify (row B, column 3). The fact that multi-site firms accounted for seventy percent of all orders indicates that the absence of industry-wide specialization was largely due to firm-level diversification and not a failure of coordination between firms.\(^6\) Thus, the combined effect of switching costs and network externalities did not discourage a diversification

\(^5\) It should be noted that most multi-reactor sites (59 of 64) planned by multi-site firms were based on a single vendor's technology. Thus, firm-level diversification resulted primarily from inter-site variation.

The dichotomy between intra-site and inter-site choices may reflect an asymmetry in switching costs. It is likely that, ex ante, the cost of a site's common facilities are lower when a single reactor type is used. However, the benefits of design complementarity would diminish if reactors at a site were not ordered at the same time and sufficient technological change occurred. Technological change in the industry, especially the increase in reactor size, was certainly significant in its extent.

In the eight cases where vendors differed at the same site (3 single-site firms and 5 multi-site firms) the period of time between order dates for the first and last units at a site averaged over five years; for single vendor sites reactors were often ordered at the same time, with the average period separating orders much less than one year. Thus, it seems that site diversification was a reasonable strategy once the corresponding switching costs were reduced by technological change.

\(^6\) If one examines the technology choices made by specialized firms (and single order firms) no pattern is apparent; each of the NSSS vendors are represented. It is not clear why these firms failed to coordinate their decisions.
strategy by many U.S. utilities.

Diversification, of course, is a familiar concept from finance theory. Risk averse investors diversify their portfolio of assets when faced with uncertainty. Similar investment behavior should be expected from risk averse managers.\textsuperscript{7} However, this diversification motive has been largely ignored in the theoretical literature on technology adoption (none of the papers cited above address this issue). The exception is work by Stoneman (1983) on the diffusion of innovations at the firm and industry levels. Individual entrepreneurs are assumed to be risk averse profit maximizers.\textsuperscript{8} Faced with a menu of technologies, each with uncertain returns, the entrepreneurs divide output among the various alternatives. Stoneman's model does not allow for the effects of switching costs, networks, or strategic behavior by suppliers.

There is some evidence that electric utilities behave in a risk averse fashion. Sommers (1980) shows that cost uncertainty influenced the choice between coal-fired and nuclear power plants, supporting the assumption of buyer risk aversion. Given the uncertainty associated with various

\textsuperscript{7} Managers may be risk averse for a number of reasons including bankruptcy costs and their own inability to diversify employment risk.

\textsuperscript{8} They maximize a utility function of the form \( V = u - b \cdot \sigma^2 \) where \( u \) is the expected mean return of a portfolio of technologies, \( b \) is a positive constant and \( \sigma^2 \) is the associated variance.
nuclear technologies' capital and operating costs in the 1960s and 1970s, one can assume that utilities considered both mean and variance in their choice of a nuclear technology portfolio. Of course, this diversification motive would need to be balanced against the cost of switching and foregone network benefits.

3. A Model of Technology Choice

The procurement of a nuclear power plant is a complex and lengthy undertaking (see McCabe (1991) for references). The ordering of a NSSS is the first important step in this process. Decisions about the design and construction of the balance of plant are conditioned on this initial step. In the model below we simplify matters by focusing entirely on the NSSS, treating the remaining characteristics (and costs) of a

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9 Although regulated electric companies rarely face bankruptcy their profits can fluctuate widely, affecting managerial compensation and employment opportunities. This occurs most often when lags in the regulatory process fail to adjust revenues in a timely fashion; if costs diverge from expectations then returns will vary in an inverse fashion (See Joskow (1974)). Risk averse behavior under these conditions is a reasonable assumption.

An extreme example of regulatory lag occurs when regulators deem utility investments as imprudent, disallowing some portion of a project's capital costs from the rate base. "Prudency" hearings held by state public utility commissions in the 1980s often resulted in losses for shareholders of companies burdened with cost overruns on nuclear projects and excess baseload capacity. Given the early market success of nuclear power in the U.S., it is clear that few utilities assigned much probability to such events during the period, 1966-74, when most orders were made. Rather, utility behavior during those years is consistent with expectations that nuclear capacity would offer low-cost power with moderate levels of risk.
plant as independent of the type of reactor system.

NSSS vendors bid for fixed-price contracts from utilities throughout the active phase of commercial ordering (1963-1978). Although the vendors projected performance levels for their reactors (e.g. a capacity factor of 70%) no warranties were given. No doubt, the potential for buyer negligence in plant operations discouraged the provision of supplier guarantees (and other forms of insurance). Thus, initially, utilities were faced with a situation characterized by well-defined NSSS capital costs and uncertain operating costs.

How long did this uncertainty last? It is safe to assume that it persisted throughout the period, 1963-1978. Because NSSSs are long-lived capital goods (initial projections ranged between 30 and 40 years) the uncertainty associated with their operation would not be resolved until well after the last orders were made.\footnote{In retrospect, the scale-up of reactor capacity (from the 400-600 MW range to the 800-1300 MW range) that occurred during the period probably postponed the resolution of this performance uncertainty. However, it is not clear that utilities or vendors anticipated this scale-up effect despite the fact that the larger plants were more complex in a variety of ways (see Bupp & Derian (1978)).} Nonetheless, vendor and utility expectations regarding reactor performance probably exhibited an asymmetry: an initial period where operating costs are uncertain followed by one or more periods where this uncertainty would be much reduced if not eliminated.

Because switching costs are easier to model than network effects in this context we first address the tradeoff between
switching costs and diversification.

Switching Costs and Uncertain Operating Costs

Consider two reactor technologies, A and B, with unit capital costs $K_A$ and $K_B$, and lifetime operating costs of $C_A$ and $C_B$. $C_A$ and $C_B$ are i.i.d. random variables with mean $C$ and variance $\sigma^2$. After one reactor lifetime, a technology's operating costs become known. If a technology is not adopted its operating costs remain uncertain. In addition, operation of one or more units of either technology requires a one-time investment of $s$ dollars.

Given the (regulated) price of electricity, buyers demand two units of baseload capacity at the beginning of each period. A period's duration is one plant lifetime, an exogenous quantity.\(^{11}\) This demand can be satisfied by the purchase of competitively-supplied, conventional (i.e. coal-fired) technologies with total lifetime costs (capital and operating costs) that are well known and equal to the revenue, $R$, generated by electricity sales. Alternatively, up to two units of nuclear capacity can be purchased, with total lifetime costs uncertain during the initial period of use.

Following Stoneman, buyers wish to maximize the following common objective function:

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\(^{11}\) We ignore questions of leadtime in plant construction, assuming that a plant can be instantaneously assembled from its constituent parts at the start of a period.
\[ V = \sum_{t=1}^{T} (u_t - b\sigma^2_t), \quad b > 0 \]  

where \( u_t \) is the expected profits from the operation of two reactors in period \( t \) and \( \sigma^2_t \) is the variance of these returns. There is no discounting. Note that a buyer's utility declines as the variability of profits increases. Given our assumptions, \( V = 0 \) when conventional technologies are purchased; thus, nuclear technologies will be adopted if \( V \geq 0 \). We maintain this latter assumption throughout the analysis.\(^{12}\)

A. Un赞助red Technologies

Here we assume that technologies A and B are supplied competitively. Thus, both A and B are sold at cost. Let \( K_A = K_B = K \). We consider two cases, \( T=1 \) and \( T=2 \).

\( T=1 \): At the beginning of the period, nuclear operating costs are uncertain. Buyers compare their utility under the two possible strategies, specialization and diversification.\(^{13}\) Under specialization, buyers purchase two

\(^{12}\) To rule out the possibility that buyers purchase both nuclear and conventional technologies in a given period we assume that \( V \) is always greater from specialization in one class of technologies for any \( t \). This condition imposes no unreasonable constraints on the parameters in (1).

\(^{13}\) In an industry with many buyers the choice of investment strategy does not affect the overall pattern of adoption. Assuming that A and B share the market when buyers specialize - this is reasonable since their expected costs are the same - both strategies result in equal shares for A and B.
units of either A or B. The buyer's utility is then

\[
V_{SB}^1 = V_{AA}^1 = R - 2 \cdot (K + C) - s - b \cdot \text{var}(2 \cdot C_A)
\]

\[
= R - 2 \cdot (K + C) - s - 4b \cdot \sigma^2
\]  \hspace{1cm} (2)

If the buyer chooses to diversify then we can write

\[
V_{AB}^1 = R - 2 \cdot (K + C) - 2s - b \cdot \text{var}(C_A + C_B)
\]

\[
= R - 2 \cdot (K + C) - 2s - 2b \cdot \sigma^2
\]  \hspace{1cm} (3)

A buyer will diversify in period 1 if \( V_{AB}^1 > V_{AA}^1 \). Using (2) and (3), this occurs if

\[
\sigma^2 > \frac{1}{2}b \cdot s
\]  \hspace{1cm} (4)

As intuition suggests, diversification is more likely when \( \sigma^2 \) and/or \( b \) is large or when \( s \) is small.

T=2: At the beginning of the second period buyers know the operating costs of the two nuclear technologies (let \( c_a \) and \( c_b \) represent these costs). Define \( c^* \) as the level of operating costs above which it is more economical to invest in conventional technologies. If buyers diversified in the first period then they compare \( c_A \) and \( c_B \) with \( c^* \) and choose the least costly alternative. In contrast, specialization in the first period may force firms to invest an additional \( s \) dollars if their initial choice of technology turns out to be more costly. Let \( \Delta c = |c_A - c_B| \). These buyers will switch to the
less costly nuclear option, i, if \( s \leq 2 \cdot A \) and \( c_i + s/2 \leq c^* \).\(^{14}\)

Knowing this, buyers at the start of the first period calculate their expected utility over both periods, and then compare the values for the two possible strategies. With diversification in the first period expected utility at the outset is

\[
V_{1,2}^{1,2} = V_{1}^{1} + (q_0 \cdot 0 + (1-q_0) \cdot (R-2K)) \\
- 2 \cdot E[\min(C_A, C_B) | C_A \leq c^* \text{ and/or } C_B \leq c^*] \\
- b \cdot \text{var}(\cdot)
\]  

(5)

where \( q_0 = \text{prob}(c^* < C_A \text{ and } c^* < C_B) \). If the buyer specializes in the first period then we have

\[
V_{1,2}^{1,2} = V_{1}^{1} + (q_s \cdot 0 + (1-q_s) \cdot (R-2K)) \\
- 2 \cdot E[\min(C_A, C_B) | C_A \leq c^* \text{ and/or } C_B + \frac{s}{2} \leq c^*] \\
- p \cdot s - b \cdot \text{var}(\cdot)
\]  

(6)

where \( q_s = \text{prob}(c^* < C_A \text{ and } c^* < C_B + \frac{s}{2}) \) and \( p = \text{prob}(C_B + \frac{s}{2} \leq c^* \text{ and } C_B + \frac{s}{2} \leq C_A) \). Note that \( q_s > q_0 \). To calculate \( E[\cdot] \) and \( \text{var}(\cdot) \) in (5) and (6) additional distributional assumptions would be

\(^{14}\) Unlike the single period case, the overall pattern of adoption with many buyers may differ depending on investment strategy. If buyers specialize in the first period, with A and B sharing the market, and \( s > 2 \cdot A \), then both nuclear technologies may be purchased in the second period. In contrast, if buyers diversify initially then only a single technology, possibly one of the nuclear options, will be sold in the second period.
necessary.\textsuperscript{15} To avoid this added complexity assume that the two \text{var}[*] terms in (5) and (6) are equal (this is a reasonable "second order" approximation). Then, if \( V_{AB}^{1,2} > V_{AA}^{1,2} \), we can write

\[
\sigma^2 > \frac{1}{2} b \cdot [ (1-p) \cdot s + (q_b - q_s) \cdot (R-2K) + 2 \cdot (E_0 - E_s) ]
\]  

(7)

where \( E_0 \) and \( E_s \) correspond to the \text{E}[*] terms in (5) and (6), respectively. The signs of the second and third right-hand-side terms in (7) are (weakly) negative since \( q_b \leq q_s \) and \( E_0 \leq E_s \).\textsuperscript{16} And because the probability, \( p \), of switching is positive, (7) thus implies that diversification will occur for values of \( \sigma^2 \) that are smaller than in the one-period model (see (4)), everything else equal.

B. Sponsored Technologies

Recall that two reactor types, the BWR and HTGR, had single sponsors. In addition, the several PWR vendors sold different versions of this technology. Given this context it is appropriate to relax the competitive supply condition of the previous section and consider the implications of

\textsuperscript{15} Note that \( \text{E}[\min(x_i,x_j)|x_i<y \text{ and/or } x_j<y] = \)

\[
\sum_{i,j=A,B} E(x_i|x_i<x_j<y) + E(x_i|x_i<y<x_j) \quad i\neq j
\]

The \text{var}[*] term (recall that \( \text{var}(z)=\text{E}(z^2)-(\text{E}z)^2 \)) is calculated in a similar fashion.

\textsuperscript{16} Actually, I have not yet established that \( E_0 \leq E_s \) is generally true. Some trial calculations, including use of the uniform distribution, suggest that this inequality holds.
strategic pricing for our analysis.

Suppose then that each technology in our model has one sponsor (sponsor A and sponsor B). Again, let \( K = K_A = K_B \). We show that sponsors can appropriate the buyer surplus that results from diversification; when specialization is preferred by buyers the standard Bertrand result holds.

Consider the single period case. We know that buyers pursue a diversification strategy when \( V_{AB}^1 > V_{AA}^1 \); specialization is preferred when \( V_{AB}^1 \leq V_{AA}^1 \). In the latter case, sponsors compete with each other to supply two reactors of the same type to each buyer. Since capital costs and expected operating costs for the two technologies are equal the unique Nash (or Bertrand) equilibrium has the two sponsors charge the competitive price \( P = K \) (see Tirole (1988), Chapter 5, for the proof). Thus, buyer utility is the same in both the sponsored and unsponsored cases.

When \( V_{AB}^1 > V_{AA}^1 \) the unique Nash equilibrium in prices is the competitive outcome only in the limit as \( V_{AA}^1 \) approaches \( V_{AB}^1 \). The intuition here is that because the benefits from diversification are "large", the sponsors' products are not perfect substitutes. Thus, a sponsor is able to charge a \( P \) such that \( P > K \) since the benefits to the buyer exceed the additional costs.

To obtain the equilibrium prices note that buyers are willing to pay a premium of up to \( V_{AB}^1 \) for two reactors of a different type (since \( V=0 \) for conventional technologies).
Thus, a logical candidate for an equilibrium is \( P^* = K + \frac{1}{3}V_{1AB} \).

This price allocates an equal share of the premium among the two sponsors.\(^{17}\) Given \( P^* \), if one sponsor, say firm A, deviates by charging a higher price, \( P' \), then buyers will prefer the conventional technologies (buyer utility is negative with this price pair).

Conversely, suppose sponsor A deviates by charging a lower price, \( P'' \). For this action to increase A's profits buyers must prefer specialization at the lower price (If they don't then charging \( P'' \) simply lowers the sponsor's profits and increases buyer utility). Buyers will prefer specialization if

\[
V^1_{AB} - \frac{1}{3}V^1_{AB} - Z \leq V^1_{AA} - 2 \cdot Z \quad (8)
\]

where the terms being subtracted, \( \frac{1}{3}V^1_{AB} \) and \( Z \), are the profit per sale for sponsor B and sponsor A, respectively (B charges \( P^* \) and A sets \( P'' = K + Z \)). In addition, for A's profits to increase it must be that \( 2 \cdot Z \geq \frac{1}{3}V^1_{AB} \).

Thus, if (8) holds and \( 2 \cdot Z \geq \frac{1}{3}V^1_{AB} \) then A will deviate. These two conditions can be combined to obtain the following inequality:\(^{18}\):

\[\text{\ldots}\]

\(^{17}\) Of course, numerous equilibria exist that involve unequal allocations of this premium.

\(^{18}\) (8) can be rewritten as \( Z \leq V^1_{AA} - \frac{1}{3}V^1_{AB} \); this inequality is binding since sponsors wish to maximize profits. Combining this result with the remaining constraint gives \( 2 \cdot V^1_{AA} - V^1_{AB} \geq \frac{1}{3}V^1_{AB} \quad (9) \).
\[ \frac{V_{AA}^1}{V_{AB}^1} \geq \frac{3}{4} \] (9)

If (9) is satisfied, however, then it is a dominant strategy for each sponsor to deviate. And with both A and B charging \( P'' \) buyers will prefer to diversify. Furthermore, \( P'' = K + Z = K + (V_{AA}^1 - \frac{1}{2}V_{AB}^1) \) is not always the equilibrium price when (9) holds. If \( \frac{V_{AA}^1}{V_{AB}^1} \) is relatively large, then charging \( P'' \) provides further incentive for price cutting. By iterating the above steps one can show that the value of \( Z \) defining an equilibrium is given by

\[ Z_n = n \cdot V_{AA}^1 - \left[ (2n-1)/2 \right] \cdot V_{AB}^1 \quad n = 1, 2, 3, \ldots \] (10)

where \( n \) is chosen to satisfy the following condition:

\[ \frac{(2n + 1)}{(2n + 2)} \leq \frac{V_{AA}^1}{V_{AB}^1} \leq \frac{2 \cdot (n + 1) + 1}{2 \cdot (n + 1) + 2} \] (11)

Thus, \( P'' \) is the equilibrium price when \( n = 1 \) and \( 3/4 \leq \frac{V_{AA}^1}{V_{AB}^1} \leq 5/6 \). Note that for any value of \( n \), \( Z_n \) increases over

---

This game is a form of the Prisoner's Dilemma. In normal form,

<table>
<thead>
<tr>
<th>Sponsor A</th>
<th>Collude</th>
<th>Deviate</th>
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<tbody>
<tr>
<td><strong>Sponsor B</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>( V/2 ), ( V/2 )</td>
<td>0, 2( Z )</td>
</tr>
<tr>
<td>D</td>
<td>2( Z ), 0</td>
<td>( Z ), ( Z )</td>
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</table>

where \( V = V_{AB}^1 \).
the interval defined by (11). However, as \( n \) increases, \( Z_n \) decreases, approaching zero for \( V_{AA}^1 \) close to \( V_{AB}^1 \). This limiting behavior arises because diversification provides little added benefit to buyers. Small price cuts are sufficient to induce specialization, forcing the equilibrium price down close to \( K \).

Of course, when the inequality in (9) is reversed each sponsor charging \( P = P^* \) is an equilibrium. Buyer utility is then zero and sponsors' profits total \( V_{AB}^1 \), divided equally. Diversification then results in a transfer of all surplus from buyers to sponsors.

Analysis of the two period case is complicated by the existence of positive second period profits under both buyer strategies. With sponsorship, diversification at the outset gives expected buyer utility of

\[
V_{AB}^{1,2}(P_1) = V_{AB}^1(P_1) + (q_0 \cdot 0 + (1-q_0) \cdot (R-2K)) - 2 \cdot E[\max(C_A, C_B) | C_A \leq c^* \text{ and } C_B \leq c^*] - 2 \cdot (p_0 \cdot c^*) - b \cdot \text{var}(\cdot) \tag{12}
\]

where \( P_1 \) refers to the price charged per reactor in the first period, \( q_0 \) is defined the same as before, and \( p_0 = [\text{prob}(C_A < c^* < C_B) + \text{prob}(C_B < c^* < C_A)] \). The \( \min(\cdot) \) operator in (5) is replaced by \( \max(\cdot) \) because in the second period the sponsor of the low cost technology can charge a price equal to \( K + \Delta c \).
if \( c_i \leq c^* \), \( i=A,B \). If \( c_i \leq c^* \leq c_j \), \( i,j=A,B \) and \( i \neq j \), then the sponsor of the low cost technology, \( i \), charges \( K + (c^* - c_i) \).

If the buyer specializes in the first period then we have

\[
V_{AA}^{1,2}(P_1) = V_{AA}^1(P_1) + (q_s \cdot 0 + (1-q_s) \cdot (R-2K) - 2 \cdot E[\max(C_A, C_B) \mid C_A \leq c^* \text{ and } C_B + \frac{1}{2}s \leq c^*] - 2 \cdot (p_s \cdot c^* - p \cdot s) - b \cdot \text{var}(\cdot) \tag{13}
\]

with \( q_s \) defined as before, \( p_s = [\text{prob}(C_A < c^* < C_B + \frac{1}{2}s) + \text{prob}(C_B + \frac{1}{2}s < c^* < C_A)] \), and \( p = \text{prob}(C_A \leq C_B + \frac{1}{2}s < c^*) \).

When \( V_{AA}^{1,2}(P_1) \geq V_{AB}^{1,2}(P_1) \) for any \( P_1 \), buyers will specialize in period one. Since the incumbent sponsor and its rival - a potential entrant - can expect positive second period profits Bertrand competition in the first period will result in prices below costs.\(^\text{21}\) Let \( \pi^i \) and \( \pi^e \) correspond to incumbent and entrant profits, respectively. Because of switching costs, \( \pi^i > \pi^e \). Since both technologies have the same expected (total) costs, we assume that buyers randomize their choice of supplier, i.e. buyers select each technology with equal probability. Thus, expected second period profits from

\(^{20}\) If \( B \) is the low cost technology, the buyer's total second period costs are then \( K + (c_1 - c_B) + c_B = K + c_3 = K + \max(c_a, c_b) \). Note that \( E[\max(x_i, x_j) \mid x_i < y \text{ and } x_j < y] = E(x_i \mid x_i < x_j < y) + E(x_j \mid x_i < x_j < y) \).

\(^{21}\) Here, "incumbent" and "entrant" are defined relative to a single buyer's purchases. With many buyers we assume that sponsors share the first period market (this is reasonable since their products' expected costs are the same). If each sponsor can discriminate among buyers in the second period, the former will employ both incumbent and entrant strategies in the second period, depending on the buyer. This latter assumption is (very) reasonable in the case of nuclear power.
the sale of two reactors are \( \frac{1}{2}\pi^1 + \frac{1}{2}\pi^E \) for each sponsor.

The Bertrand equilibrium for this case cannot be obtained in the usual fashion by imposing the constraint that total expected profits equal zero. If both sponsors set the price of a single reactor, \( P_1 \), equal to \( K - \frac{1}{2}(\pi^1 + \pi^E) \) (total expected profits per buyer are \( \frac{1}{2}(\pi^1 - \pi^1 - \pi^E) + \frac{1}{2}(\pi^E - 0) = 0 \)) then one firm can raise its price any amount and forgo the first period market, receive \( \pi^E \) in the second period, and thus increase its expected profits. To avoid this outcome, it must be the case that neither firm can increase its profits by deviating above or below \( P_1 \). Let \( P_1 = K - \frac{1}{2} \cdot Z \). The three relevant profit constraints are then

\[
\pi^E \leq \frac{1}{2}(\pi^1 + \pi^E - Z) \tag{14}
\]

\[
\pi^1 - (Z + \varepsilon) \leq \frac{1}{2}(\pi^1 + \pi^E - Z) \tag{15}
\]

\[
0 \leq \frac{1}{2}(\pi^1 + \pi^E - Z) \tag{16}
\]

where \( \varepsilon \) is arbitrarily small and positive. Constraints (14) and (15) correspond to deviations above and below \( P_1 \), respectively. (16) is a sponsor's participation constraint (nonnegative profits). For (14) and (15) to be satisfied simultaneously it must be true that

\[
Z = \pi^1 - \pi^E \tag{17}
\]

Given (17), (16) is obviously satisfied (since \( \pi^E > 0 \)). Thus, the two sponsors setting \( P_1 = K - (\pi^1 - \pi^E) \) is the (unique)
equilibrium price when buyers prefer first period specialization. Note that expected equilibrium profits (\(= \pi^f\)) are positive, even though the technologies are perfect substitutes in the first period.

Analysis of diversification in a two period model, that is, when \(V_{AB}^{1,2}(P_1) > V_{AA}^{1,2}(P_1)\) for all \(P_1\), is a straightforward extension of the single period case. Because expected second period profits, \(\pi (\pi < \pi^1)\), are the same for both sponsors, equilibrium prices in the first period are defined under essentially the same conditions as before.

Recall that we obtained the equilibrium prices by analyzing the premium that buyers are willing to pay for two reactors of a different type. If the reactors are priced competitively in both periods then this (first period) premium equals \(V_{AB}^{1,2}\) (equation (5)). Since prices exceed costs in the second period (see equation (12)), this premium is reduced somewhat and is equal to \(V_{AB}^{1,2}(K)\).

Following our earlier analysis, the logical candidate for an equilibrium is \(P_1^* = K + \frac{1}{2}V_{AB}^{1,2}(K)\). Given \(P_1^*\), if one sponsor, say firm A, deviates by charging a higher price, \(P_1''\), then buyers will prefer the conventional technologies.

Conversely, suppose sponsor A deviates by charging a lower price, \(P_1'''(= K + Z)\). As before, buyers will prefer specialization at this price if

\[
V_{AB}^{1,2}(K) - \frac{1}{2}V_{AB}^{1,2}(K) - Z \leq V_{AA}^{1,2}(K) - 2\cdot Z \quad (18)
\]
However, for A's profits to increase it must be that

\[ 2 \cdot Z \geq \frac{1}{2} V_{AB}^{1,2}(K) - \Delta \pi \]

(19)

where \( \Delta \pi = \pi^1 - \pi > 0 \). The additional term in (19), \( \Delta \pi \), arises because first period behavior affects second period profits. Collusive behavior produces expected profits of \( \pi \) for each sponsor; the price-cutting firm can expect \( \pi^1 \) in the second period.

Thus, if (18) and (19) hold then A will deviate. These two conditions can be combined to obtain the two-period version of (9):

\[ V_{AA}^{1,2}(K) \geq (3/4) \cdot V_{AB}^{1,2}(K) - \frac{1}{2} \Delta \pi \]

(20)

Since \( \Delta \pi \) is positive, smaller values of \( V_{AA}^{1,2}(K) \) will satisfy (20) for any value of \( V_{AB}^{1,2}(K) \). Furthermore, (20) may hold even when the gains from collusion in the first period exceed those from price cutting, i.e., \( 2 \cdot Z \leq \frac{1}{2} V_{AB}^{1,2}(K) \); negative values for \( Z \) are not ruled out.

When (20) is satisfied, it is a dominant strategy for each sponsor to deviate. With both sponsors charging \( P''(= K + Z = K + V_{AA}^{1,2}(K) - \frac{1}{2} V_{AB}^{1,2}(K)) \) buyers will prefer to diversify. At this price sponsors may have an incentive for further price-cutting. Again, the value of \( Z \) defining an equilibrium is given by

\[ Z_n = n \cdot V_{AA}^{1,2}(K) - [(2n-1)/2] \cdot V_{AB}^{1,2}(K) \quad n = 1, 2, 3, \ldots \]

(21)
where \( n \) is chosen to satisfy the following condition:

\[
\frac{(2n+1)}{(2n+2)} \cdot V_{AB}^{1,2}(K) - \frac{1}{(n+1)} \cdot \Delta \pi \leq V_{AA}^{1,2}(K) \leq \frac{2(n+1)+1}{2(n+1)+2} \cdot V_{AB}^{1,2}(K) - \frac{1}{(n+2)} \cdot \Delta \pi
\]

(22)

The limiting value for \( Z \) is not zero as in the single-period case; it depends on the values for buyer utility and \( \Delta \pi \). Finally, when the inequality in (20) is reversed each sponsor charging \( P = P_1^* \) is an equilibrium.

**Networks and Uncertain Operating Costs**

When operating costs are influenced by the total number of reactors in operation the existence (or absence) of coordination among buyers' technology choices is a key factor determining the pattern of adoption. In the model of switching costs these choices are made independently. Here we permit operating costs to be a decreasing function of the number of reactors in operation.

As before assume that operating costs for technologies \( A \) and \( B \), \( C_A(\cdot) \) and \( C_B(\cdot) \), are i.i.d. random variables with mean \( C(\cdot) \) and variance \( \sigma^2 \) (to simplify the analysis, \( \sigma^2 \) is assumed to be constant). Mean lifetime operating costs of a given reactor technology are a function of the number of similar units operating during period \( t \):

\[
C(n) > C(n+1), \quad n = 0, 1, 2, \ldots \quad (23)
\]

\[
C(n-1) - C(n) > C(n) - C(n+1); \quad C(n) > 0 \text{ for } n=\infty
\]
Implicit in this formulation is the assumption that network effects are not greater for units operated by a single buyer.\textsuperscript{22}

There are $n$ buyers. Each firm demands two units of baseload capacity at the beginning of the period and receives revenue of $R$ dollars for the electricity generated. The buyers' share the same objective function (equation (1)). Other relevant features of the switching cost model are preserved.

We consider only the single period, unsponsored technology case. Analysis of the more complicated cases - two periods and/or sponsors - corresponds closely to that seen with switching costs.\textsuperscript{23}

Unsponsored Technologies

Technologies A and B are supplied at cost. Again, assume equal capital costs: $K = K_A = K_B$. We analyze two equilibria - all buyers diversifying and all buyers specializing - and postpone questions of uniqueness to a later time.

\textsuperscript{22} Relaxing this assumption does not change the basic conclusions of the analysis. See Lester & McCabe (1991) for an empirical analysis of intra-firm vs. inter-firm network effects in the nuclear industry.

\textsuperscript{23} One new issue that arises in the two-period network case is the possibility that costs for one of the two technologies may not become known after the first period. If buyers choose to specialize and select technology A, then B's costs in the second period remain uncertain. This is because uncertainty in the model is resolved only after one reactor lifetime.
Suppose then that each buyer purchases two units of the same technology. Buyer utility is then

\[ V_{bb}^1 = V_{aa}^1 = R - 2 \cdot (K + C(2n)) - b \cdot \text{var}(2 \cdot C_A) \]
\[ = R - 2 \cdot (K + C(2n)) - 4b \cdot \sigma^2 \] \hspace{1cm} (24)

If buyers choose to diversify then we can write

\[ V_{ab}^1 = R - 2 \cdot (K + C(n)) - b \cdot \text{var}(C_A + C_B) \]
\[ = R - 2 \cdot (K + C(n)) - 2b \cdot \sigma^2 \] \hspace{1cm} (25)

A buyer will diversify in period 1 if \( V_{ab}^1 > V_{aa}^1 \). Using (24) and (25), this occurs if

\[ \sigma^2 > \frac{[C(n)-C(2n)]}{b} \] \hspace{1cm} (26)

To check that no single buyer will prefer specialization when (26) holds consider the utility of a buyer that defects from the proposed equilibrium and purchases two units of A:

\[ V_{aa}^{1*} = R - 2 \cdot (K + C(n+1)) - 4b \cdot \sigma^2 \] \hspace{1cm} (27)

\( V_{ab}^1 > V_{aa}^{1*} \) implies that

\[ \sigma^2 > \frac{[C(n)-C(n+1)]}{b} \] \hspace{1cm} (28)

This inequality holds since we know that \( C(n)-C(2n) > C(n)-C(n+1) \). Thus, diversification by all buyers is an equilibrium when (26) is satisfied. As in the case of switching costs, diversification is more likely when \( \sigma^2 \) and/or \( b \) is large or when the analog of \( s, [C(n)-C(n+1)] \), is small.
Conversely, suppose that (26) does not hold and buyers specialize. To check that no single buyer will prefer diversification consider the utility of a buyer that defects from the equilibrium and purchases one unit of each technology:

\[ V_{AB}^* = R - 2K - OC(2n-1) - OC(1) - 2b \sigma^2 \]  

(29)

\[ V_{AA}^1 > V_{AB}^* \] implies that

\[ 2b \sigma^2 < [C(2n-1) + C(1) - 2 \cdot C(2n)] \]  

(30)

A sufficient condition for (30) to hold is \( V_{AB}^1 > V_{AB}^* \) or \( 2 \cdot C(n) < C(2n-1) + C(1) \). Since the \( C(\cdot) \) function decreases with \( n \) at a diminishing rate this condition is satisfied.

**Discussion**

There are several extensions of the models presented above that tighten the correspondence between basic assumptions and conditions in the industry, and in some cases help explain the observed pattern of adoption. First, although we have considered them separately, switching costs and network effects coexisted in the nuclear industry. Combining them in a single model is not difficult and results in relationships governing buyers' investment decisions that

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24 Under the assumptions of the model buyer utility is the same whether A or B is the technology chosen for specialization, posing problems for market coordination. To break this tie we can let capital costs differ by \( \epsilon \); the lower cost option would then be chosen by all buyers.
are similar to those seen earlier.

A more interesting extension involves relaxing the assumption that buyers have a common objective function. By allowing buyers to have different risk coefficients we can account for the fact that not all multi-site firms diversified. For example, in the switching cost model, small values of \( b \) make it likely that a buyer will specialize (see equation 4). Thus, buyer strategies can vary as observed. Furthermore, in the case of sponsored technologies, if buyers' objective functions are common knowledge then the equilibrium prices will vary accordingly. The network model can also be modified in this fashion.

Our analysis has also assumed identical capital costs. In addition, operating costs were specified to be i.i.d. random variables. Relaxing one or both of these assumptions adds some complexity without affecting the basic results. However, to assist in explaining the demise of the HTGR design it is useful to consider the implications of different assumptions.

As noted earlier eight of the nine HTGR reactors ordered were later cancelled. In four cases, the utilities cited financial constraints and regulatory uncertainty as the primary factors affecting their decisions. These factors were often cited in cancellations involving LWRs as well. However, in the remaining cases the vendor, General Atomic was forced to renege on its contractual obligations, citing unexpected escalation in capital costs. Since the utilities involved were
unwilling to renegotiate their contracts GA's only other option would have been to recoup its losses on these projects with future contracts. The general downturn in the reactor business during the mid-seventies, however, made this scenario unlikely and GA chose to withdraw from active participation in the NSSS market.

The interesting point here is how a change in capital costs affects a buyer's investment strategy. Two of the contracts cancelled by GA involved a multi-site firm that had ordered four other reactors as well - BWRs from General Electric. Thus, the utility's refusal to renegotiate its contract suggests that the net benefits from diversification were eliminated with GA's announcement of higher capital costs. In terms of our model, if we let A and B correspond to LWR and HTGR technology, respectively, then initially it was true that $V_{AB}^t > V_{AA}^t$. GA's announcement reversed the inequality, changing the utility's investment preferences.\textsuperscript{25} The fact that GA needed to increase its price to the buyer suggests that the increase in capital costs exceeded any excess rents it may have enjoyed as a sponsor of the HTGR.

The failure of GA's effort in the U.S. market can thus be seen as a consequence of both bad timing and design immaturity. Because of a negative demand shock GA needed a

\textsuperscript{25} When capital costs differ, $V_{AB}^t \leq V_{AA}^t$, t=1, implies that $\sigma^2 \leq [1/(2b)] \cdot (K_B - K_A + s)$
more competitive product to survive. However, the fact that
the HTGR was locked-out in 1975 and not 1965 (when the LWR
bandwagon market began to take shape) suggests that some
utilities were willing to include the HTGR in their nuclear
portfolio - despite the first mover advantage enjoyed by the
LWR - as insurance against perceived economic risks.
Furthermore, it appears that once subsequent events indicated
that the LWR advantage was larger than anticipated this
diversification strategy was no longer desirable.

Finally, some advocates of a "second nuclear era" cite
the advantages associated with the HTGR - especially its
promise of superior safety - as reason enough to switch
technologies. Although assessments of safety will influence
the future of nuclear power the economics of various reactor
designs cannot be ignored. The HTGR's relative immaturity
remains a barrier to entry in any future U.S. market.

Empirical Extensions

This paper's theoretical examination of technology choice
assumes a tradeoff between diversification and specialization
and analyzes the implications for strategic pricing. Ideally,
a test of this model would employ not only information on
utility choices but also, at a minimum, data on the prices bid
by NSSS vendors for various contracts, reactor capital costs,
and the expected distribution of operating costs. This price
and cost information could be used to determine whether
suppliers anticipated the tradeoff facing buyers and set prices accordingly, resulting in the observed pattern of reactor orders. Although development of such a data base is a priority, it is nonetheless a notoriously difficult task to accomplish in industrial organization. A compromise solution might entail interviews with individuals involved in supplier pricing and buyer adoption decisions. Although anecdotal in nature, these interviews would provide some indication of whether a diversification/specialization tradeoff influenced industry behavior.
TABLE 1

Number of utilities ordering two or more different types of reactors, 1963-1978:

<table>
<thead>
<tr>
<th>Types</th>
<th>1. All Firms (N=56*)</th>
<th>2. Single-Site Firms (27)</th>
<th>3. Multi-Site Firms (29)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. HTGR, LWR</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>B. HTGR, PWR BWR</td>
<td>21</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>C. GA, B&amp;W CE, W, GE</td>
<td>29</td>
<td>3</td>
<td>26</td>
</tr>
</tbody>
</table>

Key: A. HTGR - High Temperature Gas Reactor; LWR - Light Water Reactor;

B. HTGRs and two classes of LWR: PWR, Pressurized Water Reactor and BWR, Boiling Water Reactor;

C. Suppliers: GA - General Atomic (HTGR); B&W - Babcock & Wilcox (PWR); CE - Combustion Engineering (PWR); W - Westinghouse (PWR); GE - General Electric (BWR)

*: the sample includes all firms ordering at least two reactors. Thirteen firms ordering a single reactor are excluded here.

**: Rows A, B and C differ in how LWR reactors are classified. In row A all LWR reactors are grouped together. The next row, B, breaks the LWRs into two groups, BWRs and PWRs. Row C allows for three types of PWRs, in addition to the HTGR and BWR designs, each corresponding to a single supplier. Thus, for example, comparing the entries in column 1 (All Firms), the difference between rows B and A (21-3=18) results from firms that ordered both BWRs and PWRs but no HTGRs; the difference between rows C and B (29-21=8) results from firms that ordered two or more types of PWR, but neither BWRs or HTGRs.
### TABLE 1 CONT'D

**Descriptive Statistics:**

<table>
<thead>
<tr>
<th></th>
<th>All Firms (N=56)</th>
<th>Single-Site Firms (27)</th>
<th>Multi-Site Firms (29)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong># of orders</strong></td>
<td>223</td>
<td>58</td>
<td>165</td>
</tr>
<tr>
<td><strong>Avg #</strong></td>
<td>3.98</td>
<td>2.15</td>
<td>5.70</td>
</tr>
<tr>
<td><strong>Min #</strong></td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Max #</strong></td>
<td>17</td>
<td>5</td>
<td>17</td>
</tr>
</tbody>
</table>

References


Staff Report to the President's Commission on the Accident at Three Mile Island: the Role of the Managing Utility and Its Suppliers, October 1979, Washington, D.C.


Chapter Three

Principals, Agents and the Learning Curve:
The Case of Nuclear Power Plant Construction
**Introduction**

Several studies of electric power plant construction costs have attempted to measure the effects of learning-by-doing (see Zimmerman (1982), Joskow and Rose (1985), Cantor and Hewlett (1988)). These authors specify empirical models similar to those seen in earlier studies of learning in manufacturing where production experience, e.g., the cumulative number of units produced, serves as a proxy for learning. (See Alchian (1963), Hirsch (1956))

In these earlier studies, a standardized or homogeneous product is manufactured in a serial run by a single firm. Typically, a pattern of declining costs (or physical inputs such as labor) is observed and is considered evidence that a learning curve exists. Several authors (Spence (1981), Fudenberg and Tirole (1983)) have studied pricing strategies in homogeneous product markets where learning plays a part in production. In these models, cost reduction is a natural consequence of profit maximization.

In contrast, power plants exhibit heterogeneous designs. Construction organization also varies. In some cases, the plants are procured by utilities (the principals) from design and construction firms (the agents). The contracts for these plants range from fixed-price to cost-plus arrangements. In other cases, utilities design and/or construct the plants themselves, using an in-house labor force.

The case of *nuclear* power plant construction is notable
because factors like design heterogeneity and the reliance on cost-plus contracting were so pronounced in the United States. Design heterogeneity was a consequence of technological change and diversity, varying utility preferences, site-specific design requirements, and evolving regulatory requirements.¹ The issue of design heterogeneity raises questions about the transferability of learning from project to project.

The switch from fixed-price to cost-plus contracts in the late 60s removed any explicit contractual incentives for agents to reduce costs over time. Although a dynamic form of yardstick competition can provide sufficient cost-reducing incentives in this context, some utilities relied on alternative mechanisms to accomplish this objective. A few firms developed the capability to perform in-house design and construction. Other utilities hired outside contractors but assumed responsibility for the project management function. In the latter case, the locus of learning may have shifted from the outside contractors to the utilities.

To date, the evidence for learning in the construction of nuclear power plants is mixed. We show here that the evidence

¹ Typically, when economists discuss product differentiation they concern themselves with a firm's choice of product, a firm's ability to raise prices above cost, etc. In the case at hand, product differentiation arises from dynamic and cross-sectional variation largely exogenous to the supplier firms we study here -- the architect-engineers and constructors. In particular, these firms bid on projects specified by the Nuclear Steam Supply System vendors, the utilities (and the U.S. Nuclear Regulatory Commission). Thus, bids for any given project involved a single set of design specifications.
is much stronger when factors such as design heterogeneity and construction organization are properly incorporated into the empirical analysis. The paper is divided into three main sections. First, we discuss the relevant institutional facts. We then formulate a dynamic model of yardstick competition to demonstrate that incentives for agent learning can exist when contracts are cost-plus. Finally, this model is evaluated using past studies and new results from a more appropriate empirical model.

1. Institutional facts

- The Construction Process/Opportunities for Learning

A completed nuclear plant is the outcome of several distinct activities -- design and engineering, equipment manufacture, materials and equipment procurement, construction. Project-wide technical and administrative functions -- quality assurance and project management -- also play an important role. (See Lester & Crocker (1938), Willenbrock & Thomas (1980)).

Although experienced-based learning is expected in all of these activities, the available data only allow us to observe the aggregate impact of such learning. Because the data are corrected for fluctuations in the costs of equipment and materials we can ignore the contribution of equipment
manufacturers to cost-reduction.² Hence, we focus our attention on architect-engineering (AE), constructor firms and/or the utilities who were responsible for the remaining tasks.

The timing of the various functions during the procurement process can be described in the broadest terms as follows: Utilities, observing a need for new capacity at some date in the future, would place an order with a Nuclear Steam System Supply (NSSS) manufacturer. Some time later bids would be accepted from AE firms to design a plant based on the NSSS specs, the utilities' preferences for the balance of plant, and site-specific criteria. While the AE's work proceeded, a constructor firm would be chosen (often the same firm performed both roles). Once a construction permit was granted by the Nuclear Regulatory Commission (NRC), actual construction would commence. Since designs were typically incomplete at this stage coordination between design and construction teams was of particular importance.³ The whole

² Note that equipment was procured on a fixed-price basis, with adjustments for inflation allowed, during the cost-plus era. See Burness, et. al. (1980).

³ Incomplete designs are particularly troublesome because engineers calculate structural loads from the top of a plant down to its foundations. Because builders necessarily start with a plant's foundations, uncertainty about the first steps in the construction process can contribute to leadtime and cost overruns.

This practice of commencing construction prior to design completion, otherwise known as "fast-tracking", was initially adopted to shorten the overall time needed to complete a project. Furthermore, shortages of trained personnel encouraged builders to embrace this approach to construction.
process, from NSSS order to plant commissioning and commercial operation, often required more than a decade to complete (in our data set construction duration averaged 8.5 years with a maximum value of 17 years.).

Opportunities for learning in this complex process were probably numerous. The expectation is that AEs and constructors, each taken separately, were able to rationalize their tasks over time, e.g. fewer engineering hours were required to tackle new projects, constructors learned how to better manage numerous subcontractors, etc. Improving the interface between design and construction, esp. designing plants that are easier to build, was another source of such opportunities.⁴

It is reasonable to expect that idiosyncratic power plant design will contribute to difficulties in transferring what is learned from one project to the next. The intuition is that each different design poses new engineering and construction problems which would otherwise be avoided if the design was

As a consequence, designs were often only 30 percent complete at the beginning of construction. (See Theodore Barry & Associates (1979), OTA (1984)). However, leadtime and cost overruns eventually persuaded some in the industry that earlier completion of a project's design was a more economical approach to construction. St. Lucie 2 was an example of this change in philosophy (See Forbes (1985)).

stable over time.\textsuperscript{5}

The sources of this heterogeneity were numerous. Technological diversity (several types of NSSS), technological change (especially the scaling up of plant size, changes in NRC mandated safety requirements), seismic requirements that varied with geography, and diverse utility design preferences that affected a plant's layout, the choice of vendor equipment, the balance of plant and its interface with the NSSS, fuel management, etc., are all commonly cited.\textsuperscript{6} Note that some of these factors contributed to design heterogeneity among coal-fired plants as well (See Joskow and Rose (1985) for details).

- Industry and Organizational Structures

A. The Evolution of Contractual Forms

Nuclear power plant procurement occurred under two different contracting regimes. The earliest projects, managed wholly by the NSSS vendors, were contracted for on a fixed-price basis. These turnkey plants were ordered in the mid-1960s. Later in the 1960s and continuing to the present time, most contracts for plant engineering and construction were

\textsuperscript{5} Abernathy and Wayne (1974) make this observation in their study of innovation in the auto industry. Abernathy (1978) is also useful in this regard.

\textsuperscript{6} See OTA (1984) and Komanoff (1981) for a general discussion of these issues. OTA (1981) and Nuclear Engineering International (1977) address utility design preferences in greater detail.
cost-plus. Such contracts generally guaranteed an agent full cost reimbursement plus a fixed fee, or profit. (see Burness et. al., Theodore Barry & Associates (TBA), and NRC)

Explanations for this particular choice and sequence of regimes have focused on vendor strategies and the evolution of economic and technical uncertainty in the industry. Early on, the NSSS vendors needed to demonstrate to utilities that nuclear power was commercially viable. The problem they faced is one common to industries where dynamic increasing returns play a role. In the words of one observer,

In the early 1960s nuclear power remained uncompetitive with coal as a source of electricity...Nuclear energy was being stymied by a Catch-22 situation: so long as nuclear was more expensive than coal, no utility would order a nuclear power plant. Yet nuclear's costs would not fall until the manufacturers gained more experience building reactors. (Hertsgaard (1983), p.42)

Two vendors, General Electric and Westinghouse, overcame this obstacle by offering fixed-price contracts that were competitive with coal. Although the risks were high, both companies were betting that the experience gained from the turnkey projects would allow them to recoup any losses later on.

The turnkey strategy succeeded. Finding the vendors' terms attractive, utilities ordered more than a dozen turnkey plants during the period 1962-66. Although the vendors did suffer considerable losses, both utilities and their suppliers were convinced that the costs of subsequent plants would decline sharply. As a consequence, orders for nuclear plants
increased dramatically, producing the so-called "bandwagon market" of the late 1960s and early 1970s. In 1967 alone NSSS vendors received orders for thirty-one additional reactors.\(^7\)

This surge of orders occurred despite the fact that vendors had abandoned the turnkey approach to contracting: AEs and constructors now negotiated directly with the utilities. At the same time cost-plus contracting for design and construction services became more common; by the 1970s this form of contracting was predominant. According to the NRC,

The use of the cost-reimbursement contract...reflects the industry's response to the situation in which power plant construction begins before the design is complete, inflation results in the expectation of widely fluctuating cost of materials and labor, and regulatory ...uncertainties make architect-engineers and contractors reluctant to "lock in" fixed-price contracts. (NRC, 1984, Appendix C, p.15; see also TBA)

My own interviews suggest that fixed-price deals were still available early in the bandwagon phase of ordering. However, their cost far exceeded what utilities thought would be possible under cost-plus contracting. It would seem then that the utilities were less risk averse at this point, willing to bet that the technical and economic uncertainty facing them would be resolved in their favor.\(^8\) Transaction cost issues also figured in the choice of cost-plus contracts. The frequent design changes expected during the course of a

\(^7\) See Burness et. al., Bupp & Derian (1978), and Hertsgaard on the turnkey strategy, Atomic Industrial Forum (1986) on reactor order figures.

\(^8\) I am presently working on a paper which models technology choice under conditions similar to this case.
typical project were difficult and costly to anticipate; cost-plus arrangements afforded the desired operational flexibility.

This reliance on cost-plus contracting begs the question of how utilities planned to induce agent learning. Given their poor incentive properties, cost-plus contracts need to be supplemented by additional mechanisms. We consider this issue in the theoretical section below.

B. Utility Involvement in Project Management

An important organizational variable in these projects was the level of utility involvement (See TBA, Lester & Crocker, my interviews, NRC). The early, turnkey projects required no involvement aside from the provision of plant specs and some minimal design and cost oversight. After the shift to cost-plus contracting, several types of utility behavior can be identified.

A few utilities with large capacity needs employed in-house design and/or construction staffs. Although development of in-house expertise was costly the advantages of this approach included the elimination of agent fees and better coordination between design and construction. In contrast, firms with more modest nuclear programs hired outside contractors to perform most design and construction tasks. Among firms of this type, those utilities involved in their first nuclear project typically concerned themselves with
contract administration, ensuring that their agents adhered to contract terms. On subsequent projects, these companies gradually increased their ability to directly manage the construction process.¹⁹

This development of expertise entailed an evolution of organizational form: from delegation of all design and construction responsibilities, to an intermediate stage where utilities managed and coordinated an agent's design and construction activities.¹⁰ According to the TBA industry survey, these changes were part of a larger long-term strategy to reduce utilities' exposure to financial risk.¹¹

¹⁹ Of course, plans for "subsequent projects" were not always realized. Because of the unexpected halt in the growth of the nuclear industry - no utility has ordered a plant since 1978; all of those ordered after 1973 were cancelled by the mid-1980s - most utilities in 1990 operate far fewer plants than was expected in the early 1970s. One consequence of these events is a large number of nuclear utilities that never started (or completed) a second project.

¹⁰ These changes occurred only gradually because experience managing conventional or fossil fuel projects was not easily transferred to nuclear plants. (see interviews, TBA, OTA (1984), NRC.) As experience accumulated at the utility and industry level utilities were able to assume more responsibility. The secular increase in industry experience was important because it helped utilities compensate for their own lack of experience -- they hired experienced managers from other firms to oversee their own projects.

¹¹ In addition to the organizational changes this strategy had two other important elements: (1) Completion of a much greater portion of a project's design prior to the start of construction. and (2) the definition of numerous, limited-scope "work packages" for which agents would be willing to submit firm-price bids. Development of a utility's project management skills can be seen then as the third piece in this strategy. Because the activities of the various work package contractors would require coordination, an experienced utility could step in and fill this vacuum. Together, these
For our purposes, the important question raised by this "middle way" is whether or not agent learning was affected by an increase in utility responsibilities. Presumably, whoever manages the construction process is also the locus of learning. Hence, as project responsibility shifted from agent to principal so should the locus of learning. In the empirical section we attempt to model the impact of these organizational changes.

C. Agent Selection\textsuperscript{12}

Although competitive bidding was observed for cost-plus projects some utilities appear to have chosen agents on the basis of relationships established earlier for conventional power projects. Presumably, state public utility commissions allowed this behavior so long as cost estimates were in line with those elsewhere in the industry.

The tendency of some utilities to prefer particular agents resulted in behavior which was not necessarily optimal. During the turnkey phase the NSSS vendors offering fixed-price contracts chose the AEs, constructors and other subcontractors. If these agents happened not to be the utility's traditional partners then it was not uncommon during various reforms were expected to reduce costs and, perhaps most important, to introduce risk sharing among the parties. Unfortunately for the utilities, the first nuclear era ended before this strategy could be widely implemented.

\textsuperscript{12} This section is based on interviews conducted with various industry participants.
later cost-plus projects -- when the utility was responsible for selecting agents -- to abandon these companies in exchange for familiar faces. If the associated switching costs were large, then construction costs for subsequent projects were likely to be higher than for projects where continuity was observed.

Other changes in the identity of agents working for a particular utility occurred primarily because the former were perceived to have taken on too many additional projects. Several firms experienced shortages of experienced managers, engineers, and construction workers during the bandwagon phase of plant ordering (see OTA (1984)). Faced with a choice between the "second-string" design/construction team of a familiar company and a new agent's more experienced staff, some utilities chose the latter option. Although either alternative might have increased the costs of subsequent plants, only the latter choice can be observed. We discuss these potential switching costs in the theory section below.

D. Industry Structure

Studies of the U.S nuclear power industry often focus on the relatively fragmented structure of the reactor supply and operations segments and its impact on performance. (See Lester (1986), Lester and McCabe (1990)) Compared to other nations, most notably France, the number of NSSS vendors, AE/constructor firms and nuclear utilities is large.
In the U.S. four firms designed NSSSs. General Electric sold boiling water reactor (BWR) systems. Westinghouse, Babcock and Wilcox, and Combustion Engineering each marketed a version of the pressurized water reactor (PWR).

Numerous companies, including the utilities themselves, provided AE/constructor services. In the data set employed here --a total of 105 reactors, including 14 turnkey and 91 cost-plus units -- 15 AEs and 21 constructor firms can be counted (the numbers differ because the same firm did not always serve in both roles). Among these firms the lion's share of AE contracts went to Bechtel Corp., which designed 39 reactors in the data set (4 turnkey and 35 cost-plus projects).\(^\text{13}\) Other firms, with five or more AE contracts, included Stone & Webster (1 turnkey, 12 cost-plus), Sargent & Lundy (4,8), Ebasco (2,5), United Engineers & Constructors (UEC) (1,4) and Gilbert (1,4). Two utilities acted as both AE and constructor for large nuclear programs: Duke Power with 7 units (the first three involved some collaboration with Bechtel) and the Tennessee Valley Authority (TVA) with 6 units.\(^\text{14}\)

\(^{13}\) Presumably, this dominant position in the industry reflected an early cost and/or scale advantage -- enhanced perhaps by the several turnkey contracts (only Sargent & Lundy had as many) -- that was later successfully exploited to increase market share.

\(^{14}\) Nuclear News' annual World List of Nuclear Power Plants has information on AEs and constructors associated with various projects. See Burness et. al. or Komanoff (1981) to identify which projects were turnkey or cost-plus.
Although many AE/constructor firms obtained contracts during the early turnkey phase of the industry's history, later entrants were observed despite the incumbents' apparent experience/cost advantage. My interviews suggest that some of the latter benefited from long-standing relationships with particular utilities. Shortages of qualified personnel among "experienced" firms may have also encouraged entry.

Aside from the two significant in-house utilities, a number of other utilities built several units. The largest among these was Commonwealth Edison with 4 turnkey and 7 cost-plus projects (ComEd acted as its own constructor on the cost-plus units). Florida Power & Light and Virginia Power each hired agents for 4 units. Five utilities built 3 units, eleven other companies completed 2 reactors and twenty-seven firms constructed a single unit.

As these numbers might suggest, some utility companies built reactors throughout the "first" nuclear era, from the turnkey period in the mid-60s to the late 1980s when construction on plants that had begun as late as 1978 was finally completed. Many other utilities made brief appearances on the construction stage, some ordering a single turnkey unit early on and others making their first (and last) orders in the mid-70s.

2. Theory
- Incentives for Cost Reduction

Earlier it was argued that transaction costs and agent risk aversion help explain the choice of cost-plus contracting by the nuclear industry following the initial turnkey projects. Although this form of contracting provides no explicit incentive for cost reduction it is still possible to elicit effort from agents if their interactions with principals are repeated over time.

The basic idea is to offer the agent a rent in each period, contingent upon some observable but not verifiable dimension of past performance.\(^\text{15}\) If the agent shirks, then the principal stops offering the rent in future periods. Since this threat is credible, the agent may decide to exert effort in equilibrium. This approach, now common in the literature on managerial incentives, can be formalized using the theory of supergames (see Tirole (1988) and references cited therein).

This dynamic perspective can accommodate the case of nuclear power. There is no evidence that experience-based cost reduction was a verifiable dimension of performance. And each cost-plus contract guaranteed a rent in the form of a fixed fee or profit, regardless of project costs. These elements together with the fact that construction was initially expected to continue into the indefinite future

\(^{15}\) If performance was observable and verifiable then a forcing contract would provide first-best incentives.
provide the justification to model learning in the industry as a supergame.

However, one potential difficulty in applying this approach to the nuclear case arises over the issue of observability. Unlike the basic supergame story, inferences about a single agent's past performance may not have been possible without using information about other agents' costs. This is because technological change and regulatory instability are likely to have rendered useless any attempt to compare a single agent's costs over time. Under these conditions, a principal's job of sorting out the effects of agent learning from other confounding factors is made much easier if some form of yardstick competition exists. Of course, implementing such an approach when agents' projects exhibit design heterogeneity poses some additional practical problems.\(^\text{16}\)

In the next two sections we model learning in the nuclear industry as a supergame. First, we consider the basic supergame where problems of observability do not exist. In the second section we show how yardstick comparisons can be used to mitigate these problems.

\(^{16}\) See Shleifer (1985) and cites therein on yardstick competition. Joskow and Schmalensee (1986) discuss the practical problems with this approach. Note, however, that these discussions focus on one-period games where yardstick competition relies on the correlation of agents' technologies but not on the nonverifiability of performance. Our supergame approach incorporates both factors.
A. The Basic Supergame

There are two participants in this game: a principal, P, and its agent, A. Their common discount factor is $\delta$. P has plans to hire A to build a single plant in each of the T=\infty periods. The design and construction process exhibits dynamic increasing returns due to learning. Prior to the start of the game a single (turnkey) plant has been constructed at cost $C_0$; the experience gained from this project is available to A in the game's first period.

Contracting is of the cost-plus form, $C + F$, where $C$ is the realization of plant costs and $F$ is a rent chosen by P. $C$ is observable by both parties. At the beginning of period $t$ the principal offers A this contract, with the value of $F$ contingent on A's performance history.

After receiving a contract in period $t$, A chooses between two levels of cost-reducing effort, $E_L=0$ and $E_H=S$ ($S>0)$,

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17 This infinite horizon need not be taken too seriously. One can introduce the possibility that P's future plans are contingent without affecting the results. Suppose that for each period the probability is $x$ (where $0<x<1$) that P's plans "survive", that is, P continues to build plants in this and future periods; $1-x$ represents the probability that P's need for additional plants disappears, or perhaps, that the technology becomes obsolete. Thus, the game ends in finite (but stochastic) time with probability 1 (since $x^\infty=0$). One can then define a new discount factor, $\delta'=\delta \cdot x$, which preserves the appearance of an infinite horizon in the supergame. See Tirole (1988), Chapter 6 for more on this point.

Note that this stochastic interpretation is implicit in our use of a supergame model to explain behavior in the nuclear industry. A halt in plant construction (as observed in the 1980s) can be seen as an event which had a nonzero probability in each period of the industry's history.
expressed in their monetary equivalents. If A chooses $E_L$ then no cost reduction takes place during $t$; if $E_H$ is chosen then the efficient amount of cost reduction results (efficient in the sense that the marginal benefits and costs of this activity are equated). A’s objective is to maximize the present discounted value of its cost reduction efforts:

$$\sum_{t=1}^{\infty} \delta^{t-1}(F_t-E_t)$$

(1)

P’s objective is to maximize the present discounted value of the net benefits from cost reduction:

$$\sum_{t=1}^{\infty} \delta^{t-1}(\Delta C_t-F_t)$$

(2)

where $\Delta C_t$ is the amount of cost reduction in period $t$. If high effort is supplied by A in period $t$ then $\Delta C_t=\Delta C$; otherwise, $\Delta C_t = 0$. In other words, we assume that the potential for cost reduction is constant over time.\(^{18}\) We also assume that

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\(^{18}\) This assumption deviates from the standard belief that learning exhibits diminishing returns over time, that is, $\Delta C_t$ is declining in $t$. It also implies that plant costs can be negative in the future. This condition can be relaxed without affecting the basic results if we assume that $E_H$ declines at the same rate as the potential for cost reduction. This insures that the agent receives positive benefits from exerting effort in each period.

Objections to $\Delta C$, being constant lose some of their bite if one considers two facts about nuclear power. One, average construction costs escalated throughout the first nuclear era. Two, a large portion of this inflation was real, due to frequent changes in technology and safety requirements. Thus, it is quite possible that these changes generated new opportunities for learning in design and construction, postponing the onset of diminishing returns. At the same time, the real cost increases may have exceeded the opposite effects of learning. It is then easy to imagine a scenario
ΔC_t - E_u = S. Thus, cost reduction is socially desirable in any period t.

Finally, we assume that, given C_0, ΔC and C_t,...,C_{t-1}, P was able to distinguish between low and high cost outcomes in periods 1,...,t-1, prior to the start of period t (yardstick comparisons are not required). Thus, P is able to offer a contract in period t with full information about A's performance history.

Now consider the firms' strategies. We require that strategies form a perfect equilibrium. That is, for any history at date t, P's (A's) strategy from date t on maximizes the present discounted value of its profits given A's (P's) strategy from that date on. Suppose P adopts the following strategy: in period one, a contract is awarded with F_t > 0. The same rent is offered in period t if in every period preceding t the agent has reduced costs efficiently. Otherwise, F is set equal to zero forever (the "grim strategy"). Given P's strategy, A will choose the level of effort in period t that maximizes (1).

Cost reduction is an equilibrium if the discount factor is sufficiently large. To see this, first consider A's effort decision in period t. If A shirks, he earns F_t in profits during t but then receives zero forever more. However, if A exerts high effort during t and all future periods then his

where plant costs are stable or even increasing over time, despite the contribution of learning in each period.
profits are

\[(F_t - S) \cdot (1 + \delta + \delta^2 + \ldots) = (F_t - S) \cdot (1 / (1 - \delta)) \tag{3}\]

Comparing these two payoffs, \( A \) will reduce costs if

\[F_t \leq (F_t - S) \cdot (1 / (1 - \delta)) \tag{4}\]

or,

\[S / F_t \leq \delta \tag{5}\]

Knowing this, \( P \) will choose \( F_t \) to satisfy (5) so long as the inequality

\[\Delta C \geq F_t \tag{6}\]

is also satisfied in each period. Thus, when both (5) and (6) hold a "learning" equilibrium exists where \( A \) exerts a high level of effort in each period.\(^{19}\) Efficient cost reduction over time is the observed result.

B. The Yardstick Supergame.

Here we relax the assumption that \( P \) is able to distinguish between low and high cost outcomes in the periods prior to \( t \) by using information on \( A \)'s cost over time \((C_1, \ldots, C_{t-1})\) and knowing \( C_0 \) and \( \Delta C \). Because of the uncertain impact of various technological and regulatory shocks on plant costs, \( P \) and at least one other principal must implement a system of yardstick competition where different agents' costs

\(^{19}\) It is easy to show that behavior off the equilibrium path is sub-game perfect.
can be compared, and thereby provide an indicator of individual agents' performances.\textsuperscript{20}

To keep things simple suppose that there are two principals, $P$ and $P'$, each hiring an agent, $A$ and $A'$, respectively, to build a single plant in each of the $T=\infty$ periods. We assume that plant designs are identical in any given period, though they may differ from period to period due to exogenous technological and regulatory factors.

The other assumptions of section 1 apply to both principal/agent pairs and are symmetric, e.g., a common discount factor, $\delta$, for all parties, the same initial costs, $C_0$, etc., except that $P$ and $P'$ need to compare their agents' costs to make inferences about agent performance. Of course, we also need to insure that these cost comparisons are themselves feasible: besides the factors influencing plant design we assume that exogenous economic shocks, e.g. inflation, in period $t$ are perfectly correlated. Thus, if effort levels have been identical during periods $1, \ldots, t-1$, and are the same in period $t$, then period $t$ costs will be the same.

Now consider the firms' strategies. As before, we require that strategies form a perfect equilibrium. Suppose $P$ adopts the following strategy: in period one, a contract is

\textsuperscript{20} A simpler alternative is to have a single principal hire two or more different agents to compete in each period. However, because this choice was not observed in the nuclear industry, we address the slightly more complex case of multiple principals.
awarded to A with F₁ > 0. The same rent is offered in period t if in every period preceding t A's costs are the same as A''s costs. Otherwise, P is set equal to zero forever. Given P's strategy, A will choose the level of effort in period t that maximizes (2). The same set of strategies are adopted by P' and A', respectively.

Provided that (5) and (6) are jointly satisfied, then it is clear that both agents exerting the high level of effort is an equilibrium. If A expects A' to reduce costs in period t and all future periods, then A reveals that he did not exert effort by building a plant at higher cost in the same period. Upon observing the high cost P offers A a zero rent in all future periods. Of course, if this expectation is reversed - A does not expect A' to reduce costs in period t or any future periods - then both agents shirking is an equilibrium as well.

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21 By jointly satisfied we mean that, contingent on both having exerted effort in the earlier periods, A's choice of high effort in period t is optimal given expectations that A' will do the same during t and all future periods.

22 Of course, if A shirks and A' doesn't then P' has no means by which to induce effort in future periods -- P's grim strategy eliminates any hope of future competition and P' responds by offering a zero rent to A' in future periods as well. Adding more principal/agent pairs does not remove this externality; with n pairs, it is possible that n-1 agents may shirk.

23 Elimination of this shirking equilibrium is possible if the principal(s) can make credible promises to reward hard-working agents. Suppose in period t that A shirks and A' exerts effort. A' then has lower costs for all future periods, given the grim strategy. P and P' would prefer to hire A' for any future projects. Provided that A' can meet the increased

1. Single-Period Principals

Our supergame analysis assumed that principals participated in the game for all $T=\infty$ periods. However, as described earlier, many utilities did not sustain a presence throughout the first nuclear era.\(^{24}\) Many firms appeared for a single period and were otherwise absent. Our framework can accommodate this feature of the industry if one assumes that a series of $T$ different principals, each appearing in the market for one period, have the same information as a $T$-period firm in period $t$.

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\(^{24}\) Using dates for construction permits (CP) and commercial operation (CO) three distinct "periods of construction" can be identified industry-wide during this era. The first period is defined in terms of the CP and CO for the first operating commercial reactor; the second period is defined in terms of the first reactor completed with a CP later than the CO of the first commercial unit; etc.
2. Design Heterogeneity and Learning

In the yardstick supergame we assumed implicitly that the two principals had identical design preferences. If we relax this assumption then it is necessary for the principals to be able to calculate how these differences affect their agents's costs over time. With single-period principals this calculation becomes more complex as time increases since the set of relevant designs increases as well.

An additional issue arises with single period principals. If an agent faces a different set of preferences in each period then it is likely that the potential for cost reduction in any period, $\Delta C$, will be smaller than if the preferences had remained constant with a T-period principal. Since the learning equilibrium requires that $\Delta C \geq F_t$ a decrease in $\Delta C$ means that cost reduction will occur for a smaller range of $F_t$.

Finally, if we mix single-period principals with T-period principals - as actually observed in the nuclear industry - the analysis is much the same.

3. Principals Involved in Construction

Since hiring an agent is costly for the principal - $F_t$ in each period - T-period firms may choose to design and construct plants themselves, saving $(F_t) \cdot (1/1-\delta)$ over $T=\infty$ periods. Balanced against these savings are the costs of developing in-house design and construction teams. Recall that
the largest utilities did in fact assume direct responsibility for one or both of the major supply functions.25

Single-period principals are less likely to choose this path because, compared to more experienced agents, they are too far up the learning curve. Of course, if δ is too small both classes of principals will have to exercise this option if cost reduction is desirable.

4. Agent Switching

In the first part of the paper we described how some "T-period" utilities changed agents over time because of staffing shortages or the desire to reestablish relationships with traditional partners. Under conditions of design heterogeneity this behavior transforms a T-period principal (not directly involved in project management) into a single-period principal from the perspective of the agents. Since

25 These two alternatives, hiring an agent on a cost-plus basis or in-house procurement, did not encompass the full range of choices available to multi-period utilities. Earlier we described how firms with medium-sized nuclear programs gradually became involved in project management as part of a long-term strategy to introduce risk-sharing (rather than save on agent fees). If the in-house or project management options were preferred by all multi-period firms, then the yardstick model may be relevant only when agents are hired by single period firms (and multi-period firms that have not yet developed the know-how to assume responsibility for project management).
the value of an agent's prior experience is less when it faces a new set of design preferences in each period, $\Delta C$ is lower in each period when a $T$-period principal changes agents. If a $T$-period principal is involved in project management, then agent switching may have additional costs.\textsuperscript{26}

5. Project Overlap

So far, our characterization of cost reduction has ignored the possibility of an agent's projects overlapping in time. Although this approach simplifies the discussion, it is necessary to relax this assumption to accommodate reality - project overlap was commonly observed in the nuclear industry.

When a project's completion date overlaps with the construction start date for another project two questions need to be addressed:

(1) How is the potential for cost reduction, $\Delta C_t$, affected?

With overlap the total number of projects completed prior to the start of the $n$\textsuperscript{th} project may no longer an integer. For example, if a project begun prior to the $n$\textsuperscript{th} unit is completed after the latter's construction start date then there is some fraction added to this total. It is reasonable to assume that "project fractions" are useful for cost reduction but that the potential size of a corresponding reduction is always strictly less than what would result if the "fractional" project was

\textsuperscript{26} Based on interviews with utilities that changed agents, these costs include the thousands of man-hours spent "getting the agent in sync with how a utility runs a project".
first completed.

A second issue that arises is how to treat the overlap itself when cost reduction for later projects is considered. Suppose the overlap is perfect, that is, an agent builds two or more projects concurrently. Is it reasonable to assume that the potential for cost reduction on a subsequent project is greater in this case than if the agent had built a single project in the prior period? Presumably, when an agent firm works on several projects at once the number of managers and engineers employed increases as well. Even if the plant designs are heterogeneous it may be that a larger "collection of minds" will enhance the cost reduction process.\(^{27}\) At the same time it is probably true that two or more projects built in series with no overlap offer a greater potential for cost reduction than when built concurrently. The assumption here is that successive rationalizations of the design/construction process are a more fertile source of cost reduction than a one-time brainstorming by a larger number of participants.\(^{28}\)

(2) How are an agent's effort costs allocated across parallel

\(^{27}\) Note that this assumption is implicit in existing studies of learning in power plant construction. In fact, these studies make no distinction between plants built concurrently and those built in series.

\(^{28}\) Project overlap and its effect on costs is to some extent an endogenous phenomenon, affected by fluctuations in demand for agent services, the supply of experienced engineers and managers, agent entry, etc. A detailed discussion of these issues is beyond the scope of the present paper.
projects?

Although some of an agent's cost-reducing efforts may be specific to individual projects (due to different designs), in any given period there are likely to be aspects of the learning process that are common to overlapping projects. This suggests that some of the corresponding effort costs can be spread over several projects, which in turn reduces the size of the rent necessary to elicit high levels of effort from the agent.

3. Empirics

Our modeling of cost reduction in the nuclear powerplant construction industry yields several testable hypotheses which we consider in this section. Past studies are evaluated against this framework. Because the earlier research fails to adequately address these hypotheses we also present results from an empirical model that is better specified for this purpose.

- Testable Hypotheses

A direct test of the model, in its basic or yardstick form, would require detailed information on actual project costs, firms' discount rates, the cost of effort to agents, the size of the fixed fees paid to agents, the potential for cost reduction, $\Delta C$, the extent to which effort was observable
by principals, etc. Unfortunately, only the first of these—actual project costs—is readily available. Thus, like past investigators in this area, we will rely on a less direct approach, one that involves regressing observed costs on various measures of agent and principal experience in addition to plant characteristics. In this way, we can evaluate whether the evidence is consistent with some aspects of the theory.

Of course, the primary question to be answered is simple: was there any learning in the industry and if so, by whom? Even if yardstick competition was difficult to implement, in-house firms should have exploited whatever potential existed for cost-reduction. With yardstick competition we can expect to observe learning by outside contractors as well.

Other questions open to investigation include the differences that probably existed between agents working for single period principals and those employed by T-period principals. Assuming that yardstick competition was effective and that principals' design preferences varied cross-sectionally, we can expect these two types of interaction to be associated with distinct learning curves. In particular, agents hired by a series of single-period firms should have reduced costs less rapidly. The same conclusion holds when a T-period firm assumes responsibility for project management except that the locus of learning may shift from agent to principal. Also, multi-period utilities that performed some
or all of the design and construction tasks associated with their plants should be classified together with agents working for T-period principals.²⁹

A related question involves T-period principals that hired outside contractors and switched them between projects. From the perspective of our model, this behavior should result in less cost reduction because the utility is transformed into a single-period firm from the agents' perspective. At the same time, if these principals were involved in project management then agent switching may have imposed additional costs. This is because considerable time and effort has to be invested before a new agent can understand a utility's approach to construction. Although it may be impractical to measure these separate effects, agent switching can be expected to increase the costs of subsequent projects.

Finally, there are two questions of model specification which are relevant to the supergame model. First, recall that in the supergame model we assumed that Δc was constant over time. This departure from the conventional story of diminishing returns can be "tested" by comparing the empirical results from linear and log-linear specifications. Log-linear models assume that learning diminishes over time; with a linear specification, the accumulation of agent experience is

²⁹ Because these utilities also saved on rents paid to agents the fixed effects (see below) associated with in-house firms should be lower than those of other agents, everything else equal.
assumed to have a constant effect on costs. Second, we can
measure experience as series learning or concurrent learning.
Contrasting the results when these different measures are used
may provide some indication of how project overlap affects the
potential for cost reduction.

- Previous Studies

Over the past decade several studies of learning in
nuclear power construction have found evidence that plant
costs are decreasing in AE or constructor experience (see
Cantor and Hewlett (1988), for references). Although none of
these analyses distinguished between single period and $T$-
period learning, several did specify a dummy variable equal to
one when a utility acted as the AE and/or constructor and zero
otherwise ("self-AE or constructor"); such firms usually, but
not always, built several plants. Typically, this dummy's
coefficient is significant and has a negative sign, that is,
costs are lower when projects are built by in-house
principals. Most authors attribute this result to utilities'
greater interest in controlling costs.\(^{30}\)

On the surface, these results seem to confirm that
incentives existed for cost reduction. The dummy variable
result is more difficult to interpret since no corresponding

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\(^{30}\) For example, Zimmerman (1982) argues that this variable
measures the rents captured by experienced AE firms which are
passed through to consumers when utilities act as their own
AEs.
T-period experience variable is included for in-house firms. Cantor and Hewlett's more recent analysis of this data raises doubts about the evidence for AE learning while making some progress in understanding the role of utilities in cost reduction.

Cantor & Hewlett (C&H) failed to find any evidence for agent learning. To investigate the role of utilities they specified a variable equal to the product of agent experience and a "self-constructor" dummy. The corresponding coefficient estimate was large and significant, indicating that utilities acting as their own constructor reduced costs over time. (The self-constructor variable is still negative and significant in their specification)

It turns out that the differences that exist between earlier studies and C&H on the issue of agent learning can be partially resolved by respecifying the models used to estimate learning effects. C&H's model includes a variable which measures construction duration, otherwise known as a unit's "leadtime". Three of the four studies cited by C&H - Zimmerman's 1982 study is the one exception - fail to incorporate a leadtime variable (see Mooz (1979), Paik and Schriver (1979) and Komanoff (1981)); all four report significant learning by agents. When included in a cost

31 These differences are not sensitive to the approach used for calculating unit costs. Two standard methods are employed, the "model cash-flow profile" (MCFP) and the "actual cash-flow profile" (ACFP). (See McCabe (1986), EIA (1986)). C&H employed ACFP; other studies have used MCFP.
equation, the leadtime coefficient is normally large, positive, and significant, indicating that plant costs are increasing in the time required for construction.\textsuperscript{32} Omitting this variable from the estimation could very well bias the results.

To explore this possibility, I re-estimated Komanoff's model using the same set of observations, variables, estimation method, etc., except that a leadtime variable was added. Using this specification, agent learning disappears but the leadtime coefficient is positive and significant. This corresponds to C\&H's result. Unfortunately, Zimmerman's results remain at odds with this finding. His model's estimates support both agent learning and the leadtime effect. I was unable to replicate his results.

Thus, to date, there is weak evidence at best supporting the proposition that utilities hiring outside contractors to build nuclear plants benefited from cost reduction. This raises questions about the viability of yardstick competition in the nuclear industry.\textsuperscript{33} Alternatively, this result may

\textsuperscript{32} Potential explanations for this result are supplied in C\&H.

\textsuperscript{33} Joskow and Rose's 1985 study of coal plant costs included experience variables for AEs and utilities. Significant cost reduction was associated with both variables. These results indicate that yardstick competition was effective (contracts for coal plants were also cost-plus during their sample period). Their study can also be interpreted as supporting the hypothesis that diverse utility design preferences reduce the potential for cost reduction when agents face a series of different principals.
reflect the failure of past studies to account for the project management role of some multi-period utilities. Also, no attempt has been made to address the question of agent switching or the possibility that cost reduction opportunities did not diminish with time. Finally, existing studies of learning in both the nuclear and conventional sectors have failed to test whether cost reduction is sensitive to the learning type - series or concurrent.

- The Empirical Model

1. Reduced Form vs. Structural Model

   To address these questions about learning it is necessary to properly specify the cost function, controlling for other factors that affect construction costs. Past studies have adopted one of two strategies. The easiest and most common approach involves a reduced form specification where plant costs are regressed on a set of plant characteristics and experience measures, all of which are assumed to be exogenous (see, for example, Joskow & Rose, and Zimmerman).

   Others have adopted a two-equation structural approach that models the utilities' choice of project duration or leadtime (see Rothwell (1986) and C&H). In these studies, the size and timing of new capacity additions are assumed to be exogenous, reflecting growth in electricity demand and/or the need to replace obsolete plants. The choice of optimal leadtime then involves minimizing the impact of leadtime on
plant costs, given interest rates, factor prices and the production relationship between factor inputs, plant size and project duration. Thus, leadtime is considered to be an endogenous variable; the one earlier study to include leadtime as an explanatory factor - Zimmerman's paper - assumed otherwise.

This structural model is typically specified as a recursive two equation system: (1) an equation that measures the direct effect of size and other factors on leadtime and (2) an equation that measures the direct effects of size, leadtime, etc. on costs. Scale economies are then calculated by combining the direct and indirect effects of size on costs.\textsuperscript{34} When measures of experience are added to these equations the only significant effects are observed in the second equation (see C&H). This suggests that by estimating equation 2 alone one can capture the entire effect of agent learning. For this reason we adopt a simpler approach below,

\textsuperscript{34} More formally, if $C=C(Q,L(Q))$ then the elasticity of cost with respect to size is

$$(\frac{d\ln C}{d\ln Q}) = \frac{(\frac{d\ln C}{d\ln Q}) \cdot (\frac{d\ln L}{d\ln L})}{(\frac{d\ln L}{d\ln Q})} \quad (a)$$

where $C$, $Q$ and $L$ are plant costs, size and leadtime, respectively. $L(Q)$ represents the first equation and $C(Q,L)$ the second in the recursive system described above. In the papers by Rothwell and H&C $\frac{d\ln C}{d\ln Q}$ is found to be positive for nuclear power, that is, costs are increasing in size, contrary to expectations. The three bracketed terms on the right hand side of (a) are significant and respectively, negative, positive and positive in sign. (Note that these authors did not include interest charges when calculating plant costs. We discuss this issue below.)
that is, we estimate only equation two.\footnote{To check for any indirect effects from learning, I estimated equation one, regressing leadtime on all the other variables used in this study except for cost. This reveals very small and insignificant effects due to experience. Thus, this approach is satisfactory for our purposes.}

2. Factors Affecting Plant Costs

As suggested above, reactor size and project duration are important explanatory factors. Larger nuclear plants were expected to benefit from scale economies. However, when both the direct and indirect effect of size on costs are considered net diseconomies are observed. Though the reasons for this result are not clear it has been suggested that the greater complexity of large plants reduced productivity enough to eliminate any beneficial scale effects (see C&H).

Besides the financing costs normally associated with a project's leadtime, there are several unobservable time-related factors that are likely to have an impact on the "bricks and mortar" costs of a plant. For example, shorter leadtimes require more inputs per unit of time; if input prices are increasing in the quantity demanded then, everything else equal, a speedup in construction would result in higher costs. However, other factors might work in the opposite direction. In particular, projects with longer leadtimes may be subject to more numerous design changes as safety regulations change over time. The net effect of these and other factors is an empirical question; past studies
indicate that plant costs, minus interest charges, are increasing in leadtime (see C&H for a more complete discussion of this issue).

In addition to plant size and leadtime several other variables are typically included in empirical models to account for regional cost variation, accounting effects and technological change. Even though we employ a regional price index to convert nominal plant costs to "overnight" or constant dollar terms (see the Appendix), regional differences in the level of input prices may still confound estimates of learning. A likely source of this variation, due to the existence of regional labor markets, is the wage paid to construction workers. To correct for this effect, a wage variable is added to the model. Everything else equal, more expensive plants are expected to be found in higher wage regions.

Another potential problem arises from the "first-unit effect". Many of the units in our data set are located at multi-unit sites. There are substantial common costs associated with design work, site procurement and preparation, spent-fuel storage facilities, etc. Because of utilitycommission rate-setting procedures, utilities have a strong incentive to assign as large a fraction of these common costs as possible to the first unit built on a site (see Joskow and Rose). Unless we control for this effect our learning estimates may be biased upward since follow-on units are more
likely to be built later in time.

Finally, changes in technology and NRC regulations are expected to (monotonically) increase plant costs over time. This effect is usually captured by specifying a time trend variable based on a significant design/construction milestone, such as the date on which a unit's construction permit was granted.

3. Construction of the Cost Variable

The plant costs reported by utilities are the sum of nominal expenditures on design and construction (bricks and mortar costs) and the associated financing costs.\(^{36}\) During the sample period input prices and interest rates often changed. To explore whether real construction costs declined with experience we would like to deflate these nominal expenditures to account for the change in prices and interest rates. In principal this is a straightforward exercise, provided that the appropriate information on expenditure patterns, capital costs, price changes, etc., is available. However, past studies have approached this problem by subtracting out AFUDC charges from reported costs and deflating the remaining expenditures on bricks and mortar,

\(^{36}\) Most U.S. utilities are not permitted to recover costs incurred by construction until a plant begins operation. To compensate for this delay, state utility commissions allow firms to add a financing charge to final project costs which is known as AFUDC or Allowance for Funds Used During Construction.
creating what is known as a plant's "overnight" costs.

Although the overnight cost of a project fails to measure the full economic cost of plant procurement, this choice does not bias comparisons of relative economic costs so long as real interest rates, leadtimes and cash-flow profiles are the same across projects. This assumption does not hold in practice: it is well known that leadtimes and expenditure patterns varied widely among nuclear (and conventional) projects (see EIA (1986), McCabe).

However, calculating real financing costs is a difficult task, in part because utility AFUDC rates often diverge from the firm's marginal cost of capital and because arriving at the correct market valuation requires the collection of so much additional information (see C&H, footnote 7). Thus, most attempts to compare power plant costs have relied on the easier overnight cost calculation. Implicit in these comparisons is the understanding that longer leadtime plants, for example, have higher economic costs even if overnight costs do not differ. Overnight costs are used in this paper as well.37 Details on their calculation are provided in the Appendix.

37 Despite the fact that financing cost are ignored here this choice will bias estimates of learning less than those of variables which are correlated with project leadtimes. Recall, for example, that plant size is positively correlated with leadtime; the financing costs associated with larger plants are thus higher, everything else equal. However, since the experience measures used in this study are not correlated with leadtime (in "equation one"), the economic impact of agent learning can be estimated using "equation two" alone.
4. The Model

The previous discussion suggests a construction cost function that relates a unit's overnight cost to a unit's size, the length of construction, regional effects, its order of appearance at a site, changes in technology and safety regulations and the experience of individual agents. Following past studies we specify the relationship between a unit's cost and its size and leadtime to be Cobb-Douglas. A linear specification is also considered.

We estimate the following cost function:

\[
(L)\text{COST} = \beta_1 + \beta_2 \cdot \text{FIRST} + \beta_3 \cdot \text{WAGE} + \beta_4 \cdot (L)\text{SIZE} + \beta_5 \cdot (L)\text{LEAD} \\
+ \beta_6 \cdot \text{CSD} + X_i \cdot \beta_i + \epsilon
\] (1)

where

- \( \beta_1 \): the intercept.

- (L)COST: (log of) a unit's overnight cost/kw in 1984 $.

- FIRST: a dummy variable equalling one when the unit in question is the first at a plant site and zero otherwise.

- WAGE: the regional average union wage for construction workers in 1976 for the Bureau of Labor region in which the unit is located.

- (L)SIZE: (the natural log of) unit size expressed in

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\(^{38}\) An industry-wide experience variable was not included here because it suffered from collinearity with the other time-trend variable in the model, the construction start date.
megawatts.

- (L)LEAD: (the natural log of) a unit's construction leadtime expressed in months. Leadtime is calculated using the unit's construction permit date and the date of commercial operation.  

- CSD: a unit's construction start date in months with the earliest month observed set equal to one (the construction permit date is used as a proxy for the start of construction).

- $\epsilon$: the error term; its structure is discussed in the section below.

- $\mathbf{X}_i \cdot \mathbf{B}_i$: $\mathbf{B}_i$ is a $K_i \times 1$ coefficient vector with $i$ ($i=1,..,5$) indicating the relevant specification of the learning variables; $\mathbf{X}_i$ is the corresponding $Z \times K_i$ vector of learning variables. We define these several alternatives below together with brief interpretive comments. Specifications 1 and 2 ignore the possibility that the locus of learning shifted when multi-period firms (relying on outside contractors) became involved in project management. Specifications 3, 4 and 5 incorporate this possibility. In the Results section further motivation is given for each specification.

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39 For some recent projects the date of commercial operation was delayed (sometimes indefinitely) despite the completion of construction activities. Seabrook in New Hampshire and Shoreham on Long Island are good examples of this phenomenon. In these cases, utilities reported when the project was complete; this date, rather than the commercial operation date, is used to calculate the unit's leadtime.
Specification 1:

- **AEexp**: the experience of a unit's AE, defined as concurrent (the sum of completed and % completed units) or series learning (completed plus % completed project generations), prior to the issuance of the construction permit (CP).

**Comment**: When concurrent measures of experience are used this specification corresponds to that seen in most of the earlier studies.

Specification 2:

- **AEexp**

- **T-period dummy·AEexp**: the T-period dummy equals one when the unit in question is at least the second non-concurrent project built by a given AE for the unit's principal and zero otherwise (two units are considered non-concurrent if their CPs were not awarded in the same month).

**Comment**: The composite variable, T-period dummy·AEexp, tests whether agents employed by the same principal for successive projects reduced costs more than when the principal's identity changed, given stability in principals' design preferences over time.

Specification 3:

- **S-Period AEexp**: the experience of a unit's AE, defined as concurrent or series learning, prior to the
issuance of the CP, when the unit's principal had not already begun construction on other projects, or, if construction had already begun on other projects, the experience of the AE that built the earliest of these projects, at the time of that project's CP issuance.

- **T-Period Utility Exp**: the experience of a unit's principal, defined as concurrent or series learning, prior to issuance of the unit's CP.

- **ΔAE**: a dummy variable equalling one if the unit's principal has changed AE's for this project and/or a project with an earlier CP date, and zero otherwise.

**Comment**: Specification 3 assumes that increases in AE experience are useful so long as a principal's prior experience is zero. **S-Period AEexp** is the same as AEexp except that its value at the start of a T-period principal's construction program (when the principal's prior experience is zero) is held constant for all later projects overseen by that same principal. **T-Period Utility Exp** is self-explanatory. ΔAE measures the costs of switching agents for a T-period principal.⁴⁰

**Specification 4:**

- **S-Period AEexp**

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⁴⁰ There were three instances where firms changed agents twice. Thus, ΔAE is a rather crude measure of switching costs. Specifications 4 and 5 are better specified to capture this fine structure.
- T-Period AE-UTIL Exp: the experience common to a unit's AE and Utility, defined as concurrent or series learning, prior to issuance of the unit's cp.

Comment: In this specification, T-Period AE-UTIL Exp replaces T-period Utility Exp and ΔAE. This variable assumes that cost reduction by an agent for a principal with prior experience is entirely relationship-specific. That is, if a principal switches agents, then costs for the subsequent plant are at the level observed when the principal had no prior experience.

Specification 5

- S-Period ΔAEexp: the experience of a unit's AE, defined as concurrent or series learning, prior to the issuance of the CP, when the unit's principal had not already begun construction on other projects, or, if construction had already begun on other projects using the same AE, the experience of the AE at the CP issuance date of the first of its projects for the unit's principal.

- T-Period AE-UTIL Exp

Comment: S-Period AEexp is replaced by S-Period ΔAEexp to test whether increases in AE experience are utilized so long as an agent has never before worked for a particular principal (rather than just if a utility's prior experience is zero). S-period ΔAEexp is the same as S-period AEexp except when a T-period principal has switched agents; when this occurs, S-
period $\Delta E_{\text{exp}}$ equals the value of $AE_{\text{exp}}$ at the start of the new principal/agent relationship and is held constant as long as the relationship survives.

5. The Data

The data set consists of 91 cost-plus projects. The sample includes all projects completed between 1971 and 1988. Table 1 gives the means, standard deviations, minimum and maximum values for each variable in equation (1). The data sources are provided in the Appendix.

6. Error Structure and Econometric Methods

We have argued that design heterogeneity is in part a consequence of diverse utility preferences. These differences, influencing a plant's basic layout, cooling system, ease of maintenance, etc., are likely to affect capital costs in a firm-specific fashion. The design philosophy and construction methods employed by particular agents may also differ, with similar cost implications (see Joskow and Rose).\(^4\) Ideally, we would like to account for both types of firm-specific effects in our estimation of (1). However, due to the limited number of observations (and the

\(^4\) Although the presence of agent-specific cost differences was not explicitly addressed in our model of yardstick competition it can be added without changing the basic results.
need to preserve degrees of freedom) we specify an error structure that accounts for only one type of effect.

Following Joskow and Rose we treat the data set as a panel, with individual reactors as observations over time on a cross-section of AEs. The data set can be thought of as a cross-section time series, except that individual reactors replace the time index. This substitution is made because the panel is unbalanced in two ways. First, the number of units varies for different AEs. Second, given a construction permit date, several new contracts are observed for some AEs.

These considerations suggest that we rewrite (1) as:
\[
\ln Y_{ij} = X_{ij} \cdot B + \alpha_i + \eta_{ij} \quad (i=1, \ldots, N) \\
(j=1, \ldots, J_i)
\]

where \( i \) indexes AEs, \( j \) indexes units, and \( B \) is a \((L \times 1)\) vector of coefficients associated with the \((Z \times L)\) vector of independent variables \( (X_{ij}) \) of equation (1). The disturbance \( \eta_{ij} \) is drawn from an i.i.d. distribution, \( \eta_{ij} \sim N(0, \sigma^2_\eta) \), and is uncorrelated with the \( (\alpha_i) \) and the columns of \( (X_{ij}) \). The unobservable AE effect, \( \alpha_i \), is assumed to be a time-invariant random variable, distributed independently across individual units, with variance \( \sigma^2_\alpha \).

If the \( (\alpha_i) \) are uncorrelated with the columns of \( (X) \) one can obtain consistent and efficient estimates using generalized least-squares (GLS). However, if the \( (\alpha_i) \) are

\[42\] When we specify a cross-section of (more numerous) utilities the results do not differ substantially except that the standard errors are larger.
correlated with the columns of \((X)\), GLS estimation is biased and inconsistent. In this case, other methods of estimation are available. For all but one of the specifications examined in this study a Hausman specification test fails to reject the null hypothesis that the \((\alpha_i)\) are uncorrelated with the \((X)\), at the 10% level of significance (see Hausman (1978), sect. 3). In these cases GLS is the appropriate estimation method. The one exception — specification 2 with concurrent measures of learning — can be estimated consistently using fixed effects.

Next, we outline the GLS procedure and the specification test used in our analysis. These methods are straightforward generalizations of the techniques described in Hausman (1978) to the case of unbalanced panel data.

The variance components of equation (3) yield a covariance matrix which is block diagonal and can be written as

\[
\Omega = V(\alpha + \eta) = I_N \otimes (\sigma^2_\alpha P_{jj} + \sigma^2_\eta I_{jj}) , \quad (i = 1, \ldots N)
\]

where \(P_{jj}\) is a \(J_j \times J_j\) matrix of ones. Here, the appropriate estimator is GLS.

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43 Fixed effects estimation is a simple alternative that produces consistent though inefficient estimates of \(B\). To obtain consistent and efficient estimates one can apply the GLS/IV methodology proposed by Hausman and Taylor (1981). Joskow and Schmalensee (1987) employ Hausman and Taylor's approach in their analysis of the performance of coal-burning electric generating units in the United States.

44 This generalized approach is outlined in Joskow and Schmalensee (1987).
\[ B_{\text{gls}} = (X'\Omega^{-1} X)^{-1} X'\Omega^{-1} Y \]

which can be expressed in least squares form when the following transformation is applied to the data,

\[ Y_{ij}^* = Y_{ij} - k Y_i, \]
\[ X_{ij}^* = X_{ij} - k X_i, \]

where \( X_i \) and \( Y_i \) are AE-specific means and

\[ k = 1 - \frac{\sigma^2}{\sigma^2 + J_1 \sigma^2_a} \]

Consistent estimates for the variance components, \( \sigma^2_\eta \) and \( \sigma^2_a \), are derived from within-unit and between-unit estimation of equation (2). (See Judge et. al. (1985))

A key maintained hypothesis in GLS estimation is that \( E(\alpha|X) = 0 \). A convenient test of this hypothesis is a \( \chi^2 \) test of the null hypothesis \( \xi = 0 \) in the following regression

\[ Y^* = X^* \cdot B + X'' \cdot \xi + \nu \]

where the \( X'' \) are simply deviations of the \( X \)'s from their unit-specific means. Note that this test's maintained hypothesis includes the independence of \( (\eta) \) and the columns of \( (X) \), a condition necessary for consistency.

Finally, to distinguish between log-linear and linear specifications of (1) we employ a specification test suggested by Wooldridge (1990). This test employs a goodness of fit measure that can be compared across transformations of a model's dependent variable. For the case at hand, define the transformation, \( \phi(y) = \log(y) \), where \( y = \text{COST} \). Let \( \phi^- \) denote the fitted values from the regression, \( \phi(y) \) on \( X \), where the \( X \) are all the independent variables in (1). Perform the bivariate
regression (no intercept), \( y \) on \( \phi^{-1}(\phi^*) \). The \( R^2 \) from this regression is then compared with that of the regression, \( y \) on \( X \).\(^{45}\) The log-linear specification is preferred if the \( R^2 \) from the bivariate regression is larger; otherwise, the linear specification is more appropriate.

7. The Results

Wooldridge's \( R^2 \) test indicates that for each version of (1) the log-linear specification is preferred by the data. Thus, diminishing returns rather than constant returns is a better characterization of learning in the nuclear industry. Because estimates from the log-linear and linear specifications parallel one another very closely (in terms of the magnitude, sign and significance of the various coefficients) we present only the log results. These are seen in Tables 2 - 6.

- Specification 1

Specification 1 (S1) assumes that all agents had an incentive to reduce costs: no distinction is made between in-house utilities and outside contractors hired by utilities. Furthermore, S1 assumes that the potential for cost reduction

\(^{45}\) We perform the two regressions, \( \phi(y) \) on \( X \), and \( y \) on \( X \), using fixed effects estimation. Note also from (1) that the \( X \) vector is transformed when we change dependent variables: LSIZE, LLEAD in the case of LCOST versus. SIZE, LEAD when COST is the dependent variable. This does not affect the validity of the test.
is the same whether an agent works for the same principal on successive projects or if the latter's identity changes over time.

Table 2 contains the results for (S1). Two sets of coefficients, corresponding to concurrent and series measures of learning, were estimated under both fixed effects and GLS assumptions. Three of the four estimates for AEexp have the wrong sign; none are significant. This outcome is not surprising given our discussion of past studies.

The results for the other coefficients are consistent with those of earlier studies. Because these estimates are robust across specifications the balance of this section focuses on the learning variables.

- Specification 2

Like S1, S2 assumes that all agents had an incentive to reduce costs. However, S2 relaxes the second assumption described above, testing whether changes in an agent's principal had some effect on the amount of cost reduction. The expectation is that the composite variable, T-period dummy·AEexp, has a negative sign.

The estimates in Table 3 offer no support for these assumptions. Of the eight coefficients, five have the wrong sign; none are significant.

Provided that opportunities for cost reduction existed,
these negative results seem to suggest that yardstick competition was not implemented in the nuclear industry. To investigate whether in-house firms reduced costs we could add a variable corresponding only to the experience of in-house utilities. In fact, C&H's model is specified this way. As mentioned earlier, their results indicate that only in-house firms reduced costs. This result can be reproduced using our larger data set.

However, it turns out that an alternative interpretation is possible. An important assumption in C&H's analysis is that principals can be divided into two categories: in-house firms and those firms that hired outside agents to perform the tasks of design and construction. But these latter firms do not constitute a homogeneous group. Some built one or two reactors during a single period; others constructed plants in two or more periods. As we described earlier, these T-period firms gradually acquired the expertise to directly manage their agents' actions. The corresponding changes in project organization may have shifted the locus of learning from agent to principal. Specifications 3, 4 and 5 address this possibility.

- Specification 3

Here we replace AEexp with S-Period AEexp, and T-period dummy*AEexp with two variables, T-Period Utility Exp and ΔAE. This specification assumes that an agent was the locus of
learning for a project only if the principal had no prior experience. Any further learning by the agent in other contexts is not exploited on subsequent projects for this principal after the latter firm has assumed responsibility for project management (S-Period AEexp is held constant on these subsequent projects). In addition, cost reduction by experienced utilities, including in-house firms, should be larger than what is associated with agents facing different utility preferences on successive projects (T-Period Utility Exp > S-Period AEexp). Finally, agent switching may be costly for principals (ΔAE > 0).

The results in Table 4 are consistent with the above expectations. In each version of S3, the coefficients have the proper sign. The estimates based on concurrent measures of experience are all significant; the same is true for three of the series results. The result for S-Period AEexp provides support for the existence of yardstick competition. As expected T-Period Utility Exp is larger than S-Period AEexp; their relative magnitudes suggest that holding design preferences constant adds considerable benefits. In the two series regressions the size of the ΔAE coefficient is comparable to that of T-Period Utility Exp. Thus, it appears that agent switching negates the benefits generated by one period of learning.

46 We tested whether in-house utilities reduced costs more than experienced firms that hired outside agents. No significant differences were observed for S3, S4 or S5.
Specification 4 is an alternative but mostly equivalent version of S3. T-Period AE-UTIL Exp is substituted for both T-Period Utility Exp and ΔAE. S4 assumes that learning by experienced principals and their agents is relationship-specific, i.e., after changing agents the principal in some sense has to start over, at the top of its learning curve. (T-Period AE-UTIL Exp has a value of zero after a change).

The results in Table 5 are consistent with these expectations. All the coefficient have the proper signs. In addition to the concurrent measures of experience, the series measures are now significant in both the fixed effects and GLS regressions. The magnitude of the series coefficients are also larger. Using the point estimates from the series regressions it appears that holding design preferences constant doubles the benefits of cost reduction. The concurrent estimates suggest an even larger advantage; however, since one agent firm, Bechtel, built so many more plants than its competitors the estimates for S-Period AEexp may be biased downwards due to outlier observations. The size and precision of the AE-UTIL Exp estimates also imply that agent switching was very costly for principals; from a cost perspective, "getting in sync" with a new agent essentially meant starting over again, at the top of the learning curve.
- Specification 5

In this specification our measure of agent learning is modified slightly to allow the experience of an agent hired by an experienced principal to provide benefits beyond those of the first agent hired by the principal. In other words, if this second (or third) agent has more experience than the earlier firm, this additional experience may benefit the principal even though the latter is the project manager.

The point estimates for S-Period ΔAEexp in Table 6 are each smaller than the corresponding results in Table 5; only one coefficients is significant. The results for T-Period AE-UTIL Exp are basically unchanged in three of four cases; the fixed effects series estimate is now smaller and insignificant. Thus, it seems that S4 is a better description of learning in the nuclear industry. In other words, after a principal assumes responsibility for project management its organization relies solely on in-house experience.

Summary

Empirical studies of learning in the nuclear industry normally adopt a methodological approach best suited for homogeneous product markets. In this context, a supplier firm's incentive to reduce costs is a natural consequence of profit maximization. To measure the learning curve, one simply regresses observed costs on a firm's cumulative output.

When this simple method is applied to the case of nuclear
power plant construction no learning is observed. This result is not surprising after one considers how nuclear plants and their procurement differ from the standard model of learning. Nuclear plants are highly differentiated products and most were procured by utilities from outside contractors under cost-plus conditions. Product differentiation raise questions about the transferability of learning from project to project. Cost-plus contracts do not provide agents with explicit incentives for cost reduction.

The existence of diverse utility design preferences contributed to this product differentiation. Although learning is observed when preferences vary, the extent of cost reduction is far greater when these preferences are held constant.

When contracts are cost-plus, a dynamic form of yardstick competition can provide sufficient cost-reducing incentives for agents. Firms with plans for one (or two contemporaneous) units may have been able to elicit effort from agents using this mechanism. The results indicate that agents hired by these firms did indeed reduce costs.

Utilities with plans for several units usually relied on alternative mechanisms to reduce costs. A few firms developed the capability to perform in-house design and construction. Other utilities hired outside contractors but assumed responsibility for the project management function. In the latter case, the locus of learning shifted from outside
contractors to the utilities. Agent switching was also observed in several cases; these changes increased the costs of a firm's subsequent units.

Finally, learning in the industry exhibits diminishing returns. Also, alternative measures of experience, concurrent and series, produced similar results.
References


Appendix: Data Sources

Construction cost data was obtained from two sources. Jim Hewlett, at the U.S. Department of Energy, supplied me with overnight cost data based on actual annual cash flows for 80 of the 91 units in the sample. Overnight costs for the remaining eleven units were derived from nominal figures reported in *Steam-Electric Plant Construction Cost and Annual Production Expenses*, an annual publication of the U.S. DOE. The methods and indices used to calculate overnight costs in each case are described in EIA (1986) and McCabe (1986).

The regional wage data are the reported average union wage plus employer benefit contribution for helpers and journeyman in the building trades. This information was obtained from the Bureau of Labor Statistics, *Union Wages and Hours: Building Trades*, July 1, 1976, Bulletin 1972, Table 12. The remaining variables are based on information available from two sources: *Historical Profile of U.S. Nuclear Power Development*, Atomic Industrial Forum, Inc. (1986) and "The World List of Nuclear Power Plants", *Nuclear News* (annual issue).
Table 1:  **Data Summary**

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<th>Maximum</th>
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Standard errors are in parentheses
* : 10% level of significance
** : 5% level of significance
*** : 1% level of significance
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Standard errors are in parentheses

*: 10% level of significance

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**: 1% level of significance
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Standard errors are in parentheses
* : 10% level of significance
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***: 1% level of significance
Chapter Four

The Effect of Industrial Structure on Learning by Doing in Nuclear Power Plant Operation

(joint with Richard K. Lester)
1. Introduction

Recent studies of technological innovation have drawn attention to the cumulative economic importance of secondary technical refinements, improvements and adaptations to products or processes after their introduction to the market (Rosenberg, 1982; Freeman, 1982). Secondary improvements may occur as a result of 'exogenous' scientific or engineering advances, or alternatively may emerge from the experience accumulated with the technology following its initial introduction. The role of experience in bringing about technological change has been extensively analysed in the literature on learning by doing.¹

In this paper we investigate the impact of learning on the operating performance of nuclear power plants of the light water reactor (LWR) type in the United States and France. Of particular interest is the effect of industry structure on the relationship between learning and operating performance. We conjecture that two structural factors prevent the benefits of operating experience from being uniformly distributed throughout national industries. First, differences in reactor technology may limit the potential for information sharing. Second, even when reactors exhibit similar technology, the additional costs associated with sharing information between plant sites and across corporate boundaries may discourage

¹ Early papers on the subject include those by Arrow (1962), Alchian (1963) and Hirsch (1956).
this activity. Performance in the U.S. nuclear power industry is likely to be affected by both factors; the first because U.S. reactors are not standardized, and the second because the ownership of reactors is spread over many firms. The French nuclear industry, in contrast, has a single owner, numerous multi-reactor sites and a high degree of plant standardization. Empirical evidence of a "structural" performance penalty in the U.S. would have important implications for decisions affecting the choice of technological standards, siting policy and firm size in the nuclear industry.

The paper is organized as follows. Section 2 describes the structure of the nuclear industry in the United States and France. In Section 3 we introduce some key aspects of nuclear power plant operations and explain our choice of plant 'availability' as an appropriate measure of operating performance. In Section 4 we present a conceptual model of learning which incorporates the potential effects of nuclear industrial structure. Section 5 describes the functional form of the estimating equation. Sections 6 and 7 discuss the data and economic methods used in estimating the equation. The final two sections contain the results and conclusions.

2. Nuclear Industrial Structure

LWR technology is the dominant civilian nuclear reactor technology in use in both the United States and France. About
two-thirds of the operable LWRs in the U. S. are of the pressurized water (PWR) type; the remainder are boiling water reactors (BWRs). All French LWRs are of the PWR type; this technology was first introduced into France under license from an American vendor.

Despite the technical similarities, however, there are major cross-national differences in the structure of both the electric power and nuclear plant supply industries, which we expect to have affected patterns and rates of learning in the two countries. The United States is characterized by high levels of disaggregation in both sectors. At the end of 1986 there were 47 U.S. utilities with operating nuclear power plants, of which 24 had only one unit in service. The other 23 firms operated 70 units, 58 of which were located at sites with at most two units. Ten of these utilities operated reactors at multiple sites. The largest nuclear utility had nine operating units; the second largest had seven.\(^2\) Seven utilities operated both PWRs and BWRs. On the supply side, design responsibility is divided between the reactor vendor (for the nuclear steam supply system (NSSS)) and the

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\(^2\) The fragmented U.S. nuclear sector reflects a more general fragmentation observed in the U.S. electric power industry. Using total generating capacity as a measure of firm size, the correlation between nuclear capacity and firm size is large (0.84) and significant (1% level) in the U.S. (This calculation is based on capacity figures provided in U.S. Energy Information Administration (1983)). The large variation in utility size is the outcome of events early in the industry's development, the absence of competition and the existence of legal barriers to merger (See Hyman (1988)).
architect-engineer (for the balance of plant). Four LWR vendors (Westinghouse (41 of the 94 reactors), Babcock & Wilcox (8), and Combustion Engineering (14) for PWRs and General Electric for BWRs (31)) and nine independent architect-engineering firms have been active in the U.S. market; in addition, several utilities have acted as their own architect-engineers. One consequence of this fragmentation has been a high level of variation in design even within each class of LWRs. The Federal government, though active in several areas of the fuel cycle, has played a relatively small role in the development of LWR technology since its initial commercialization. The government's major technical contribution has been to carry out safety-related research in support of nuclear regulation.

The case of France lies at the other end of the spectrum of nuclear industrial structures. The state-owned utility, Electricité de France (EdF), is the sole owner of commercial nuclear power plants. The other major industrial participants are Framatome, the sole NSSS vendor, Alstom Atlantique, the sole nuclear turbine-generator supplier, and the governmental Commissariat de l'Energie Atomique (CEA), which has a major industrial presence in all stages of the fuel cycle, as well as a responsibility for basic research and development. EdF acts as the architect-engineer, construction coordinator, and overall project manager for nuclear power plant projects. Led by EdF, the French industry has implemented a more far-
reaching standardization program than any other country, building long series ('tranches') of almost identical reactor units. These reactors are mostly located in 4-unit clusters. The manager of each 4-unit site reports directly to EdF headquarters. There have been two 'pre-series' and two major series of 900 MWe units, a 1300 MWe series, and in recent years a new 1450 MWe series has been started (Degot and Lebreton, 1985). The design differences between the various 900 MWe series and pre-series are quite modest. (The data base for the present study consists only of 900 MWe units.) The centralized industrial structure and the high level of design standardization might be expected to increase the effectiveness of information transfer between reactors.

3. Nuclear Power Plant Operations

In this paper we use the annual "availability factor" to measure plant operating performance. This is defined as the total amount of energy that the plant could have generated during the course of the year had it been called on to be operated continuously at full power, divided by the hypothetical maximum annual energy output at continuous full power operation. Several previous studies of operating performance have used the annual "capacity factor" as the principal performance indicator. This is defined as the energy actually generated by the plant during the course of the year, divided by the total amount of energy that the plant
would have generated had it operated at its design power rating continuously throughout the year. For plants operated in baseload mode, the availability factor is identical to the capacity factor. This is the case for virtually all U.S. nuclear plants. In some circumstances, however, nuclear plants may be operated in a "load following" mode. This will occur if, for example, the total generating capacity available to the operating utility exceeds the load. In France, where nuclear plants now account for nearly half of the total generating capacity, nuclear plant load following occurs during part of the year. In these circumstances, the annual capacity factor would understate the performance of the plant and its staff; hence our choice of the availability factor.

The maximum theoretical availability factor for LWRs is less than 100% because reactors of this type must be shut down periodically for a number of weeks for refueling. Such outages are planned many months in advance. During the refueling outage a fraction of the core -- typically 1/4 or 1/3 -- is replaced with fresh fuel. Maintenance work that cannot be done while the plant is in service is also carried out at this time.\(^3\) Apart from these scheduled refueling and maintenance outages, forced outages or deratings may also occur as a result of operator error, equipment malfunction or

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\(^3\) Most reactors were originally operated on a 12-month fuel cycle. Many utilities are now finding it economically attractive to switch to longer cycles (e.g., 18 months, or in some cases even two years).
degradation, or the violation of safety specifications.

The availability is a composite indicator of how well the plant has been designed, built, operated and maintained. The underlying assumption is that both suppliers and operators seek to maximize plant availability subject to the technical constraints imposed by refueling requirements. While this is likely to have been true during the period covered in this study (i.e., through 1986), it may not continue to be true indefinitely, at least insofar as operators are concerned. Over time, nuclear plants, like any other item of capital equipment, will wear out, and the cost of maintaining them will increase. Utility planners must balance these costs against the increased cost of purchasing or generating replacement energy during nuclear plant outages. Eventually, the economically optimal course of action may be to settle for lower nuclear plant availabilities.4 Since this decision may already have been made by operators of older units we allow for this possibility in our model.

4 Since each utility has a different portfolio of replacement power options available to it, the availability tradeoff will be strongly firm-specific. Moreover, the sharp increases in nonfuel operating and maintenance (O&M) costs at U.S. nuclear plants in recent years -- 45% between 1982 and 1986 (see U.S. Energy Information Administration, 1988a and 1988b, for evidence and analysis of this trend) -- suggest that the point at which the optimal availability level for most plants falls below 100% (minus some minimum refueling outage) may be reached sooner rather than later as the reactor population ages. Although it is beyond the scope of the present study, further research is needed which explicitly examines the relationship between factors such as age, O&M expenditures, replacement power costs and plant performance.
Nuclear plant vendors and utilities originally anticipated that nuclear plants would be capable of operating with availabilities and capacity factors between 70% and 80%. In some countries, average nuclear plant performance is approaching and in some cases even exceeding these levels. In the United States, however, although some plants have been consistently strong performers, average capacity factors throughout most of the last decade have failed to exceed 60%. The causes of good and bad performance have attracted increasing attention in recent years. Both technical and organizational factors have been identified. Technical contributors to good performance include plant designs into which operability and maintainability considerations were incorporated at the outset, effective preventive maintenance, equipment upgrades that permit power ratings to be increased and longer fuel cycles. It has also been suggested that smaller plants, because of their generally simpler designs, are easier to operate and maintain.

The importance of managerial and organizational factors has been particularly stressed in recent studies of the U.S. nuclear power industry. Plant reviews have revealed wide differences in the extent of management involvement in plant operations, in the training and qualifications of operations and maintenance personnel, in the extent and effectiveness of

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5 See, for example, the studies by the U.S. Atomic Industrial Forum (1984) and the U.S. Office of Technology Assessment (1984).
incentive programs oriented towards plant performance, and in the general attitudes of management and technical staff towards their tasks, their environment and each other. Performance is also affected by the experience of the operating and maintenance staff, and by the effectiveness of programs to augment this knowledge by incorporating the lessons of experience from other plants of similar types. Fragmentation in the electric utility industry inhibits the acquisition and application of knowledge, and may create a higher than optimal level of dependence on suppliers of equipment and services (Lester, 1986).

External factors also influence performance. Safety regulatory authorities on occasion order plants to be shut down or derated pending the completion of safety analyses, inspections, equipment modifications or 'backfits', or operator retraining.\(^6\) Regulatory behavior varies from nation to nation in both style and substance. Economic regulators may also affect performance. Some state public utility commissions in the United States have recently begun adopting financial incentive programs which penalize or reward utilities depending on the operating performance of specific generating units. While the eventual impact of these programs may be considerable, their introduction came too late to

\(^6\) On occasion, events at a particular unit dictate a response with an industry-wide impact. The response of U.S. regulatory authorities to the accident at the Three Mile Island unit in 1979 is a case in point.
affect performance during our sample period (1975-1986).

4. Learning in Nuclear Power Plant Operations

It is useful to distinguish between two different forms of learning occurring in nuclear plant operations. First, experience gained from plant operations may result in a clearer understanding of design-performance relationships, leading in turn to design improvements in subsequent generations of the technology ('embodied' learning). Alternatively, learning may result in the adoption of new operating or maintenance practices which improve performance without requiring design modifications ('disembodied' learning). With respect to the latter, two mechanisms might be expected to lead to improved performance at a particular unit as it matures (Joskow and Rozanski, 1979). First, despite the best efforts of the commissioning team, there will be specific technical 'bugs' -- improperly installed equipment, defective parts, incorrectly written software, and so on -- which will become evident during the early stages of operation and which will be corrected. Second, as operations and maintenance personnel gain familiarity with the plant, they will develop progressively greater facility in their tasks; fewer errors will be made over time, and improvements will continually be made to plant procedures.

The opportunities for learning will grow scarcer with time, and there will be a gradual decline in the rate of
improvement. Moreover, despite the best efforts at preventive maintenance, individual plant components will begin to wear out. Eventually, performance will be allowed to decline as the marginal cost of maintaining high levels of availability exceeds that of alternative sources of power. Though the nominal design lifetime of nuclear power plants is 30 years, some deterioration can be anticipated well before this.⁷

What is learned at a particular unit is presumably also applicable to other units, provided that there are sufficient similarities in designs and operating procedures. We conjecture, however, that this body of knowledge will not be symmetrically transferred to older and newer units, since a fraction of it is likely to be 'age-specific' -- in the sense of pertaining only to the same general stage of a unit's life at which it was originally learned. We therefore expect that information derived from operations at a given plant will tend, on average, to be more valuable to younger units than to older ones.

Furthermore, it is likely that inter-reactor learning will be influenced by industry structure. Since it is likely that the cost of information sharing is larger for inter-site learning, we anticipate that the potential for learning will be exploited more when units are located at the same site.

⁷ PWR steam generators are a case in point. Contrary to early expectations, corrosion and related problems have necessitated major overhauls and in some cases even replacement of steam generators several years after plant startup.
(Indeed, some pooling of operations and maintenance personnel is typical at multi-unit sites.). When information is transferred between sites, moreover, we conjecture that the impact of learning will be greater when the plants involved are owned by the same utility; ownership boundaries in the U.S. may obstruct the communication of operating experience.

It is also expected that the value of communication will be greater for units which are technically more closely related to the source units. As noted earlier, LWR technology includes two distinct design types, pressurized water reactors (PWRs) and boiling water reactors (BWRs). Although France's installed nuclear capacity consists of only PWRs, the U.S. industry operates both types. Hence, we expect that learning in the U.S. industry will exhibit a dichotomous pattern with the most benefit arising from information transfers within a given type of unit.

Embodied improvements will become possible as designers learn more about the operating problems experienced by units that are already in service. In some cases these design modifications may be made at the direct request of the user; in others they will be initiated by the designer.\(^8\) (The designer will, of course, make some improvements based on

\(^8\) Despite proprietary restrictions, designers probably also derive some benefit from studying the performance of plants supplied by their rivals. But the much greater access to their own units -- it is not unusual for engineers from the supplier firm to remain in residence at the plant site after operations begin -- leads us to expect that this will be the dominant communication channel for embodied learning.
'exogenous' scientific or engineering advances, i.e., improvements that are independent of prior operating experience.)

Previous studies have provided partial insights into the effects of some of these factors. Komanoff (1976) regressed the capacity factors of U.S. nuclear power plants from 1968 to 1975 on reactor age and size. He observed maturation effects in PWRs but not in BWRs. No attempt was made to estimate intra- or inter-utility learning. In a more detailed analysis Joskow and Rozanski (1979) studied a sample of 72 U.S. and foreign LWRs during a 12-month period in the mid-1970s. They found evidence of significant learning by plant operators, but their model did not incorporate the effects of transfers of knowledge between plants. Furthermore, PWR performance was found to improve at a rate faster than that experienced by comparable BWRs. Some evidence of supplier learning was also detected, although the model did not permit this to be attributed to the effects of prior operating experience. No differences were discerned between the effects of learning in the U.S. and overseas. Both Komanoff and Joskow-Rozanski reported a significant inverse correlation between capacity factor and unit size.

Roberts and Burwell (1981) studied the relationship between reactor operating experience and performance in the U.S. power reactor population between 1969 and 1978. In this case, however, the measure of operating performance was the
annual frequency of Licensee Event Reports (LERs), which utilities are required to submit to the Nuclear Regulatory Commission following operating events that could have a bearing on plant safety. A single-variable regression model was used. Learning effects were again observed, and the authors found that learning was enhanced at multi-reactor sites compared to single reactor sites.

5. The Model

The model proposed in this work is the log-linear availability regression shown in equation (1). This multiplicative specification assumes that performance is a separable function of the various factors (an approach also employed in the previously cited performance studies). The

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9 The criteria defining these 'reportable occurrences' are specified in a series of NRC regulations. (See, for example, U.S. Nuclear Regulatory Commission, 1977.) Roberts and Burwell were interested primarily in the implications of the learning process for plant safety, and used the LER frequency as a measure of safety performance. The capacity factor (or availability) would have been a less suitable measure for this purpose. It is sometimes asserted that a reliable plant is also a safe plant. In the long run there is probably much truth to this, since the skills and qualities required of the plant staff that would enable them to sustain a high availability over a prolonged period are similar to those required for safe operation. In the short term, however, a high availability is not necessarily indicative of safe operation; indeed, it might even have been achieved only because certain safety margins were sacrificed. As E.P. Wilkinson, formerly President of the Institute of Nuclear Power Operations, has noted: "If emphasis is placed on safety and reliability, a good capacity factor is a natural result. If, however, the principal emphasis is on capacity factor, adequate safety is not a natural result." (Wilkinson, 1983).
The basic version of the U.S. model is as follows:

\[
\ln \text{UNAV}_{it} = A + \beta_1 \text{AGE}_{it} + \beta_2 \text{AGE}_{it}^2 + \beta_3 \text{PREINTRASITE}_i + \beta_4 \text{INTRASITEM}_i \\
+ \beta_5 \text{INTRASITE2}_{it} + \beta_6 \text{PREINTRA FIRM}_i + \beta_7 \text{INTRA FIRM1}_{it} \\
+ \beta_8 \text{INTRA FIRM2}_{it} + \beta_9 \text{PREINTER FIRM}_i + \beta_{10} \text{INTER FIRM1}_{it} \\
+ \beta_{11} \text{INTER FIRM2}_{it} + \beta_{12} \ln \text{SIZE}_i + \beta_{13} \text{VENDOR}_i + \beta_{14} \text{VINTAGE}_i \\
+ \beta_{15} \text{TMI1} + \beta_{16} \text{TMI2} + \epsilon_{it} \\
(i = 1, \ldots, 76) \\
(t = 1975, \ldots, 1986) \tag{1}
\]

\text{UNAV}_{it} is the reactor 'unavailability' (defined as (1-annual availability) for unit i in year t). Factors expected to improve (erode) performance should therefore be associated with reduced (increased) unavailability. In recognition of the fact that refueling outages are an unavoidable feature of LWR operation rather than the outcome of avoidable operator problems, and that there is some minimum refueling period that cannot be further reduced through learning, reported annual availability losses for years in which refueling occurred were adjusted downwards by subtracting an estimated minimum availability loss associated with refueling. Details of this procedure are given in the Appendix.

The equation intercept is A. The next two variables on the right hand side of (1) constitute the 'learning curve' for an individual reactor. \text{AGE}_{it} (the time since reactor i entered

\[10\] As discussed in the Results section, we also estimate a more general version of the U.S. model which considers the possibility that information transfers between different technologies are not as effective as those between the same technologies.
commercial operation, expressed in years) is used as the measure of operating experience. The form of the learning curve is quadratic, to account for the possibility of degradation in performance as the reactor gets older.

The next nine variables in equation (1) account for the effects of information transfers from other reactors. The model allows for three different sources of information with respect to ownership and location: (1) reactors owned by the same utility and located at the same site (-INTRASITE-); (2) reactors owned and operated by the same utility but located at other sites (-INTRAFIRM-); and (3) reactors owned and operated by different utilities (-INTERFIRM-).

For each of these three source categories, the model further differentiates between three different information channels: (1) information transfers from older reactors before reactor i enters service (PREINTRASITE$_i$, PREINTRAFIRM$_i$, PREINTERFIRM$_i$); (2) transfers from these older units after reactor i has started up (INTRASITE$_{1it}$, INTRAFIRM$_{1it}$, INTERFIRM$_{1it}$); and (3) information transfers from newer units occurring after they have started up (INTRASITE$_{2it}$, INTRAFIRM$_{2it}$, INTERFIRM$_{2it}$). Each variable is computed by summing the relevant number of reactor-years of service over all the reactors in that category. The implicit assumption is

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"Newer units" are those reactors which began operation in the same month as reactor i or later. "Older units" are those reactors which began operation in the months (and years) prior to reactor i's month of commercial operation.
that the value of a year of service (in a learning sense) is invariant across reactors and across time within each category of information transfers. Note also that no quadratic term is needed for the inter-reactor learning effects because, unlike the reactor learning curves themselves, these effects do not have an associated degradation component.

\( \textrm{SIZE}_i \) (the net power rating of reactor \( i \) in electrical megawatts) accounts for the effects of scale on performance.

\( \textrm{VENDOR}_i \) (the total number of reactor-years of operating experience accumulated by the earlier units supplied by the NSSS vendor for reactor \( i \) prior to the construction start of reactor \( i \)) and \( \textrm{VINTAGE}_i \) (reactor \( i \)'s construction start date minus the construction start date of the earliest reactor supplied by the same NSSS vendor, expressed in months) account for the effects of embodied learning and 'exogenous' design improvements, respectively.\(^{12,13}\) Note that although these

\(^{12}\) Besides the NSSS vendors, other potential contributors to improved reactor design are the architect-engineers and the utilities themselves.

When embodied learning and vintage variables corresponding to both NSSS vendors and AEs are included in the more general version of the U.S. model (see note 10), coefficient estimates for the latter have the wrong sign; if the NSSS variables are omitted, the AE coefficients have the proper sign but are not precisely estimated. On the other hand, the magnitude of the two NSSS coefficients change when the AE variables are absent but their (correct) signs do not; VENDOR is statistically significant in both cases. (Note that other coefficient estimates in the model are generally unaffected by these changes in model specification). Because the NSSS variable pair performs better under these mildly collinear conditions, we exclude the AE variables from our model, keeping in mind that supplier effects are difficult to disentangle.

Regarding the role of utilities, only three firms in the
sample benefited from prior operating experience at the time construction began on their most recent plants, affecting a total of five reactors; and even these firms had far less experience to draw on than the NSSS vendors. Furthermore, it is not likely that any utilities were involved in the type of research and development programs typically associated with 'exogenous' design improvements. When utility versions of VENDOR and VINTAGE were included in the same version of the U.S. model together with their NSSS and/or AE counterparts, we could not reject (at the 10% level) the null hypothesis that both coefficients were equal to zero; moreover, their absence had no significant impact on other coefficient estimates. Thus, we omit these variables from the U.S. model.

A remaining question is whether embodied learning and vintage effects should be modeled solely as an intra-firm process or expanded to include inter-firm exchanges as well, i.e., a vendor (or AE) learning from other vendors' (or AEs') experience. For several specifications of the general version of the U.S. model we could not reject (at the 10% level) the null hypothesis that inter-firm design improvements for NSSS vendors and/or AEs were nonexistent.

The construction start date was chosen as the endpoint for development of a reactor's design after considering the chronology of important milestones in the planning and construction of nuclear power plants. Although a characteristic feature of U.S. nuclear power projects during the sample period was for detailed design to continue throughout much of the construction period, the choice of NSSS vendor, which usually preceded the start of construction by at least one year (and sometimes by as much as three or four years), can be considered the primary design decision faced by utilities. Once this choice was made, an AE's plans for the balance of plant necessarily dovetailed with the technical demands of a particular NSSS. Because delivery of NSSS components normally occurred two to three years after the start of construction (see Willenbrock and Thomas, 1980, chapters 7 and 15), following a lengthy fabrication process, it is safe to assume that most major design issues relevant to reactor operations had either been resolved (for the NSSS) or largely predetermined (in the case of the balance of plant) by the time construction had commenced. Of course, our choice of endpoint may not be appropriate in all cases; in particular, design 'backfits' imposed by the NRC often occurred later in the construction process. However, there is reason to doubt that these design changes actually improved plant operations (see U.S. OTA, 1984, chapter 6.)

Interviews with French nuclear industry officials conducted by one of the authors in 1985 indicated that the construction start date is, if anything, more appropriate to
variables estimate average rather than firm-specific effects, the assumption underlying this specification is that the design improvements are firm-specific, e.g., in the case of embodied learning, designers only learn from operating experience obtained from units that they themselves have previously designed.

The next two variables in (1) account specifically for the reactions of regulatory authorities and utilities to the Three Mile Island accident in March 1979. TMI1 (= 1 for t ≤ 1979 and 0 for later years) is a dummy variable specified to capture the expected negative impact of the accident on reactors which began operations prior to the accident. TMI2 (= 1 for reactors which began commercial operation after 1979 and 0 otherwise) is a dummy variable specified to investigate whether the designers and operators of post-TMI reactors were better able to respond to changes in the regulatory environment. These changes affected both design ('backfits') and operating and maintenance practices.

use as the design endpoint in the French case. Normal practice there has been to complete a much higher fraction of the design prior to starting construction than in the U.S.; moreover, regulatory backfits during construction have reportedly been less common.

The issues addressed here (and in the previous footnote) are relevant to our interpretation of the empirical results. To argue convincingly that observed improvements in reactor performance are due to disembodied learning rather than changes in design requires inter alia that we properly control for the latter. We believe this requirement has been satisfied.

14 We thank Paul Joskow for suggesting that TMI2 be included to distinguish between pre- and post-TMI reactors.
Any attempt to measure more general trends in safety regulation faces the intractable problem of overcoming collinearity with the industry-wide learning variables (INTERFIRM-) and VINTAGE. Since regulatory requirements became increasingly stringent during the sample period, and the available evidence suggests that this had an adverse effect on plant availability (see U.S. OTA (1984) and Beckjord et al. (1986)), it is likely that our model underestimates the contribution of industry-wide learning and/or vintage effects. Finally, ε_{it} is the error term whose properties we consider in the methods section.

The model we estimate using the French data has fewer variables because of the simpler industrial structure (one utility, one NSSS vendor), the lack of variation in reactor size (all 900 MW reactors) and the few observations prior to TMI (only two French reactors were operating in 1979). Furthermore, because only one LWR technology is observed in France (the PWR), we estimate one basic model. The French model, with variables defined as before, is as follows:

\[
\ln \text{UNAV}_{it} = A + \beta_1 \text{AGE}_{it} + \beta_2 \text{AGE}^2_{it} + \beta_3 \text{PREINTRASITE}_i + \beta_4 \text{INTRASITE1}_{it} \\
+ \beta_5 \text{INTRASITE2}_{it} + \beta_6 \text{PREINTRAfirm}_i + \beta_7 \text{INTRAfirm1}_{it} \\
+ \beta_8 \text{INTRAfirm2}_{it} + \beta_9 \text{VENDOR}_i + \beta_{10} \text{VINTAGE}_i + \epsilon_{it}
\]

(i = 1, ... 28)

(t = 1979, ... 1986) (2)
6. The Data

The data sample consists of 104 LWRs, 76 from the United States and 28 from France. The sample includes all of the LWRs in the two countries larger than 300 MWe that had begun commercial operation by the beginning of 1985. Annual availability factor data for U.S. reactors were obtained for each year from 1975 to 1986, where applicable; for reactors entering service after the beginning of 1975, the data series begins with the first complete calendar year after the in-service date. The French data series begins in 1979 and is also unbalanced. The sources of data are given in the Appendix.

Tables 1 and 2 give the means, standard deviations, minimum and maximum values for each variable in equations (1) and (2), respectively, as well as the total number of reactor/year observations.

15 The exceptions here are the U.S. units Millstone 1 and 2 (a 660 MWe BWR and a 870 MWe PWR, respectively). These are the only units in either country located at the same site and exhibiting different technology. More observations than this would be required to permit confident estimation of the effect of reactor type on reactor learning among units located at the same site. By excluding these units from the U.S. data set we are able to put aside this issue when estimating intra-site learning effects. Note, however, that these units' operating experience is incorporated into the industry-level variables (INTERFIRM-).

16 We imposed the 1985 cutoff because our estimation technique, which includes the within-unit estimator, requires at least two years of observations. Our most recent observations occur in 1986.
7. Econometric Methods

The challenge in estimating relationships that combine time-series and cross-sectional data is to specify a model that will adequately allow for differences in behavior over time and across units subject to the limitations of the available data (e.g., because T, the number of observations for each unit, is often quite small, some pooling of the time series is necessary). A standard solution to this problem involves pooling the observations to estimate a linear model whose error structure is specified to include unit and/or time-specific components.\(^{17}\) By specifying \(\epsilon_{it}\) in this fashion, we can write equation (1) or (2) as follows,

\[
\ln Y_{it} = X_{it} \beta + \alpha_i + \eta_{it} \quad (i = 1, \ldots, N) \quad (3)
\]

\[
(t = 1, \ldots, T_i)
\]

where \(\beta\) is a \((L \times 1)\) vector of coefficients associated with the \((1 \times L)\) vector of independent variables \((X_{it})\) of equation (1) or (2). The disturbance \(\eta_{it}\) is drawn from an i.i.d. distribution, \(\eta_{it} \sim N(0, \sigma^2_\eta)\), and is uncorrelated with the \((\alpha_i)\) and the columns of \((X_{it})\). The unobservable individual effect, \(\alpha_i\), is assumed to be a time-invariant random variable, distributed independently across individual units, with variance \(\sigma^2_\alpha\).

If the \((\alpha_i)\) are uncorrelated with the columns of \((X)\) one can obtain consistent and efficient estimates using

\(^{17}\) In the case at hand, these unit-specific effects correspond to the idiosyncratic design characteristics and operating practices associated with individual reactors.
generalized least-squares (GLS). However, if the \((\alpha_i)\) are correlated with the columns of \((X)\), GLS estimation is biased and inconsistent. In this case, other methods of estimation are available.\(^\text{18}\) For each of the models examined in this study for which the estimated value of \(\sigma^2_\alpha\) is nonnegative, the specification test presented by Hausman (1978, sect. 3) fails to reject the null hypothesis that the \((\alpha_i)\) are uncorrelated with the \((X)\), at the 10% level of significance. Hence, GIS is the appropriate estimation method. In the remainder of this section we outline the GLS procedure and the specification test used in our analysis. These methods are straightforward generalizations of the techniques described in Hausman (1978) to the case of unbalanced panel data.\(^\text{19}\)

The variance components of equation (3) yield a covariance matrix which is block diagonal and can be written as

\[
\Omega = V(\alpha + \eta) = I_N \otimes (\sigma^2_\alpha \cdot J_{T_i} + \sigma^2_\eta \cdot I_{T_i}), \quad (i = 1, \ldots, N)
\]

where \(J_{T_i}\) is a \(T_i \times T_i\) matrix of ones. Here, the appropriate estimator is GLS,

\(^{18}\) Fixed effects estimation is a simple alternative that produces consistent though inefficient estimates of \(\beta\). But use of this technique precludes estimation of time-invariant factors, e.g., the impact of reactor size on performance, vendor learning, etc. To obtain consistent and efficient estimates of both time-varying and time-invariant factors one can apply the GLS/IV methodology proposed by Hausman and Taylor (1981). Joskow and Schmalensee (1987) employ Hausman and Taylor's approach in their analysis of the performance of coal-burning electric generating units in the United States.

\(^{19}\) This generalized approach is outlined in Joskow and Schmalensee (1987).
\[ \beta_{\text{gls}} = (X'\Omega^{-1} X)^{-1} X'\Omega^{-1} Y \]

which can be expressed in least squares form when the following transformation is applied to the data,

\[ Y_{it}^* = Y_{it} - kY_i, \]
\[ X_{it}^* = X_{it} - kX_i. \]

where \( X_i \) and \( Y_i \) are unit-specific means and

\[ k = 1 - \frac{\sigma^2_\eta}{(\sigma^2_\eta + T_i\sigma^2_\alpha)} \]

Consistent estimates for the variance components, \( \sigma^2_\eta \) and \( \sigma^2_\alpha \), are derived from within-unit and between-unit estimation of equation (3). (See Judge et. al.(1985)) Note that if \( \sigma^2_\alpha \) has a value of zero, the transformation reduces to simple OLS. Also, the method for calculating \( \sigma^2_\alpha \) does not rule out negative values; if this occurs the usual approach is to set \( \sigma^2_\alpha \) equal to zero and proceed with OLS.

A key maintained hypothesis in GLS estimation is that \( E(\alpha|X) = 0 \). A convenient test of this hypothesis is a \( \chi^2 \) test of the null hypothesis \( \xi = 0 \) in the following regression

\[ Y^* = X^*\beta + X''\xi + v \]

where the \( X'' \) are simply deviations of the \( X \)'s from their unit-specific means. Note that this test's maintained hypothesis includes the independence of \( (\eta) \) and the columns of \( (X) \), a condition necessary for consistency.

8. Results

1. United States

A. Homogeneous Technology. The simplest specification of
the model treats all U.S. reactors as drawn from a homogeneous technology, as in equation (1). This specification assumes that the hypothesized relationships determining reactor unavailability are the same across reactor types, and in particular, that information transferred between units has no greater value within reactor types than between them. The results for this model are shown in Table 3. Note that all of the variables that are significant (at the 10% level or better) have the expected sign.

AGE and $AGE^2$ have the expected magnitude and sign but only $AGE^2$ is significant. The point estimates indicate that performance improvements based on experience gained from operation of an individual reactor continue to occur only for about three years, after which equipment aging effects increase unit unavailability.

The effect of pre-operational learning from older reactors located at the same site (PREINTRASITE) has the expected sign and is significant at the 10% level. The coefficient estimate suggests that five years of such experience reduces initial unit unavailability by some 30%. In contrast, PREINTRAFIRM, the coefficient associated with pre-operational learning from reactors owned by the same

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$^{20}$ Collinearity between AGE, INTERFIRM1 and INTERFIRM2 is a likely explanation for AGE's lack of significance. Using the procedure suggested by Belsley, Kuh and Welsch (1980), we found a high condition number (>30) and associated high variance-decomposition proportions (>0.5) for these three regression coefficients, thus satisfying BKW's double condition for diagnosing "degrading collinearity".
utility but located at different sites, has the wrong sign, is estimated with less precision and is an order of magnitude smaller.

The four coefficients for post-operational learning from both older and younger units operated by the same utility at the same site and at other sites are relatively small and insignificant; two of these have the incorrect sign.

The results for inter-utility learning suggest that the entire population of U.S. reactors benefited from the accumulation of industry-wide experience during the sample period. Although PREINTERFIRM (pre-operational learning) is small and insignificant, both INTERFIRM1 and INTERFIRM2 are much larger in magnitude and are significant at the 5% and (almost) 10% levels, respectively. However, a comparison of these variables with PREINTRASITE and INTRASITE2 suggests that, as expected, inter-utility learning is less effective than learning which involves units at the same site.

The estimated effect of the TMI accident (TMI1) indicates that reactor availability losses were on average 30% smaller in 1975-1979 than in the subsequent 7-year period, offsetting to some extent the benefits of the accumulated industry-wide experience.\(^{21}\) In contrast, units which began their operation

\(^{21}\) To get some sense of the magnitudes involved here, consider the case of a utility operating a single PWR which began service in January, 1975. Ignoring individual reactor learning, but taking into account learning from the population of older and younger units during the subsequent years, the inter-firm estimates suggest that not until 1984 was this unit's level of performance on par with its pre-TMI (1979)
after TMI may not have suffered the same consequences: TMI2 is comparable in size to TMI1, thus neutralizing the impact of this accident, but it is estimated imprecisely.

Significant supplier effects were observed only for the embodied vendor learning function, VENDOR. The coefficient for VENDOR is significant at the 5% level and is reasonably large in size. For example, a reactor operating with a NSSS supplied by a vendor whose earlier projects had accumulated five years of operating experience prior to the start of the unit's construction, would enjoy, other things being equal, a 10% reduction in unavailability over its operating life.

The effect of unit size on unavailability is given by the coefficient of lnSIZE. The coefficient is significant at the 1% level and, consistent with previous studies, the effect is large and positive. By way of illustration, a 50% increase in unit size leads to, other things being equal, a 47% increase in lifetime unavailability.

B. Heterogeneous Technology, Equal Learning Coefficients. Because the U.S. industry includes both PWRs and BWRs it is appropriate to consider the possibility that some or all of the hypothesized relationships may differ across design types. Here we relax the homogeneity condition of the previous section somewhat by allowing for differences in learning based on whether the information transfer occurs within or between level.
design types. This is accomplished by allowing a subset of the model variables to vary according to the reactor type (BWR or PWR) generating the operating experience. We indicate this distinction by appending the letters ST (same technology as reactor i's) or DT (different technology than reactor i's) to the affected variables (-INTRAFOIRM- and -INTERFIRM-). Employing a $\chi^2$ test, we are able to reject the null hypothesis that these differences in the learning coefficients do not exist, at the 1% level of significance. The results for this specification are shown in Table 4.

The subset of coefficients whose variables are defined as before show, for the most part, little change in size, magnitude or significance.

The time at which equipment aging effects offset the benefits of additional operating experience at individual reactors occurs somewhat later (about 4 rather than 3 years). Even so, the rapid appearance of aging among U.S. reactors is surprising and deserves further research.

PREINTRASITE has the same magnitude and is more precisely

---

22 Recall that this distinction is relevant only for the inter-site/intra-utility and inter-utility learning variables; for the units in the sample all reactors at any given site were of the same design type.

23 To apply this test correctly the GLS transformation associated with the unrestricted model is used to calculate both the unrestricted and restricted error-sum-of-squares.

24 Again, the lack of precision in the estimate of the AGE coefficient can be attributed to collinearity with the -INTERFIRM-variables.
estimated. INTRASITE2, which measures the effects of post-operational experience generated by younger units located at the same site, is now significant at the 5% level. Its magnitude suggests that 5 years of such experience reduces unavailability by 9%, a benefit derived from just over one year of PREINTRASITE experience. This result is consistent with the expectation that experience with older units is more valuable to operators of recipient units.

VENDOR is unchanged in size and significance. VINTAGE, which accounts for exogenous design improvements, now has the expected sign (see below); it remains imprecisely estimated.

The adverse effects of TMI1 and reactor size are essentially unchanged. Although the sign of TMI2 suggests that post-TMI reactors perform better than their older counterparts, the magnitude of this effect is decreased and remains imprecisely estimated.

The results for the technology-specific intra-firm and inter-firm learning variables are basically consistent with our prior expectations of a dichotomous pattern of learning. In general, the signs of the coefficients associated with same-technology (ST) learning exhibit the expected negative sign; the opposite is true of the different-technology (DT) coefficients. Furthermore, the only significant results are obtained with the ST variables.

We first consider the inter-firm results. The signs of both PREINTERFIRM coefficients (ST and DT) follow this
pattern. As in the homogeneous technology case, they are relatively small and insignificant. The inter-firm post-operational learning coefficients are larger in magnitude, with those associated with ST learning larger and more precisely estimated. Learning from older reactors of the same reactor type (INTERFIRM1(ST)) improves reactor performance, is significant at the 1% level and has more than twice the impact of INTERFIRM1 in the homogeneous specification. Learning from older reactors of the other design type (INTERFIRM1(DT)) has the opposite effect, less than half the magnitude and is not significant. The coefficients associated with learning from younger reactors (INTERFIRM2(ST) and INTERFIRM2(DT)) have the proper sign with only INTERFIRM2(ST) significant, at the 10% level. INTERFIRM1(ST) is about 50% larger in magnitude than INTERFIRM2(ST), confirming our expectation that experience derived from older units tends to be more useful to operators than experience from units of later vintage.²⁵

²⁵ As before, using the inter-utility results together with the estimated effects of TMI, our hypothetical PWR's performance does not fully attain its pre-TMI levels until sometime in 1984. The Operating Plant Evaluation Code (OPEC-2) database for U.S. plants used in the present study (see Appendix I) indicates that regulatory outages specifically related to TMI were essentially over by the end of 1981 (Hulkower, 1986). This suggests that other factors have been responsible for the apparent subsequent failure of the utility industry to achieve its pre-1979 performance level, despite both collective and individual utility efforts to upgrade operating and maintenance practices in the aftermath of the accident. One probable contributor has been an increase in regulatory activity not specifically related to TMI, which, again according to the OPEC-2 data, has led to an increase of more than a factor of two in the average down-time per plant attributed to regulatory interventions since 1979 (Hulkower,
Now consider the intra-firm results. Each of the DT coefficients have the wrong sign, are relatively small in magnitude and are imprecisely estimated. In contrast, two of the ST coefficients (INTRA\text{FIRM1} (ST) and INTRA\text{FIRM2} (ST)) have the expected negative sign, with INTRA\text{FIRM1} (ST) comparable in size to INTRASITE2 and significant at the 5\% level. The one notable exception to the pattern described above is PREINTRA\text{FIRM} (ST), which has the wrong sign. Though not precisely estimated, its general effect is to reduce the beneficial contribution of intra-firm learning from older reactors located elsewhere. An estimate of the joint effect of PREINTRA\text{FIRM} (ST) and INTRA\text{FIRM1} (ST) on reactor performance, using the point estimates evaluated at their sample means, indicates that the benefits of intra-firm learning from older reactors are about one-half less than those associated with INTRA\text{FIRM1} (ST) alone.

To gain further insight into this result we reestimated the model, substituting a dummy variable (INTRADUMMY1 (ST), which equals 1 if PREINTRA\text{FIRM} (ST) > 0 and zero otherwise) for the PREINTRA\text{FIRM} (ST)/INTRA\text{FIRM1} (ST) variable pair. This dummy variable measures the average effect of pre- and post-operational, intra-firm learning from older reactors. The estimates for this specification are shown in Table 5. For the

1986). These non-TMI related problems arose independently in both the BWR and PWR populations; when we estimate separate TMI dummies for the two groups the results are very similar (see section C).
sake of comparison, we have also substituted similar dummies for the PREINTRASITE/INTRASITE1 and PREINTRAfirm/INTRAfirm1(DT) variable pairs (SITEDUMMY1 and INTRADUMMY1(DT), respectively). All other variables are defined as before.

The results indicate that the average effect of intra-firm learning from older reactors at other sites is small. Point estimates suggest that the benefits of intra-site learning are almost fifteen times as large as those accruing from ST intra-firm learning from other sites; moreover, the intrasite learning variable SITEDUMMY1 is significant at the 1% level whereas the off-site intrafirm learning variable INTRADUMMY1(ST) is estimated with very little precision. As expected, INTRADUMMY1(DT) has the wrong sign and is not significant. The other model coefficients are essentially unchanged in all respects.

In sum, results for intra-site and inter-firm learning suggest that reactor performance can be improved by applying the lessons learned from other reactors of similar technology, with the most benefit deriving from knowledge generated by other reactors at the same site and from older rather than younger units. Our analysis also suggests that firms operating reactors at two or more sites may have obtained far

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26 Because all reactors in the sample except the oldest one have positive values for PREINTERFIRM it is not practical to attempt the same substitution in the case of inter-firm learning.
fewer performance benefits from this deployment than if the reactors had been colocated. Indeed, intra-firm communication between sites may have been no more effective in a learning sense than inter-firm exchanges.  

C. Heterogeneous Technology, All Coefficients Differing.
Here we permit all of the coefficients in part B to differ according to design type. That is, we estimate twice as many parameters as in the previous section, one subset corresponding to the PWR design and one to the BWR design. Employing an appropriate $\chi^2$ test we cannot reject the null hypothesis that the PWR and BWR parameter subsets are identical, at the 10% level. Therefore, we consider the results of part B to be best in a statistical sense, and do not proceed any further.  

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27 For example, using the point estimates for PREINTERFIRM(ST) and INTERFIRM1(ST) from Tables 4 or 5, evaluated at the mean values of the corresponding INTRAFIRM-variables, it turns out that the impact of industry-wide learning on reactor performance is less than the average effect of PREINTRAFIRM(ST)/INTRAFIRM1(ST) but larger than that of INTRADUMMY1(ST).

28 One reviewer also suggested that running the U.S. "homogeneous technology" model using PWRs alone would provide a useful comparison with the French results. When we performed this calculation, the results differed little from the those of section B above. In particular, estimates for the inter-reactor learning variables in the homogeneous specification were virtually the same as the corresponding ST parameters in section B.
2. France

The equation estimated for the French industry is simplified by the fact that there is only one utility operating a single type of reactor and that all the units in the sample are the same size. Furthermore, in our attempt to apply GLS to the French data, the value of $\sigma^2_u$ was found to be negative, suggesting that OLS should be used for estimation. The OLS results are shown in Table 6.

The two individual reactor learning coefficients, AGE and $\text{AGE}^2$, have the expected sign. AGE is far more precisely estimated but neither is significant at standard levels.\(^{29}\) The point estimate for AGE is more than four times as large as the corresponding U.S. value; the estimate for $\text{AGE}^2$ is also somewhat larger than seen earlier. Together they indicate that performance improvements based on experience gained from operation of an individual reactor continue to occur for about eleven years, after which equipment aging effects increase unit unavailability. Since the oldest reactor in the sample had been operating for about nine years by the end of 1986, it is probably best to conclude that meaningful aging effects have yet to be observed in the French reactor population. This contrasts sharply with the corresponding U.S. result.

The intra-site coefficients all have the expected

\(^{29}\) Application of the Belsley, Kuh and Welsch diagnostic indicates that collinearity problems involving AGE, AGE2, INTRASITE1 and INTRAFIRM2 may explain this lack of statistical precision.
negative sign but are not precisely estimated (see note 28 regarding INTRASITE1). The magnitudes of the point estimates suggest that information transferred from older reactors is more useful than transfers from younger reactors.

Two of the intra-firm learning coefficients (PREINTRAFLM and INTRAFIRM1) have the expected sign. Although PREINTRAFLM is relatively small and insignificant, INTRAFIRM1, the coefficient for post-operational learning from older reactors located at other sites, is larger and significant at the 5% level. INTRAFIRM2 has the wrong sign but is small and insignificant. Together, these results translate into a large improvement in the performance of newer units during the period, 1979-1986. Furthermore, the magnitude of PREINTRAFLM and INTRAFIRM1 are substantially larger than the comparable inter-firm estimates for reactors of the same type in the U.S. This result suggests that inter-site information sharing in France is more effective, though it does seem primarily to benefit newer units. Such an interpretation is consistent with the expected pattern of

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30 Consider a hypothetical unit that began service in January, 1982. Ignoring individual reactor learning, but taking into account the population of older and younger units operating in France, the intra-firm results indicate that this unit's unavailability losses decreased approximately 60% by 1986. Note that unavailability losses in France, adjusted for refueling outages, averaged about 19% during the sample period.

31 Since we found that intra-firm learning in the U.S. differs little from inter-firm learning, this is an appropriate comparison. See note 27.
learning in an industry with highly standardized reactor designs and a strong central mechanism for coordination and technical support of site operations and maintenance. The French practice of rotating teams of start-up engineers and operators from one site to the next as new plants approach operation is a specific example of the kind of arrangement that would explain the relatively strong result for inter-site learning.

VENDOR and VINTAGE are both larger than their U.S. counterparts, although neither is significant. VENDOR's lack of significance is not surprising given that all but two reactors in the sample began construction before any operating experience had accumulated in the French industry.

For the sake of comparison with the U.S. results, we also estimated a version of the model which substitutes a dummy variable (SITEDUMMY1), defined as before, for the PREINTRANSITE/INTRASITE1 variable pair.\(^32\) The results are shown in Table 7. The average effect of intra-site learning from older reactors appears to be substantial, reducing availability losses by some 25%. SITEDUMMY1 is significant at the 5% level. Note the similarity with the corresponding U.S. result. Although the remaining coefficients are generally

\(^{32}\) In the case of France, this is not practical for the PREINTRAFIRM/INTRAFIRM1 variables.
unchanged, AGE is now significant at the 10% level.  

9. Discussion and Conclusions

The results for the United States and France generally support our expectation that industry structure influences the relationship between operating experience and performance. In the United States, the adoption and diffusion of two types of LWR technology has reduced the potential benefits from inter-reactor learning. Inter-reactor learning (both within and among firms) is observed only when reactors of the same type (BWRs or PWRs) are involved. This dichotomy is avoided in France where only standardized PWRs are employed. The organization and size of firms has also affected industry performance. As expected, inter-reactor learning is greatest at multi-unit sites. However, because reactor ownership in the U.S. is spread over many firms, multi-unit sites are relatively scarce. In contrast, the existence of a single public utility in France has made it possible for all reactors there to be located at multi-unit sites.

This evidence of a "structural" performance penalty in the U.S. raises several questions regarding the choice of technological standards and the size and organization of firms operating reactors in the domestic nuclear power industry. First, should we characterize the U.S. outcome as inefficient?

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33 AGE's greater precision is not surprising, of course, because this variable suffers from collinearity with an omitted variable, INTRASITE1. See note 29.
Second, what actions might be taken to improve performance among the existing population of reactors? And, finally, what are the lessons for government and industry decisionmakers as they plan for a second nuclear era?

The question of efficiency is not as simple as the preceding analysis might suggest. With regard to standards, the failure of the U.S. industry to select a single reactor type reflects the pioneering role of the U.S. in the commercialization of nuclear power. Early uncertainty about the capital and operating costs of different technologies promoted the adoption of several types of reactor. By the time this uncertainty was resolved in the 1970s, distinct networks of BWR and PWR operators had emerged. Informed by the U.S. experience, the French choice of PWR technology was made at this time. Thus, although the existence of multiple networks can be considered inefficient in an ex post sense, it may be seen as one feasible outcome of a market operating with incomplete public information.\(^{34}\)

It is possible that the existence of a more concentrated industry would not have affected the selection of both BWR and PWR designs in the U.S. (Japan and Sweden, which both have more concentrated electric utility industries, each adopted both types of reactor systems.) However, it is clear that inter-reactor learning among each class of LWR would have been

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\(^{34}\) One of the authors, McCabe, is at work on a paper which formally addresses these issues.
enhanced by the increase in multi-unit sites associated with a shift to larger operating organizations.\textsuperscript{35} Why did the industry fail to address this and related issues? One factor often cited is naive expectations - few observers foresaw the need to redesign institutions to accommodate a technology "that was just another way to boil water". The utilities, accustomed to declining costs and predictable demand growth, used their past success with conventional power sources as a guide for the future.\textsuperscript{36}

Despite these structural problems the results suggest a potential area for improvement among the existing population of reactors. Contrary to our expectations, larger U.S. utilities with more than one nuclear site do not appear to have been very successful in devising internal systems to promote information exchange between sites. For these firms, the benefits of inter-site learning appear to be many times smaller than those accruing from intra-site learning. Indeed, information exchanges between sites operated by the same firm may have been no more effective in improving performance than inter-firm exchanges. Although direct comparisons with French experience are difficult to make, the impact of inter-site

\textsuperscript{35} Other dimensions of U.S. nuclear industry performance benefited from large operating organizations as well. For example, McCabe (1990) shows that learning during plant construction was greater for firms building several reactors. An earlier discussion of this general subject is found in Lester (1986).

\textsuperscript{36} See Bupp & Derian (1978) on this point.
learning appears to be larger at the French utility. How much of this is attributable to the high degree of PWR design standardization and how much to organizational practices and systems that could be adopted in the future by U.S. utilities is unclear and deserves further research.\textsuperscript{37}

The "structural" lessons of our analysis are more useful to the architects of a second nuclear era in the United States. Regarding plant operating performance, two general recommendations are apparent. First, future reactor designs should be more highly standardized to enhance inter-reactor learning. Also, to avoid the reliability problems associated with the previous generation of large capacity units, the new reactors should be smaller and less complex. Second, operating organizations should be large enough to populate one or more multi-unit sites (within a reasonable amount of time) since this type of siting increases the benefits derived from inter-reactor learning. Efforts should also be taken to

\textsuperscript{37} The fact that inter-reactor learning at multi-unit sites is comparable in the two nations despite the differences in PWR standardization may imply that greater inter-site learning in France is due to superior organizational practices. If this is true, then U.S. utilities with multiple nuclear sites should be able to introduce the necessary changes without much difficulty.

Even if inter-site communication within firms can be improved, the problem of inter-firm communication remains. It is possible that the utility-sponsored Institute of Nuclear Power Operations (INPO) could serve as a vehicle for improved industry-wide learning. INPO, which was created after the TMI accident, facilitates communication among nuclear utilities on issues related to plant safety and reliability. We tested the hypothesis that industry-wide (INTERFIRM) learning in the U.S. was greater after the TMI accident (in our sample, the years 1980-86). No differences were found.
improve inter-site communication within and between these organizations; the French system may be a useful model.
References


Freeman, C., 1982. The Economics of Industrial Innovation (2nd ed.), MIT Press, Cambridge, MA.


Table 1  
United States Data Summary

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Total reactor/year observations: 709

* : Because so many of the observations for these variables assume a zero value, we have calculated the corresponding statistics using only observations with positive values. The number of positive observations in each case is contained in the parentheses following the designated variables.
### Table 2: French Data Summary

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<td>0</td>
<td>109.30</td>
</tr>
<tr>
<td>SITEDUMMY1</td>
<td>0.55</td>
<td>(0.50)</td>
<td>0</td>
<td>1</td>
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</table>

Total reactor/year observations: 137
Table 3  
GLS Results for the United States  
Homogeneous Technology

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<th>Estimate</th>
<th>Standard Error</th>
</tr>
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<td>1.3850&lt;sup&gt;c&lt;/sup&gt;</td>
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<tr>
<td>TMI1</td>
<td>-0.3631</td>
<td>0.0742&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>TMI2</td>
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<td>0.2669</td>
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<td>-0.0342</td>
<td>0.0412</td>
</tr>
<tr>
<td>AGE&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.0060</td>
<td>0.0025&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>0.0358&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>INTERfirm2</td>
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<td>lnSIZE</td>
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<td>VENDOR</td>
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</tr>
<tr>
<td>VINTAGE</td>
<td>0.0005</td>
<td>0.0023</td>
</tr>
</tbody>
</table>

<sup>a</sup> Two-tailed t-test indicates significance at a 10% level  
<sup>b</sup> Two-tailed t-test indicates significance at a 5% level  
<sup>c</sup> Two-tailed t-test indicates significance at a 1% level
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<th>Standard Error</th>
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<tr>
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<tr>
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<td>0.0024&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>0.0010&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>INTERFIRM2(ST)</td>
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<td>INTERFIRM2(DT)</td>
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<td>0.0011</td>
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<td>0.0085&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>VINTAGE</td>
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<sup>a</sup> Two-tailed t-test indicates significance at a 10% level
<sup>b</sup> Two-tailed t-test indicates significance at a 5% level
<sup>c</sup> Two-tailed t-test indicates significance at a 1% level
### Table 5
GLS Results for the United States
Heterogeneous Technology, Equal Learning Coefficients

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<thead>
<tr>
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<th>Standard Error</th>
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<td>A</td>
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</tr>
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<td>0.0010&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>INTERFIRM2(ST)</td>
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<tr>
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<tr>
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<td>0.0021</td>
</tr>
</tbody>
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<sup>a</sup> Two-tailed t-test indicates significance at a 10% level
<sup>b</sup> Two-tailed t-test indicates significance at a 5% level
<sup>c</sup> Two-tailed t-test indicates significance at a 1% level
Table 6  OLS Regression Results for France

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<th>Standard Error</th>
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<td>AGE^2</td>
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<tr>
<td>VINTAGE</td>
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</tbody>
</table>

^a Two-tailed t-test indicates significance at a 10% level
^b Two-tailed t-test indicates significance at a 5% level
^c Two-tailed t-test indicates significance at a 1% level.
Table 7  OLS Regression Results for France

<table>
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<th>Estimate</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
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<td>INTRASITE2</td>
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<td>INTRAFFIRM1</td>
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<td>0.0055</td>
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<tr>
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<tr>
<td>VINTAGE</td>
<td>-0.0023</td>
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</tr>
</tbody>
</table>

\(^a\) Two-tailed t-test indicates significance at a 10% level
\(^b\) Two-tailed t-test indicates significance at a 5% level
\(^c\) Two-tailed t-test indicates significance at a 1% level.
APPENDIX

Calculating the effective unavailability

The measure of operating performance used in this study is the plant 'unavailability'. Nuclear power plant performance is routinely characterized by the annual availability factor, defined as the total energy that the plant could have generated during the course of the year had it been called on to operate continuously at full power, divided by the energy that the plant would have produced if it had operated continuously at full power. Plant unavailability may be defined simply as \((1 - \text{annual availability factor})\). However, since we wish to estimate the effects of learning on performance the unavailability figures should exclude any outages that are not susceptible to learning-based reductions. The most important source of such outages for light water reactors is refueling, which requires the reactor to be shut down for some minimum period, and which may or may not take place each year. The lower limit for the duration of these outages depends on the technical requirements of the refueling operation, and may possibly also be constrained by regulatory requirements. Since these limits could not be determined directly, a minimum refueling outage was estimated for each country and subtracted from the reported unavailability of each unit in that country in each year that refueling took place. The minimum refueling outage observed in each nation during the sample period was the basis for these estimates.
(Note that when a refueling outage spanned two consecutive years, e.g., beginning in December of year $t$ and ending in February of year $t+1$, the appropriate fractions of this minimum outage period were used to adjust availability figures for years $t$ and $t+1$.)

In recent years some utilities, motivated by economic considerations, have begun to shift to fuel cycles longer than the standard 12-month period. By adjusting the annual unavailabilities as described above, we have corrected for the 'non-learning-based' performance improvements associated with this shift.

**Data Sources**

Availability factor data for the U.S. plants were obtained, in part, from the Operating Plant Evacuation Code (OPEC-2) database, compiled by the S.M. Stoller Corporation initially for the Electric Power Research Institute (Koppe et. al., 1984), and more recently for the Institute of Nuclear Power Operations (INPO). The OPEC-2 database was made available to M.I.T. by INPO. French availability factor data were provided, in part, by Electricite de France.

Each national data set was originally acquired during the course of a parallel study at M.I.T. (Beckjord et. al., 1986), and were generously provided to the authors of the present study. These data were compared for consistency with, and in some cases supplemented by, the performance analysis reports
published annually by the International Atomic Energy Agency (IAEA), *Operating Experience with Nuclear Power Stations in Member States* (Vienna: IAEA, various years). The IAEA reports also provided information on the incidence of refueling outages.

Data on reactor size, dates of construction start and start of commercial operation, and the reactor vendor and operator in the U.S. case were obtained from several sources: *Nuclear Engineering International*, July Supplement, 1985, *Nuclear News*, "World List of Nuclear Power Plants", August 1986, the Atomic Industrial Forum's *Historical Profile of U.S. Nuclear Power Development* (January 1, 1986) and the annual IAEA volumes.