DEVELOPMENT AND COMMERCIALIZATION OF THE LIGHT WATER REACTOR, 1946-1976

PREPARED UNDER A GRANT FROM THE NATIONAL SCIENCE FOUNDATION

ROBERT PERRY,
with A. J. ALEXANDER, W. ALLEN, P. deLEON,
A. GANDARA, W. E. MOOZ, E. ROLPH, S. SIEGEL, K. A. SOLOMON

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PREFACE

The generation of electrical power from the heat product of a nuclear reaction has become a commonplace of modern industrial society. To what extent that society--particularly in the United States--will, or should, become dependent on nuclear power is nonetheless a matter of continuing concern to the nation's citizens and to national policymakers. Questions of safety, of proliferation and terrorism, and of environmental consequences have dominated recent debates on the subject. Public participation in the decision process has been enlarged through hearings by regulatory and legislative bodies and by such events as the "nuclear initiative" movement in California and elsewhere. A nuclear industry has come into being over the past three decades, both in the United States and abroad. The reliance of utilities on the generation of power from nuclear reactors has greatly increased in the past decade alone. The oil crisis precipitated by the 1973 Mideast War has sharpened the division between those who see nuclear energy as essential to satisfying the energy dependence of our society and those who look on nuclear energy as a threat to the continuation of that society. The economies of nuclear energy are argued as heatedly as are the implications of its technology. Even its morality has been debated. If the scientific community, the political community, the community of economists, and the public are so at odds with one another, and among themselves, where are answers to be sought?

Concerned by such problems, the National Science Foundation through its Office of Energy Policy commissioned The Rand Corporation to undertake a study of the economic, technological, institutional, and historical factors that affected the development and commercial adoption of the light water reactor.[1] Its purpose was to provide an information base and an

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[1] A light water reactor (LWR) uses ordinary H_2O as both the coolant and the moderator for a controlled nuclear reaction. There are two basic types: Pressurized Water Reactors (PWR) keep water under high pressure and achieve high temperature without boiling in the primary system, and Boiling Water Reactors (BWR) generate steam directly. In both, the steam produced drives turbines that generate electricity.

analytical framework for decisionmakers to use in government and industry in evaluating options for the future course of nuclear (and other) power development and commercialization.

This is a historical treatment of the development and commercial exploitation of light water reactors. It has limitations that should be acknowledged early. Perhaps Arthur Schlesinger put it best:[1]

> One cannot doubt that the study of history makes people wiser. But it is indispensable to understand the limits of historical analogy. Most useful historical generalizations are statements about massive social and intellectual movements over a considerable period of time. They make large-scale, long-term prediction possible. But they do not justify small-scale, short-term prediction.... History, in short, can answer questions, after a fashion, at long range. It cannot answer questions with confidence or certainty at short range. Alas, policymakers are rarely interested in the long run--"in the long run," as [John Maynard] Keynes used to say, "we are all dead"--and the questions put to history are thus most often the questions which history is least qualified to answer.

Expectations of the rapid commercialization of nuclear energy for power generation in the United States have in many respects been disappointed. The slower than anticipated pace of the program and the surprisingly high cost of generating electricity on a large scale by means of nuclear reactors have troubled government at all levels, the developers and manufacturers of nuclear plant equipment, the using utilities, regulatory boards and agencies, and the public. Plant performance, safety, and efficiency have remained uneven. The future availability and the future price of uranium are as uncertain as the price and availability of fossil fuels. What has often been characterized as a "ponderous" licensing procedure continues to be widely credited with retarding the growth of what would otherwise have been a "healthy" nuclear industry. Cost, technological, incentive, demand, and regulatory matters have interfered with the resolution of major uncertainties about the future of nuclear power. Yet, more than three-fourths of the 111

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[1] Arthur Schlesinger, Jr., "The Problem of Hope: Contemporary History," originally in *Encounter*, November 1966, pp. 10-17, but much reprinted.

commercial-scale power reactors operating somewhere in the world in early 1976 were of light water design.[1] Few were of other than American design; most were of types conceived, developed, and successfully demonstrated by the U.S. government and private American firms between 1950 and 1976.

The study has involved research and analysis in several related but separate areas, each chosen for detailed examination because of its obvious relevance to the central question. The broad topics treated here and in companion studies in this series include: (1) the historical course of research, development, and demonstration of light water reactors between 1946 and the start of commercial-scale plant construction in 1963; (2) experience in the critical early years of commercial plant construction and operation, particularly in terms of expected and incurred costs, and technical difficulties; (3) the interactive roles of government, the utilities, and the manufacturers in commercializing the LWR; (4) the influence of regulation (and associated legislative actions, environmental influences, and similar institutional factors) on the commercialization process; and (5) how nuclear power "commercialization" efforts were managed, and how well they succeeded, in other nations. Except to the extent they arose in addressing the foregoing, many other related and relevant issues--proliferation, the fuel cycle, the administration of nuclear energy programs, safety, environmental policy, and uranium resource issues and prices--have *not* been addressed. Choices of topic and emphasis were made in an effort to confront what appeared to be the *principal* themes, problems, strategies, and successes and failures of the national effort to obtain commercially competitive electrical power from light water reactors.

The results are presented in four separate Rand reports:

- This report, which captures the themes of three other reports, encapsulates general findings, and addresses issues of cost, contracting practices, nuclear technology, foreign programs, and R&D policy. (Robert Perry et al., *Development and Commercialization of the Light Water Reactor, 1946-1976*, R-2180-NSF, June 1977.)

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[1] *Nuclear Engineering International*, April-May 1976, p. 23.

- A report that covers the research, development, and demonstration phases of LWR evolution between 1945 and 1963. (Wendy Allen, *Nuclear Reactors for Generating Electricity: U.S. Development from 1946 to 1963*, R-2116-NSF, June 1977.)
- A report concerned chiefly with regulatory issues. (Elizabeth Rolph, *Regulation of Nuclear Power: The Case of the Light Water Reactor*, R-2104-NSF, June 1977.)
- A report treating the role of the utilities. (Arturo Gandara, *Utility Decisionmaking and the Nuclear Option*, R-2148-NSF, June 1977.)

Unfortunately for those who prefer their history sliced into neat topical segments with comprehensive labels, the events that marked the commercialization of light water reactors were not at all clearly delineated. There are many overlapping chronologies, not one. Technology and legislation are intermingled with national prestige, the consequences of several small wars, an environmental movement, and a good many unrealistic expectations--to mention a few of the better known (if not well understood) influences. There is no "nuclear industry" as such: The phrase encompasses an amalgam of risk-averse utilities, scientists and engineers dedicated to advancing the state of the nuclear technology, regulatory bodies concerned with the cost of electricity to the consumer, plant operators impatient of demands for ever more extensive safety precautions and intervenors convinced that catastrophe is imminent, reactor manufacturers concerned with their sales prospects, and major or minor participants in abundance with roles that extend from extracting uranium to keeping an existing plant "on line" at all possible times.

By the early 1960s, the state of nuclear technology was widely advertised as "well in hand." Making the electricity generated by nuclear plants cost competitive with the electricity output of fossil-fuel plants had been an acknowledged national goal since at least 1953; in 1977 it is not at all obvious that nuclear power could economically compete with fossil-fuel power in many areas of the United States--and that it is competitive at all may be viewed as an accidental consequence of the upward trend in fossil-fuel prices between 1967 and 1977. For a time in the mid-1960s it seemed that the high construction costs associated with nuclear plants would make them so unattractive that no utility could seriously consider more than marginal reliance on nuclear energy for electricity generation; inflation in the construction industry and the influence of the environmental movement of the late 1960s so increased the cost of fossil fuel plants that by 1973 nuclear energy had largely regained its early promise. In the 1960s uranium was so abundant that the federal government had to subsidize its price to maintain production; in the 1970s the supply was so uncertain that the prospect of future shortages was the chief justification for a breeder reactor development program that promised to cost some $200 billion. American light water reactors have become the design standard of most of the world, but the United States has also vainly attempted to perfect nearly a dozen variant fuel cycle concepts with a lack of success that mirrors the nationalistic nuclear programs aborted by France and Britain.

All that, and much more, is the stuff of light water reactor commercialization. It certainly is not a tidy lot, and the "facts" of its history often seem to be viewed and interpreted in as many different ways as there were participants and observers.

The approach adopted here has been to treat the main issues and events more or less chronologically (with occasional departures for the discussion of particular topical items) through the late 1960s, by which time the construction of nuclear plants was no novelty and other matters were more important than the course of technology, construction cost problems, and the success of the effort to make the future progress of nuclear power a province of private enterprise (or, for public utilities, at least semi-private enterprise). Two topics required separate handling: regulation, and nuclear plant developments abroad. Both are occasionally treated, also, as elements in the earlier chronology.

SUMMARY

Whatever success the long, difficult, and costly effort to make nuclear power commercially viable in the United States has had must be credited partly to developments and events unanticipated when the effort began and partly to a succession of astute decisions. The light water reactor (LWR), which by 1976 was the most widely used source of nuclear energy for generating electricity, existed in prototype (the pressurized water reactor--PWR--developed for submarine propulsion) in the early 1950s.[1] Although several reactor designs based on different principles and concepts remained nominal candidates for adoption until well into the 1960s, and some were from time to time judged to be more technically or economically attractive, the LWR was the successful survivor. A national decision arising more in political than in technical evaluation prompted a search for reliable rather than cheap nuclear power and thus established the pattern of subsequent development. The boiling water reactor (BWR), based on a cycle not fundamentally different from the PWR, was selected for commercialization because its prospective vendor--General Electric--saw it as the least risky, most surely available alternative to the PWR and thus the best avenue for obtaining a share of the market for power reactors.

The important obstacle to early adoption of the LWR for power generation was understandable reluctance of the utilities to invest in a costly new technology before its commercial promise had been adequately demonstrated. Between 1953 and 1960, the Atomic Energy Commission (AEC) subsidized an extended series of demonstration efforts (formalized in 1955 as the Power Reactor Demonstration Program--PRDP) aimed at providing clear evidence of commercial worth. The PRDP involved not only light water reactor designs but extended also to a considerable variety of other concepts. Most showed insufficient promise; technology was the usual problem, although AEC unwillingness to accommodate to (or experiment with) institutional obstacles probably contributed to the early

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[1] Figure 1 presents a chronological schematic of the main events of LWR commercialization.

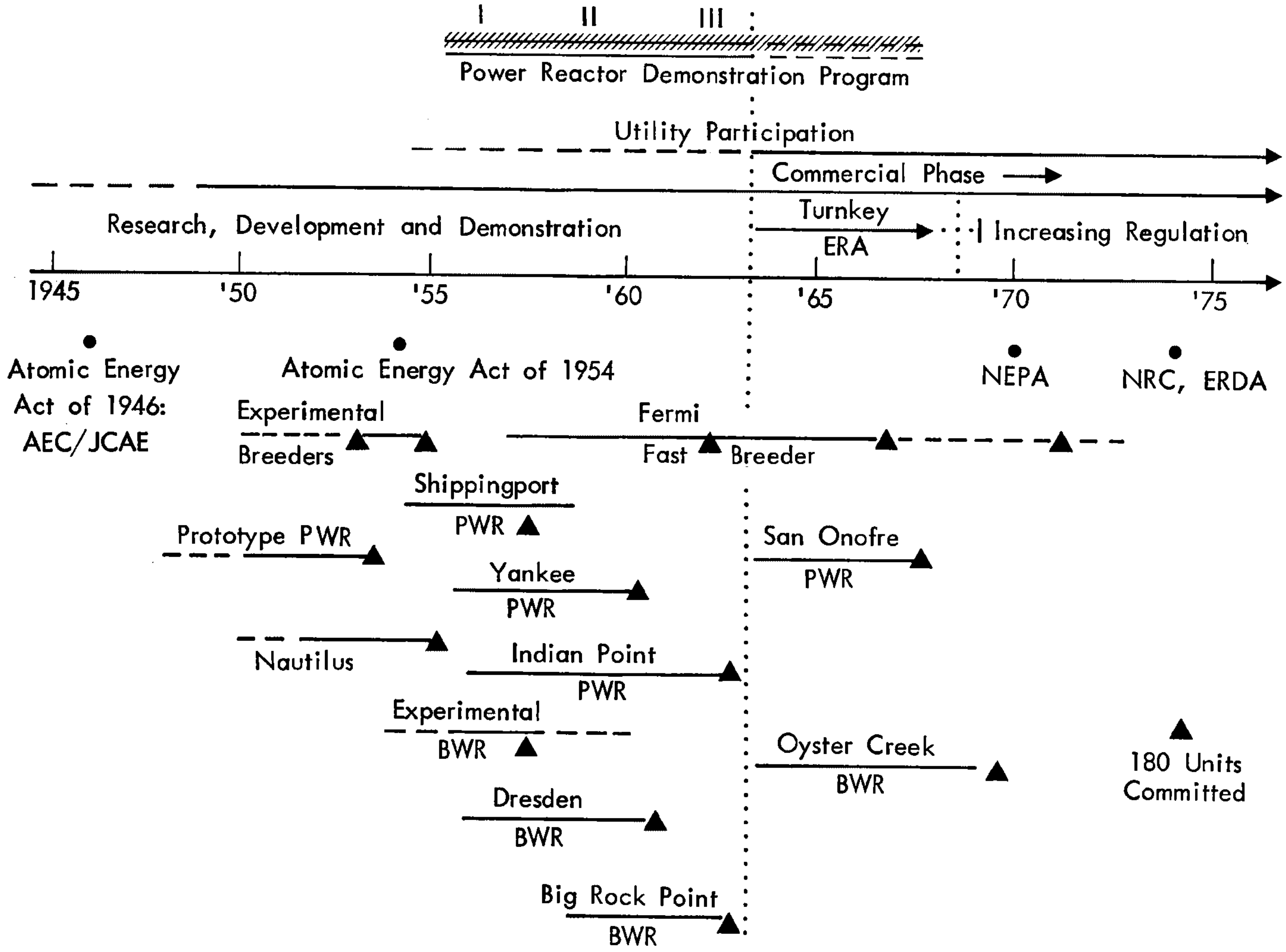

Fig. 1—Reactor commercialization

demise of some. In the long term, that could have become important only if the LWR had faltered. It did not.

Contrary to the hopes and expectations of the AEC, the PRDP did not provide sufficient assurance of the cost competitiveness of nuclear power to satisfy the utilities, and the sales efforts of the manufacturers--chiefly General Electric and Westinghouse at that point--were largely unavailing. Until 1963, no reactor was sold under free market terms;[1] subsidies of one sort or another (underwriting R&D or design costs, government ownership of the reactor, various fuel allowance clauses, or similar devices) were provided for all the reactors constructed in the United States. Although over a period of ten years the LWR concept had proven sound in small reactors (none larger than 200 MWe)[2] and in a variety of settings (the Yankee PWR and Dresden BWR reactors being the most convincing examples), the utilities would not invest in unsubsidized reactor-based central power stations.

In 1963, first General Electric and then Westinghouse (followed by other manufacturers) offered reactor plants with generating capacities of more than 400 MWe. Initial acceptance, starting with the Oyster Creek plant, was also stimulated by vendor offers to construct and guarantee the operability of the plants for firm fixed prices--the turnkey plant contracts. Ten utilities purchased 12 such plants from GE and Westinghouse between mid-1963 and mid-1966 (and another bought one on a controlled price basis); in the same period, utilities also contracted for a larger number of additional plants in about the same size range (400 to 1000 MWe) but under open market terms similar to those they had long favored in purchasing fossil fuel plants. All sales reflected the acceptance by manufacturers and utilities of several critical assumptions, the two most important being that in some locations nuclear plants would generate electricity at costs competitive with those of similarly sited fossil fuel plants, and that the capital costs of nuclear plants were

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[1] The Price-Anderson Act of 1957 (with later amendments), which limits the liability of a licensed nuclear plant operator and provides indemnification against public liability claims in excess of a certain amount, has functioned as a form of continuing subsidy.

[2] MWe: megawatts of electrical output; a megawatt is 1000 kilowatts.

as predictable (or controllable) as fossil fuel plant costs of the time.

In the event, those and some associated assumptions proved to be hollow. By mid-1966 it was obvious that for both turnkey and non-turnkey plants, bid prices considerably understated probable manufacturing costs. When the first 25 plants were finally completed, their capital investment costs were roughly twice what had been estimated when they were purchased. The utilities bore the costs of the non-turnkey overruns, and Westinghouse and General Electric absorbed losses on the order of $850-plus millions on their turnkey contracts. In terms of the advantages both the utilities and the reactor vendors had sought, the first few years of nuclear plant construction were notably unpromising, although some utilities got bargains.

But other events altered users' perspectives. Coal prices started a sharp rise in the mid-1960s and by the late years of that decade had again made the nuclear option appealing on cost grounds alone. In the first years of the environmental movement, some utilities may have opted for nuclear rather than coal plants because the nuclear alternative promised cleaner power, particularly important in areas where air pollution concerns were emerging. By the early 1970s, some utilities consciously adopted a policy of fuel diversification in their long-term plant construction planning, which reinforced an earlier tendency to "go nuclear" to offset fossil fuel transportation costs. That interest peaked in 1973, when oil prices and availability became uncertain.

There were countervailing influences in all of those events. The 1973 oil crisis brought on an unanticipated drop in the growth of demand for electricity, created cash flow problems for utilities already burdened by the effects of inflation, and ultimately induced some utilities to cancel or postpone the scheduled construction of nuclear plants. The increasing (and increasingly bothersome) length of time required for nuclear plant construction made fossil-fuel plants, which could be built more quickly, comparatively attractive in cost and cash-flow terms. Not until the mid-1970s was the financial situation of the utilities to improve.

Although construction delays had been troublesome since the first "commercial scale" plants were begun in the late 1950s, they did not substantially affect the progress of LWR commercialization until the late 1960s. Early delays resulted mostly from the flawed premises of 1963-1965, chiefly the assumption that nuclear plants would be no more difficult to design and construct than fossil-fuel plants of the same generating capacity. As plants increased in size, so did delays in their completion. The after-the-fact explanation that regulatory obstacles and the intervention of anti-nuclear organizations seriously influenced construction schedules in the 1960s is, however, difficult to validate. In a few instances, most arising from site selection controversies, proposed plants were rejected either by local jurisdictions or by AEC licensing authorities. But it was not until 1971 that the AEC assumed responsibility for policing the nonnuclear consequences of plant construction, and it took the courts (in the Calvert Cliffs decision) to bring about a significant change in the nuclear advocacy position of AEC regulators. Nor did the AEC take firm measures to quiet the concerns of those alarmed about the safety features of power reactors until the early 1970s. Although emergency core cooling systems (ECCS) were first installed in reactors starting in 1966 and were retroactively fitted to all existing reactors by 1974, controversy about the adequacy of the ECCS requirement was not stilled either by such actions or by assurances (based on the contested results of various studies) that existing ECCS standards were conservative enough.

With the exception of safety features, neither great controversy nor particular difficulty influenced power reactor technology once the basic PWR and BWR designs had been proven sound in the late 1950s. Unlike many other government-subsidized research and development activities, LWR development was little hampered by the late discovery of major technical or engineering inadequacies. The PWR was somewhat less troubled than the BWR by design and engineering defects that appeared as plants were completed or when they first were operated, a consequence of the more extensive experience with PWRs accumulated by both manufacturers and utilities before commercial-scale construction began in the early 1960s. General Electric had been obliged by commercial necessity to forgo its original plans for gradually progressing from experimental through demonstrator to "target" and eventually "large" BWR plants. With limited construction and operating experience, GE had in fact taken a very large technological jump in agreeing to build the first 400-750 MWe installations. Westinghouse, although having considerable experience in the naval reactors program and its offshoots, initially built somewhat smaller capacity plants than GE. Nevertheless, with allowances for the very considerable financial losses GE incurred by way of its turnkey contracts, the more abrupt and riskier course that vendor elected did not prove any less successful than the more cautious Westinghouse approach.

Although by 1970 most of Europe had gone over to the American BWR or PWR designs for nuclear plants, the American example was not initially attractive enough to dissuade the French, the British, and to some extent the Germans from investing heavily in efforts to create their own power reactors. The British were still persevering in 1976, citing the uncertain safety of the LWR plants and the greater economic benefits of their preferred designs as justification for a third effort to make a native British reactor commercially acceptable; but the French came over in 1970, and the Germans even earlier withdrew their wavering support of both the French effort and some embryonic German-originated concepts. Scientific nationalism certainly had some influence on both French and British preferences in the 1960s, but it was reinforced by economic necessity: national inability to finance more than one major reactor development effort at a time. The Canadians, constrained by a lack of uranium enrichment resources but having access to a supply of heavy water and possessing an abundant supply of natural uranium, also elected to pursue a single design, the CANDU.[1] In an economic situation at least as precarious as that of the French and the British, the Canadians pulled it off, not because their scientists were more skilled or their economists better, but because they chose a more conservative technical approach, because major changes in world fuel economies made CANDU costs increasingly attractive, and because CANDU fuel did not require reprocessing--an advantage of particular interest to prospective buyers who did not wish to be dependent on third states for key aspects of the fuel cycle.

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[1] CANDU: Canadian Deuterium Uranium.

One of the more interesting questions about LWR development in the United States is whether the AEC's chosen course of supporting various alternative approaches to power reactor development (through the PRDP) was a key factor in the eventual success of the American power reactor development effort. Parallel development--having a feasible alternative at hand in the event the main effort should fail--is one of the fundamental precepts of conservative R&D. The availability of alternatives to any of the several reactor concepts tried under AEC auspices in the late 1950s certainly permitted that agency to discontinue obviously unpromising programs without having to worry about the failure of the entire demonstration effort. It seems likely that if the more advanced LWR programs had encountered great problems, whether technical or economic, one or another of the then less attractive options--for example, a heavy water reactor design--might have been pushed to successful completion. But that did not occur. In fact, the 1953 decision by Hyman Rickover to favor the PWR over all alternatives, a decision based almost entirely on conservative engineering judgments, was quite sound. Subsequent PWR progress was made easier because of a government commitment to make the United States the first nation to have "peaceful nuclear power" available both for domestic use and for export. (The British won the race, if race there was.) Yet one key factor of LWR commercialization appears to have been that the PRDP permitted the sequential demonstration of successively larger and more efficient LWRs, not that it consistently offered nominal alternatives to the LWR. Still, the AEC's premature discontinuance of R&D support for non-breeder[1] programs after 1963 may have been partly responsible for lack of a real competitor to the LWR. Supporters of the high temperature gas reactor (HTGR), which has theoretically better efficiency than either a BWR or a PWR and is by some accounts "safer," have made that argument.

By 1976 more than 70 percent of the operating power reactors in the entire world were either PWRs or BWRs, as were the vast bulk of those under construction or firmly scheduled. Although LWR power sources

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[1] A breeder reactor produces more fissile material than it consumes and thus has greater economic attractiveness than reactors that do not.

were not in fact truly competitive with fossil fuel power in large areas of the United States, in other areas fossil fuel was noncompetitive with nuclear power. If conditions and circumstances unforeseen and unforeseeable in the early 1950s were actually responsible for the "success" of LWR commercialization, it was nonetheless true that the research, development, demonstration, and marketing processes had achieved what the Congress, the utilities, and the novice power reactor developers of the early 1950s had sought. Whatever problems remained (uranium supply, future enrichment services, reprocessing, and waste disposal, for example), the development and deployment of the reactors had worked well. Whether the enterprise had been worth its cost was a question for the future.

The technological evolution of the light water reactors and their competitive acceptability in the United States and abroad were not problem free, but progress was steady. In less than 20 years, the plants grew from 100 MWe to 1250 MWe and the fuel, uranium dioxide clad in Zircalloy, evolved from a novel laboratory material into a highly successful commercial product. Despite technical and institutional problems, the operational history of the large nuclear plants was as good as or better than large modern fossil fuel plants.

Conclusions and findings fall into four general categories: (1) elements of the approach to LWR commercialization that have obvious advantages and probably are transferable to similar energy development programs, (2) procedures and trends that might usefully have been altered and that generally should be avoided in such programs, (3) observations on development strategy and on the principal developmental functions of government and industry, and (5) general recommendations for the conduct of future programs.

Most of the initial phase of LWR development extending from experimentation through demonstration appears to have been well handled and, except perhaps for parts of PRDP, could serve as a model for future programs. However, the need for parallel multiple approaches is best evaluated on a program-by-program basis.

Early AEC indifference to the institutional aspects of LWR commercialization (except in the effort to "create" a nuclear industry) and excessive optimism about the predictability of cost, schedule, and performance outcomes hampered the eventual transition from "large demonstrators" to "full-commercial-scale" plants. That is likely to be a problem whenever the developer is also the promoter.

It seems likely that industry (vendors and the utilities) will be even more cautious about investing heavily in unsubsidized, high uncertainty, high financial risk energy programs of the future. More extensive government subsidies may be unavoidable.

During the final phases of the transition to "commercial-scale" plants, manufacturers working with customers are more capable managers of technology than are government institutions. But government intervention in the public interest is both inevitable and, when motivated by sensible goals, desirable.

The future prospects of such programs as are adequately represented by LWR development experience can be appreciably enhanced by greater attention to cost estimating (and cost control), by more careful hedging against unlikely but not implausible alternative futures, and by clearly distinguishing between conflicting objectives when evaluating rival technologies.

ACKNOWLEDGMENTS

This report is the final distillation of a research, analysis, and composition process that occupied more than 18 months. Over that period, many people assisted by providing information, advice, and criticism. In its final form, the report owes much to Rand colleagues W. E. Hoehn, Jr., and W. S. Baer, whose insightful comments have been reflected in both shape and substance. F. A. Camm, Jr., provided useful advice on an earlier draft. I am also indebted to my co-authors for assistance in revision; most of the substance of the report derives from research they performed, documented both in material sent to the National Science Foundation, sponsor of the study, and in the three companion reports cited in the Preface. James Plummer, formerly of the Office of Research Planning and Policy, National Science Foundation, who was the project sponsor and monitor during the period of intensive research and analysis, provided exceptional research support augmented by very sensible advice on how and where to proceed. Members of a project Advisory Board often met with the Rand research team as individuals, and twice as a group, contributing unstintingly of valuable advice on the scope and content of early draft reports; they included Lawrence Badash (Professor of History, University of California, Santa Barbara), Joseph Dietrich (Chief Scientist, Nuclear Power Systems, Combustion Engineering Inc.), Joseph Hendrie (Chairman, Department of Applied Science, Brookhaven National Laboratory), Richard G. Hewlett (Chief Historian, Energy Research and Development Administration), and John F. Hogerton (Executive Vice President, S. M. Stoller Corporation). Victor Gilinsky, Commissioner, and Samuel Chilk, Secretary, of the Nuclear Regulatory Commission, vigorously supported the efforts of the authors to get access to primary documentation, as did Richard Hewlett. Of many industry people who patiently explained details and background events, S. M. Stoller (of S. M. Stoller Associates) deserves particular acknowledgment.

For any errors of fact, interpretation, or emphasis that have escaped the scrutiny of all those who assisted and contributed, I am wholly responsible.

CONTENTS

I. INTRODUCTION: THE EARLY YEARS[1]

THE NUCLEAR REACTION

The physical phenomenon that makes it possible to generate heat in a nuclear reactor is nuclear fission, splitting the nucleus of a heavy element into two parts, which releases some 200 million electron volts[2] and two or more free neutrons. These free neutrons then move on, sometimes hitting other nuclei, which split to produce more energy and more neutrons, and so on. This process, called a chain reaction, occurs when a particular fissionable material is assembled in a particular configuration of sufficient mass. The mass sufficient to sustain a chain reaction is called the "critical mass," and reactors are said to "go critical" or to "achieve criticality" when a controlled chain reaction has been induced. A reactor is designed to enable its operators to control the chain reaction and energy release by regulating the rate at which neutrons are produced.

The principal materials that undergo fission when bombarded with slow or thermal neutrons are uranium-235, plutonium-239, and uranium-233. Fission can also be produced by bombarding these and other fissionable materials, particularly uranium-238, with fast neutrons. In a reactor, fission takes place in the core where fuel elements containing nuclear fuel are arrayed. Among the fuel elements are positioned control rods, which absorb neutrons and can be inserted or withdrawn to control the level of reactivity. Some 90 percent of the energy generated in the core occurs as heat in or near the fuel. Coolant circulates around the fuel elements to remove this heat, which is then transferred out of the core, or primary coolant loop, and is used to generate steam to drive the turbine-generator unit.

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[1] This section is partly based on Wendy Allen, *Nuclear Reactors for Generating Electricity: U.S. Development from 1946 to 1963,* The Rand Corporation, R-2116-NSF, June 1977, which should be consulted by those seeking additional detail.

[2] An electron volt is a unit of energy equal to the energy gained by an electron passing from a point of low potential to a point one volt higher in potential.

TYPE OF NEUTRON	ENERGY LEVEL
Slow or thermal neutrons	< 1 electron volt (ev)
Intermediate neutrons	> 1 ev and < 1000,000 ev
Fast neutrons	> 100,000 ev

Most reactors used commercially in the United States today are light water reactors (LWRs). Light water is ordinary water--H_2O--as distinguished from heavy water (typically deuterium oxide--D_2O). Water is used as coolant in light water reactors, which are of two types, either pressurized or boiling. Pressurized water reactors (PWRs) operate at high pressure (about 2250 pounds per square inch, or psi) to prevent the coolant from boiling. Boiling water reactors (BWRs) operate at about 1000 psi and the coolant boils in the core. (See Figure 2.)

When fission takes place in these reactors, the neutrons generated move with different energies. Most are high energy or "fast" neutrons. Because water reactors are fueled by either natural or slightly enriched uranium,[1] the atoms of which can be split only by a neutron of a certain energy level, a chain reaction cannot be sustained unless the neutrons are slowed down by a material called the moderator; LWRs use water to moderate the neutrons as well as to cool the core and to transfer heat. Fast breeder reactors (called "breeders" because they produce more fissionable material than they consume) use highly enriched uranium (20-30 percent to 92 percent) or plutonium, can maintain a fission chain reaction using fast neutrons, and therefore require no moderator.

Reactors can be engineered using different combinations of materials for fuel, coolant, and moderator. Although focused on light water reactors, this report also notes the development of a number of competing

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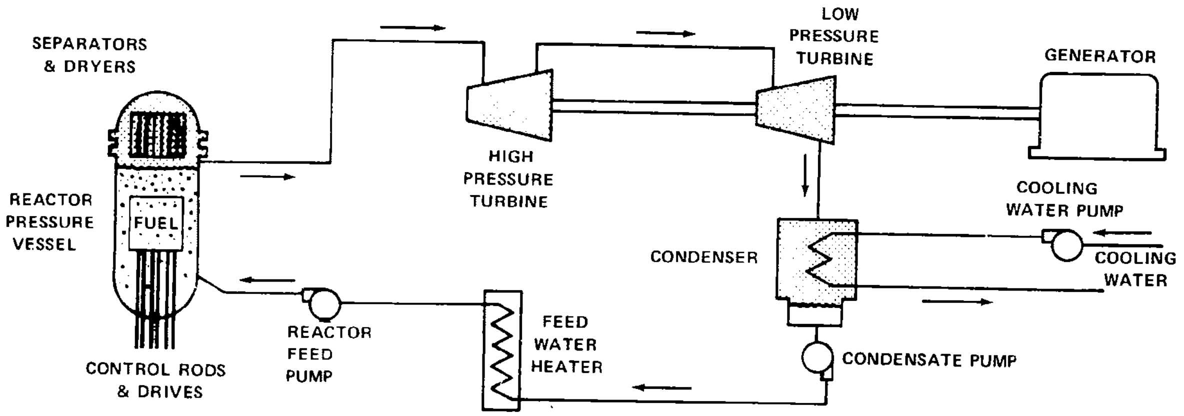
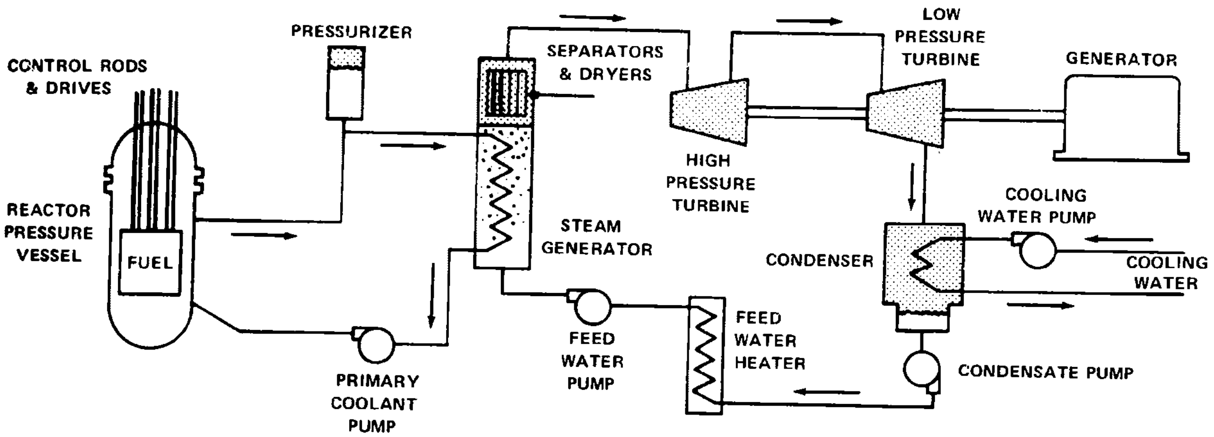
[1] Uranium occurs in nature as a mixture of U-234 (0.01%), U-235 (0.71%), and U-238 (99.28%). Enrichment is the separation of these three isotopes to make a material with an increased concentration of uranium-235. Slightly enriched uranium, such as that used in light water reactors, has a concentration of between 2 and 4 percent.



GENERAL ELECTRIC

FUEL Slightly enriched uranium oxide clad with zirconium alloy
MODERATOR Boiling water
COOLANT Boiling water
PRESSURE OF PRIMARY SYSTEM 1,000 psi
OUTLET TEMPERATURE 550° F

Boiling Water Reactor Power Plant



BABCOCK & WILCOX
COMBUSTION ENGINEERING
WESTINGHOUSE

FUEL Slightly enriched uranium oxide clad with zirconium alloy
MODERATOR Water
COOLANT Water
PRESSURE OF PRIMARY SYSTEM 2,250 pounds per square inch
REACTOR OUTLET TEMPERATURE 605° F

Pressurized Water Reactor Power Plant

Fig. 2 — LWR schematics

Source: WASH-1345.

concepts, such as sodium cooled, graphite moderated reactors, reactors that use organic materials for both coolant and moderator, heavy water moderated and cooled reactors, and fast breeder reactors. An understanding of these parallel development efforts is essential to appreciating why, by the late 1960s, light water reactors became the preferred nuclear power sources of the Western world.

TRANSITION

From the time the concept of controllable nuclear fission first appeared, physicists recognized that nuclear fission generated heat that could be harnessed as steam to operate machinery to produce electricity. But nuclear physics turned first to creating nuclear weapons, and not until 1946 was serious effort centered on reactors with civil applications. After the passage of the Atomic Energy Act of 1946 and the transfer of responsibility for nuclear research from the wartime Manhattan Engineering District to the civilian Atomic Energy Commission (AEC), scientists experienced largely in bomb development turned their attention to more peaceful concerns. There was no clear appreciation of how much time might be needed to develop power reactors that could generate electricity as cheaply as fossil fuel plants, but it was widely assumed that the task was feasible. The success of the Manhattan Project provided evidence that American ingenuity, enterprise, skill, and money were sufficient for the task. What remained was to resolve some uncertainties about reactor design and to bring engineering talent to bear on demonstration and development problems.[1]

Of the many assignments Congress gave the AEC, that of providing laboratories where basic research could be conducted without regard for its economic justification was most relevant to eventual power reactor development. But military and civilian applications for atomic energy were not separately addressed, and the security of atomic secrets took primacy over encouraging private research and development. Like weapons information, reactor technology was "restricted data" not releasable

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[1] Richard G. Hewlett and Francis Duncan, *Atomic Shield 1947-1952, Vol. 2, A History of the United States Atomic Energy Commission,* Pennsylvania State University Press, University Park, 1969.

without assurances that the release would not adversely affect national security. There was little opportunity for prospective developers and customers for nuclear reactor power to make objective evaluations of the commercial potential of its development.

A PREFERRED TECHNOLOGY EMERGES

With the Atomic Energy Act of 1946, Congress in effect created a legislative framework within which the development of nuclear power in the United States could proceed--monitored by the Joint Committee on Atomic Energy (JCAE). But not until 1948 were there stirrings of interest in what was eventually to become the light water reactor program. Initial work proceeded on an experimental basis through 1953. By that time the engineering feasibility of a reactor using pressurized water as coolant and moderator had been effectively demonstrated. For practical purposes, the national commitment to the pressurized water reactor was made in August 1950, when then-Captain Hyman Rickover concluded that a proposal originated by the Oak Ridge National Laboratories and taken up by Westinghouse was the best prospect for the development of a power reactor for submarines. His selection of the pressurized water reactor was based on little more than informed intuition and the judgment that light water reactor technology held promise for the immediate future. *In Rickover's terms,* two alternative concepts concurrently in development had become noncompetitive because they were either too complex or too costly.[1] Rickover chose on the basis favored by Robert Watson-Watt: always select the third best; the first-best never comes, the second-best comes too late, and one must have something to be going on with.

Although interesting tangents developed after 1948, by 1953 the equipment manufacturers and elements of the AEC that had been involved in the various tasks of reactor development generally agreed that commercialization required little more than solving definable engineering problems and convincing American utility firms that the nuclear power era had begun. Between 1953 and 1963, the AEC's reactor development program consistently emphasized eventual production of nuclear power that would be

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[1] Richard G. Hewlett and Francis Duncan, *Nuclear Navy, 1946-1962,* University of Chicago Press, Chicago, 1974, pp. 44-92.

economically competitive with the power generated by fossil fuel plants. There was no realistic expectation that nuclear power would displace fossil fuels in any cost-sensitive applications before 1958 or 1960. Nevertheless, the AEC and the utilities assumed that with government assistance of various kinds, nuclear power could be made commercially available in the early 1960s. How to finance and support an intervening ten years of development, demonstration, and proof remained, for the moment, uncertain.

The AEC decided, as a first step, to sponsor a series of developmental and demonstration projects in which both industry and potential utility users might participate. The decision was influenced by several factors, not the least of which was the determination of the Eisenhower Administration to show the world that the United States had a sincere commitment to the peaceful application of nuclear energy.

A number of objections surfaced in the course of the debate that preceded the decision. The first objection was basically technological: that electricity generated from nuclear power could make a significant contribution to the economy of the United States in less than 20 years seemed problematic to a number of informed observers. Second, it was not obvious that government support of an expanded reactor development program would indeed accelerate the availability of commercially competitive nuclear power; costs, prices, and demand were large uncertainties. Third, the prestige advantage of being first in the world to put a civilian nuclear powered reactor on line was intangible. Finally, an investment in or commitment to the generation of nuclear power was contingent upon the abandonment of existing national security policies: Between 1946 and 1953 the nuclear power generating process had been contained within security barriers, treated as only slightly less sensitive than the process of creating new nuclear weapons. To make available to industry the information necessary to translate nuclear engineering competence into nuclear power plants required a transformation of the fundamental American policy about the secrecy of most elements of atomic energy technology. (The possibility that nuclear power might be generated under government sponsorship, a

TVA-like arrangement, remained more or less in the wings until the late 1950s.)[1]

How much government help was needed, and to what end, was not explicitly addressed except as an adjunct to the question of which was indeed the most promising design approach to commercialization. One viewpoint was that the most efficient and effective mode of commercializing nuclear energy could not be determined from the technical and cost information available in 1953. The second, epitomized by Rickover, was that the pressurized water reactor offered a direct avenue to the early achievement of a reliably operating nuclear power plant. The eventual determination was made on grounds more political than technical. The National Security Council ruled in 1953 that the early development of nuclear power was a prerequisite in maintaining the U.S. lead in the atomic field. If that indeed was the national judgment, and a government-sponsored civilian power reactor was wanted, then the pressurized water reactor was the most promising candidate.

A verdict in favor of the light water reactor derived also from the technical success of earlier experimentation. No major competitor existed in 1953, by which time Rickover's prototype Mark I pressurized water reactor was operating reliably and impressively.

The final decision--to build a small pressurized water reactor at Shippingport, Pennsylvania--thus was driven by various policy considerations supported by the technical observation that the pressurized water reactor promised near-term, reliable nuclear power, although there was no certainty that cheap nuclear power would eventually result from its widespread adoption. If cheap nuclear power had been the long-run goal, then the pressurized light water reactor might not have been so promptly chosen. But foreign developments of 1951-1953 suggested that unless the United States made a choice and concentrated national resources on achieving its goal, either the British or the Russians would probably be able to construct and operate a power generating reactor sooner.[2]

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[1] AEC 655/24, January 5, 1955, and AEC 665/1, June 23, 1952. (AEC documents are cited by file/document number and date.)

[2] In the end, the British did precisely that: Their Calder Hall reactor, gas cooled and graphite moderated, became operational in December 1956. And so did the Russians, although with only a 5 MWe (megawatts of electrical output; a megawatt is 1000 kilowatts) demonstration plant.

National prestige and foreign policy considerations prompted a decision based on some impressive technological achievements not necessarily relevant to economic factors.[1]

Technology was in some respects the least certain of the factors considered. In 1953, the research and development subcommittee of the Congressional Joint Committee on Atomic Energy concluded that the pressurized water reactor and the sodium graphite reactor could enter large-scale experimental testing in two or three years and the boiling water reactor in about five. The homogeneous reactor and the fast breeder, then assumed to have the greatest promise for eventually generating electricity at costs competitive with fossil fuel plants, were not expected to be ready for large-scale experimental testing in less than five years. In 1954, when legislation was proposed to permit developers and users to participate actively in the commercialization process, the pressurized water reactor was judged—in terms of economics—to be the least promising of all the proposed reactor concepts. Nevertheless, its technological situation made the pressurized water reactor the only "large" experimental reactor the AEC could reasonably sponsor for near-term development. Preliminary work on the 60 MWe plant at Shippingport was proceeding well. Nothing else was as advanced. Based on engineering concepts developed in the course of the U.S. Navy's reactor propulsion program, the pressurized water reactor was the Westinghouse candidate for development as a nuclear power source for commercial applications; and having had extensive experience in the Naval Reactors Program, Westinghouse was by a considerable margin the most experienced reactor builder in the United States.[2]

The proponents of the 1954 Atomic Energy Act thought that merely opening nuclear technology to commercial development would stimulate a

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[1] AEC 434/12, March 31, 1952; AEC 649/8, August 6, 1953; J. F. Hogerton, "The Arrival of Nuclear Power," *Scientific American*, February 1968; Hewlett and Duncan, *Nuclear Navy*, pp. 338-339.

[2] Joint Committee on Atomic Energy, *Report of the Subcommittee on Research and Development on the Five-Year Reactor Development Program Proposed by the AEC*, Washington, D.C., March 1954, pp. 2-14.

surge of interest from the utility industry.[1] But concrete proposals to finance and build nuclear plants were not forthcoming. Most utilities, traditionally risk averse, held that although nuclear power might in the long run become competitive with conventional power, investing R&D funds in that possibility had no early payoff. What they wanted was hard evidence that electricity could be produced from nuclear power at costs no greater than those of generation by conventional thermal plants. Estimates current in the early 1950s suggested that such cost levels were achievable for dual-purpose reactors, which would produce both commercial electricity and plutonium for weapons. By 1953, however, the military requirement for plutonium was being satisfied by AEC reactors, and revenues from government repurchase of plutonium had to be deleted from the cost calculations. Without that "subsidy," power reactors had smaller economic attractiveness; costs and returns were uncertain, owing to the immaturity of reactor technology. Although notably nervous about the possibility of nationalized nuclear power, neither utilities nor manufacturers were interested in financing open-ended nuclear projects.[2]

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[1] The main provisions of the new law included (1) private ownership of facilities and private use (but *not* ownership) of nuclear materials, formerly prohibited; (2) greater private access to information about reactor technology; (3) the liberalization of patent laws; and (4) the supply of AEC services and materials to commercial firms. Public Law 83-709 (68 Stat. 919) (1954).

[2] Harold P. Green, "The Strange Case of Nuclear Power," *The Federal Bar Journal*, 17, April-June 1957.

II. THE APPROACH TO COMMERCIALIZATION, 1954-1967[1]

The rationale for the government-industry partnership as it was conceived in the 1954 Atomic Energy Act was quite simple:[2]

> Many technological problems remain to be solved before widespread atomic power, at competitive prices, is a reality. It is clear to us that continued Government research and development, using Government funds, will be indispensable to a speedy and resolute attack on these problems. It is equally clear to us, however, that the goal of atomic power at competitive prices will be reached more quickly if private enterprise, using private funds, is now encouraged to play a far larger role in the development of atomic power than is permitted under existing legislation. In particular, we do not believe that any developmental program carried out solely under government auspices, no matter how efficient it may be, can substitute for the cost-cutting and other incentives of free and competitive enterprise.

But such encouragement did not sufficiently lessen the reluctance of private industry to invest large sums in risky programs with uncertain returns. The AEC therefore decided to offer limited government support to encourage private financial commitment.

THE POWER REACTOR DEMONSTRATION PROGRAM

In January 1955 the AEC announced the "first round" of its Power Reactor Demonstration Program (PRDP), intended "to bring private resources into the development of engineering information on the performance of nuclear power reactors and to advance the time when

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[1] Much of this section is based on Wendy Allen, *Nuclear Reactors for Generating Electricity: U.S. Development from 1946 to 1963*, R-2116-NSF, which should be consulted both for a more comprehensive account and for additional documentation.

[2] U.S. Congress, Senate Report No. 1699, 83rd Cong., 2d Sess., to accompany S.3690, in *Legislative History of the Atomic Energy Act of 1954 (Public Law 703, 83rd Cong.)*, Vol. 1, Washington, D.C., 1955, p. 751.

nuclear power will become economically competitive."[1] Three kinds of assistance were proposed, with levels of government support to be negotiated and fixed in advance. Fuel use charges would be waived for seven years, an agreed share of preconstruction R&D work would be performed in government labs without charge, and R&D aspects of post-construction operations would also be subsidized, although by law the AEC could not fund the actual construction of reactors to be used commercially. Otherwise, the developers, the suppliers, and the users were to bear all the risks associated with building and operating the reactor and power generating facility.

Of the four proposals received, the AEC accepted two (Yankee[2] and Fermi) under the terms of the first round and approved a third (Hallam), which eventually proved more appropriate to second round terms. The Yankee PWR project was a striking success. It was completed on time and under budget and began operating in 1960. The Fermi fast breeder encountered licensing problems during Construction Permit hearings. After a 1965 start-up it suffered a core meltdown in 1966, was again operational in 1970-1971, and thereafter had continuous operating problems. The Hallam sodium graphite reactor (SGR) operated on and off during 1963-1964, but it also experienced major technical problems. Even though the SGR concept had been considered very promising ten years earlier, the AEC discontinued development of the design in 1964, effectively terminating the approach.[3]

Because the economics of nuclear power had been imperfectly demonstrated, utilities still did not express much interest in buying reactors for central station electricity generation. Most of the cost

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[1] U.S. Atomic Energy Commission, Press Release No. 589, January 10, 1955; *Hearings Before the Subcommittee on Legislation of the Joint Committee on Atomic Energy*, 88th Cong., 1st Sess., on Cooperative Power Reactor Demonstration Program, 1963, Washington, D.C., 1964; *Operating History, U.S. Nuclear Power Reactors*, Division of Reactor Development and Technology, U.S. Atomic Energy Commission, WASH-1203-73, Washington, D.C., 1974.

[2] Although Yankee is often referred to as Yankee-Rowe, to distinguish it from the later Connecticut Yankee, the original usage will be observed here.

[3] AEC 777/11, June 30, 1955; *Nucleonics*, Vol. 19, March 1961, pp. 59-61.

and all of the risks of the Yankee and Fermi projects were borne by consortia, a dozen or more utilities and manufacturing companies who joined forces. Yankee's success was subsequently attributed to excellent management and to the happy circumstance that PWR technology was actually advanced enough for demonstration. Fermi's failure reflected the immaturity of breeder technology and unwarranted optimism about the resolution of technical uncertainties. Hallam was a project of the Consumers Public Power District of Nebraska, a single, publicly owned utility, which agreed to provide only 25 percent of the estimated total costs. Although SGR technology was earlier considered to be as advanced as PWR technology, that ultimately proved not to be true.

The second round of the PRDP was intended to attract the participation of small, publicly owned utilities in the construction of small-scale (up to 40 MWe) experimental power reactors. The AEC financed reactor construction and retained ownership of the reactor portion of the plant. A goal of the first round had been to hasten the time when nuclear power would be competitive, which made short-term technical and economic feasibility a crucial consideration. In the second round, technical advance was sought and received bonus points in the evaluation of proposals. Not unpredictably, many of the proposed second round plants were more nearly experimental than demonstration level projects. As the second round proceeded, it also became apparent that small, publicly owned utilities were not the best candidates for the large financial risk associated with the uncertain technology of experimental nuclear plants. Most could not afford more than the cost of a conventional power plant.

In addition to the Hallam sodium graphite reactor, the AEC eventually funded two of the second round proposals: the Piqua, Ohio, organic reactor and the Elk River, Minnesota, boiling water reactor (BWR). The original ratios of federal to nonfederal funding were 6:1 in Piqua and 3:1 in Elk River. Costs proved higher than estimated, the contracts had to be renegotiated, and the proportion of federal funding increased. Neither project was technically successful. The

Piqua reactor operated fitfully for about three years; Elk River operated for five years. Both were eventually shut down.[1]

In retrospect, the reasons for the failure of the second round projects became obvious. The AEC had coupled reactors of high technical risk with low sponsor capability to assume the associated financial risks. If inducing small utilities to participate in the demonstration program were important to the AEC (and it did have considerable political significance to legislators representing districts where small public utilities were usually found), low risk reactors of conservative design, probably small light water reactors, should have been built. If the AEC's primary goal was to test the commercial feasibility of outlying reactor technologies, then consortia of utilities and manufacturers able to assume the considerable financial risks of such undertakings would have been more appropriate participants. The three small utilities involved in the second round of the PRDP could not provide the funds needed to maintain the original sharing ratio arrangements once major technical obstacles arose and costs increased. The institutional and economic setting of the second round of the PRDP was incompatible with the technology it invoked.

In January 1957, the AEC announced a third round of PRDP projects and offered government assistance similar to that of the first round. Five proposals were received and two plants were constructed under third round terms, which required that construction be completed by 30 June 1962. They were Pathfinder, a super-heated BWR[2] located in South Dakota,

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[1] AEC Press Release No. 695, September 21, 1955; "Supplemental Report of the Selection Board of the Second Round in the Power Demonstration Reactor Program," July 5, 1956; AEC 777/24, 777/30, and 777/31, November 27, 1956, and January 4 and 28, 1957; AEC 777/41 and 777/44, "Power Demonstration Reactor Program--Status Report(s)," May 10 and June 10, 1957; AEC 777/108, "Status and Potential Problems of Second Round Plants," January 11, 1958.

[2] Super heating involves recovering steam after its passage through a turbine and pumping it through another heater, increasing its temperature and decreasing its moisture content. The super-heated steam is then recirculated through the turbine, increasing the efficiency of the total electricity generation process. The inefficiency of the LWR as a primary steam generator was recognized early in the PRDP phase. Problems (chiefly) of fuel cladding limit the temperature at which the reactor core can operate, making it impossible to produce steam at temperatures

and the Carolinas-Virginia Tube Reactor (CVTR), a heavy water pressure tube reactor built in South Carolina. A third project (Peach Bottom, a high-temperature, graphite moderated, helium cooled reactor built in Pennsylvania) began after the Commission had extended the construction deadline to mid-1964. Third round results were mixed. Pathfinder was closed down after about a year of operation, but the heavy water tube reactor operated successfully. Peach Bottom, designed by General Dynamics to operate for five years as a research and development project, survived fuel element failure and many lesser difficulties to become a reasonably successful demonstration project.

By means of such demonstration projects, the AEC had hoped to determine whether several varieties of nuclear reactors had commercial potential. But in the process, the important distinction between demonstration projects and experimental R&D projects was blurred, and most second and third round PRDP projects lived in a half-world between success and failure. PRDP experience served to highlight the inadequacy of earlier R&D, but that did little to resolve questions about commercial potential because no real "demonstration" could be conducted. In some instances, the most that was "demonstrated" was that some particular species of reactor was not quite ready for demonstration.

Although not formally part of the demonstration program, four additional reactors were begun between 1959 and 1962 under terms similar to those of the second and third round projects. The BONUS nuclear super heat 16 MWe BWR project, built in Puerto Rico, and the 50 MWe La Crosse BWR (LACBR), located in Genoa, Wisconsin, generally conformed to second round arrangements. The AEC provided about 20 percent of the funds for the Big Rock Point, Michigan, 75 MWe BWR, typical of the support provided for the third round projects. The completed plant has operated reasonably well since 1962. Built with more than 85 percent private financing, the 375 MWe PWR San Onofre I plant, the first of several power reactors

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and pressures as high as those in fossil-fuel boilers. In addition to the several variant reactor concepts unsuccessfully tried in the course of the PRDP, there were continuing experiments with super heating, both internally to the reactor and as an add-on stage. None successfully demonstrated the engineering or economic feasibility of generating "high quality" steam in an LWR.

at the same California site, continues to operate successfully today. BONUS proved consistently troublesome and eventually was shut down. LACBR, renamed Genoa, continues to operate, although intermittent shutdown episodes have kept cumulative reactor and plant availability at less than 60 percent.

In August 1962, under the terms of a modified third round of the PRDP, the AEC invited proposals for large (400+ MWe) nuclear power plants. Only "proven concepts," reactor designs that had demonstrated engineering feasibility, were wanted. In practice, that meant water moderated and cooled reactors without nuclear superheat. In addition to subsidies similar to those for third round reactors, the AEC agreed to provide additional preconstruction engineering and design support, including site evaluation, planning, and construction project design. Two PWRs were proposed under those terms and one was built. The 490 MWe Connecticut Yankee Haddam Neck plant, about 85 percent privately funded, still operates successfully. A similar plant proposed by the Los Angeles Department of Water and Power was abandoned in the wake of strong public objections that the site was astride a major earthquake fault.[1]

The Power Reactor Demonstration Program was nominally intended to demonstrate the technical and economic attributes of several different reactor designs in operational settings. If a particular reactor proved unsuccessful, the AEC could abandon it without disrupting the balance of the total program. Bidders retained a broad range of choices. That several of the designs proved to be technically unsound may have been unfortunate, and in some instances may have had misleading implications for the future of that reactor, but a single project failure never obliged the AEC to invest massively in remedial R&D. Further, although the pace probably seemed forced to the participants, in fact the demonstration program extended over a period of 15 years and had aspects of sequentiality. Shippingport, a design descendant of the submarine propulsion PWRs, did not begin operating until two years before Yankee--larger but somewhat similar in concept--went critical (1960), but much

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[1] AEC, *Major Activities in the Atomic Energy Programs, 1962*, Washington, D.C., 1963; AEC, *Operating History, U.S. Nuclear Power Reactors*, WASH-1203-73.

experience was carried over. The contracts for Yankee's successors, the 375 MWe San Onofre plant and the 463 MWe Connecticut Yankee Haddam Neck plant, were not signed until 1963, by which time Yankee had provided highly useful operating experience, which perhaps did more to lessen the reluctance of utilities to invest in commercial-scale reactor plants than any other factor.

One of the most useful lessons of the PRDP era was that neither the pace nor the eventual direction of new, uncertain technology is credibly predictable. Two of the designs considered most promising in 1954, the sodium graphite and the homogeneous reactor concepts, were within ten years acknowledged to be quite infeasible.[1] The example of the British, French, and Canadians in setting forth confidently on single-path reactor development programs is instructive.[2]

The AEC's effort to exploit the PRDP concept came nearest to failure through insufficient understanding of the institutional factors on which the adoption and eventual commercial success of nuclear power ultimately turned. Until the late 1950s, the AEC and the Joint Committee were wedded to the notion of technological urgency--an appreciation that if adequately attractive technology could but be demonstrated, a market for it would automatically develop. The government sponsors were preoccupied, at times almost to the exclusion of other considerations, with finding avenues for demonstrating variant reactor designs and with solving a number of technical problems that troubled design, construction, and operation. There were, indeed, recurrent expressions of concern for the economics of nuclear power, but the subject often was treated as though technology alone would provide adequate means of settling all questions of commercial application. The impression that a nuclear reactor was only a uniquely efficient heat source that could

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[1] "Infeasible" technology can describe a situation in which engineering problems are so intractable that the reactor, if built, would not operate. Or it can describe a situation in which ten years of trying have not produced a solution to known engineering problems, although another five years might, if experimentation and development could be continued. Infeasibility, then, characterizes combinations of constraints--temporal, economic, institutional, *and* technical.

[2] See Sec. VI.

be hooked into the turbine section of a conventional power plant lingered long after evidence to the contrary. Attempts to insure the development of a healthy, diversified nuclear industry, to induce large and small producers and utilities of all sizes to participate, failed. The failure occurred not merely because nuclear reactors were expensive to develop, or plants were costly, but because few developers or users were either accustomed to or financially able to assume the considerable risks of developing, building, and operating nuclear reactors of uncertain profitability. In no instance before 1963 was any power reactor built without at least some direct or indirect federal subsidy, which is perhaps the strongest evidence for the persistent lack of industry confidence in the commercial future of nuclear power. And a similar situation elsewhere may be equally significant: The sturdiest industrial support for reactor development came from two large, financially stable firms with extensive experience in other kinds of government sponsored, high risk research and development. Firms with institutional traditions different from those of Westinghouse and General Electric were more cautious, and, in the main, less successful.[1]

The AEC had not ignored the nontechnical uncertainties that so troubled the PRDP, but those uncertainties were never viewed as problems that could be attacked by experimentation and evaluation, the tactics favored for surmounting technical obstacles. For the most part, institutional problems were simply not dealt with, the underlying premise being that they would solve themselves once the technical virtues of reactors had been demonstrated and the government got out of the reactor business.

Between 1953 and 1963, the Atomic Energy Commission, using a variety of contractual and institutional arrangements, supported a succession of demonstration projects with the aim of discovering (and proving) the technical and commercial feasibility of different approaches to the exploitation of nuclear power. At the end of that era, although only five plants had been built (or were being built) that might be candidly

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[1] Less successful technologically, but not necessarily financially, is a characterization generally applicable to Combustion Engineering and Babcock and Wilcox. Allis-Chalmers encountered great problems in both spheres.

described as prototypes of commercial nuclear power installations, the effort appeared to have been successful. The evidence was an event of July 1963: General Electric contracted with New Jersey Power and Light to build a nuclear powered generating plant of 515 MWe (net) capacity at Oyster Creek--the first nuclear plant not at least partly subsidized by the federal government, the largest yet attempted, and the first to be chosen on the strength of the assumption that the cost of nuclear power was competitive with the cost of fossil fuel power. In 1963, therefore, the 1953 decision to invest substantial national resources in the development of economically feasible, commercially competitive nuclear power sources for the generation of electricity was endorsed in the manner traditional to American private enterprise: an offer to sell, and free market acceptance.

THE EARLY REACTORS: COSTS AND EXPECTATIONS

Electricity generated by a nuclear power plant first became commercially available in the United States with the completion of the testbed Shippingport reactor for Duquesne Light Company in 1957, three years after construction began. The economics of the process had very little to do with Duquesne's decision to invest in the plant.[1] Duquesne agreed to purchase steam from the AEC-owned reactor at about 8 mills per kilowatt-hour (kwh), introducing that steam into its own turbine generator. Duquesne also provided the site for the reactor, contributed $5 million toward reactor research and development, and agreed to operate and maintain the plant. Turbine generators cost about $17.5 million, so that Duquesne's investment consisted of $22.5 million plus the cost of the site: about $250 per kilowatt in the 90 MWe plant. Using the presumably conservative assumptions of 80 percent capacity factor and 10 to 15 percent interest rate, Duquesne had to expect to incur capital charges of 3.5 to 5.5 mills per kwh plus steam charges of about 8 mills per kwh plus operating, insurance, and maintenance costs. Even though Duquesne did not finance the reactor, the company's incurred energy costs probably were not lower than 11.5 to 13.5 mills per kwh which certainly was not

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[1] Although at the time the agreement was made Duquesne may have expected capital cost savings to offset the higher energy generation costs.

competitive with fossil fuel alternatives available in the same region during that period.[1]

In the mid-1950s, when Shippingport was completed, the average cost of generating electricity with fossil fuel in the United States was on the order of 5.5 to 7 mills per kwh for the entire country, with regional extremes ranging from about 4 mills to about 12 mills. Utility interest in electricity generated by nuclear power was tempered by perceptions of its unpromising economics. That factor alone was probably enough to encourage the AEC to sponsor the Power Reactor Demonstration Program as a means of inducing utilities to build demonstration reactors from which the AEC could gain technical data and the utilities could gain experience with a new technology. By a variety of subsidy agreements, the AEC in effect lowered the capital costs to the utilities and reduced their fuel costs.

It is difficult to determine how effective AEC assistance was in lowering the utilities' cost of producing electricity under the PRDP plan. Different utilities used different rules for establishing their capital charge rates, and the reactors themselves operated with differing capacity factors. Still, the unsubsidized economics of the early plants was scarcely a major factor in inducing utility participation. Nor did experience with the PRDP plants support the conclusion that the economics of AEC assistance either influenced any utility to spend its own money to build a nuclear plant or brought nuclear power generating costs into real competition with fossil fuel costs. In March 1961, power from Yankee, the largest of the PRDP plants, cost an estimated 11 to 15 mills per kilowatt, of which capital charges represented 8 to 10 mills and fuel plus operation and maintenance the remaining 3 to 5 mills. The expectation of that period was that such costs might decrease, coming closer to the 9 mill fossil fuel costs then typical of New England.

Only three plants in the PRDP set were built without substantial financial assistance from the Atomic Energy Commission: Commonwealth Edison's Dresden I, Consolidated Edison's Indian Point I, and Pacific Gas and Electric Company's Humboldt Bay. Dresden I was built for

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[1] AEC 649/19, 10 March 1954.

capital costs of about $225 per kilowatt against the expectation that after a few years of operation the plant might generate power at a cost approaching that of electricity from the coal-fired plants of 1955. The Humboldt Bay plant was built for about 30 percent more (dollars per kilowatt) in the expectation that after its second fuel loading it might generate power for about 8 mills per kwh. Although that was not competitive with the costs of power generated by conventional fossil fuel plants in the period, plant construction was undertaken at least partly in anticipation of a time when "coal, oil, and gas will not be abundantly available...." The Indian Point plant cost more than twice as much as Dresden I (in dollars per kilowatt) and had prospective total energy costs of about 11.5 mills per kwh. Typical fossil fuel electricity costs in New York at the time were about 9 mills, so it is unlikely that Indian Point was expected to produce power competitively.[1]

INCENTIVES AND CONTRACTS

The Atomic Energy Commission used a variety of financial and contractual devices to stimulate the development of commercial power reactors. The AEC's approach was to share risks through government financing and by retaining ownership of reactors (the riskiest part of nuclear electrical generating systems), through lump-sum R&D grants to utilities, and through insurance against liability for nuclear accidents.

Between 1953 and 1963, the Atomic Energy Commission had to contend with two problems that inhibited private investment in nuclear power reactors. The first was that large uncertainties still affected assumptions of the performance and reliability of reactors and the generating costs of electricity. The second was that the estimated costs of nuclear power were appreciably higher than the known costs of alternative power sources. The AEC initially addressed the uncertainties by constructing and operating the nuclear portions of the facilities and selling the product--steam--to their participating electrical utilities in accordance with a predetermined cost schedule. Thus, the AEC shouldered the open-ended risk of the uncertain technologies. In an effort to overcome the

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[1] "Analyzing Nuclear Power Costs," *Nucleonics*, July 1964; *Nucleonics*, December 1959.

cost difference between nuclear and conventional power, the AEC also made substantial financial contributions to the R&D aspects of the early projects. In some projects, both types of incentives were used.

There were three kinds of contractual relationships during the precommercialization stages in the development of nuclear power. In one arrangement, the AEC purchased the reactors and made them available. In another the AEC provided R&D funds, waived fuel charges, or provided other support. The third and preferable alternative from the AEC's standpoint was to have the utilities buy directly from the reactor manufacturers.

These three approaches led to quite different outcomes. Four of the five cases in which the AEC was responsible for the construction of a reactor incurred substantial cost overruns and all encountered major construction delays, regardless of the type of contract under which the project was conducted. Two of the five were cost contracts, one was a cost plus fixed fee contract with a ceiling, and two were fixed price contracts. In contrast, of the ten projects in which the AEC provided only R&D assistance, actual R&D spending by the AEC never exceeded planned expenditures. The AEC held firm to its original commitments despite several cases of great technical difficulty, cost overruns, and pleas from firms for additional assistance.[1]

The contractual relationships between the utilities and the manufacturers changed in response to shifting patterns of experience. Clearly, reliance on fixed price contracting for Indian Point I in 1955 was premature.[2] Subsequently, turnkey arrangements appeared to be the way of overcoming the financial hesitancy of the utilities.

Although a dominating principle of AEC involvement in the early demonstration projects was that the participating utilities (sometimes small companies that could not afford large or open-ended commitments) should show neither profit nor loss by their participation, in fact many utilities incurred substantial financial losses. The government

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[1] AEC 649/33, October 24, 1957.

[2] M. J. Peck and F. M. Scherer, *The Weapons Acquisition Process: An Economic Analysis*, Harvard University Press, Cambridge, 1962, pp. 62-63, describe the Indian Point project.

attempted to and in many instances was required to absorb (or transfer) the cost risks, and in some instances the reactor manufacturers eventually bore the costs of overruns.

The AEC had limited ability to control costs and schedules by means of contracting devices during the demonstration phases of commercialization. Costs were determined by the product, in which risk was embodied, rather than by the financial arrangements. Because the product was unique, initial contracts could do little more than specify best-estimate ceilings or targets. When those estimates proved incorrect, a frequent response was to rewrite the contract rather than abandon the project.

In some instances, when costs and technical problems increased to disturbing levels, the AEC discontinued support of a program or refused to revise its original commitment. The reason commonly offered was that they were "of no further pragmatic interest." The reactors had been built as "demonstration" projects to generate information. When that information had been accumulated, the project presumably had little additional value to the AEC. That the reactor technology in question was of uncertain near-term value for the production of commercially competitive electricity certainly contributed to the withdrawal of support. But the successful demonstration of two LWR designs and a post-1963 shift of AEC R&D emphasis to breeder reactors also contributed. The production of marginally cost-competitive power from some LWRs (such as Dresden, Connecticut Yankee, and San Onofre) permitted the AEC to reject requests for funding support of alternative reactor designs and justified cancellation of "unpromising" projects.

Among the first power reactors to be announced were three covered by cost contracts, which provided reimbursement of incurred costs and flexible provisions regarding fees. Of these, two were owned by the government (Shippingport and Hallam) and one by a consortium of utilities and manufacturers (Fermi). All three pioneered new technologies, and the latter two were treated as part of the AEC's nuclear power demonstration program. The next three projects to be announced--Dresden, Indian Point, and Yankee--were largely private ventures, although Yankee received R&D subsidies from the AEC. Dresden and Yankee designs derived from existing reactor experience. Dresden took advantage of the AEC's

Experimental Boiling Water Reactor and GE's earlier development activities; Westinghouse undertook the design of the Yankee facility on the strength of experience in ship and submarine reactor programs and the experimental Shippingport power reactor. Dresden and Yankee were completed on time and more or less within predicted costs. Indian Point, which used an advanced technology reactor core, encountered various development difficulties; costs rose well past the original fixed-price ceiling. Consolidated Edison, the owner of the Indian Point facility, released the builder from the original contract and revised it on a cost-plus-no-fee basis. Thereafter, Consolidated Edison exerted detailed supervision of the engineering and accounting practices of the builder in very much the same manner as military buyers operate in concert with private firms in high technology projects of uncertain outcome.[1]

The evidence indicates that costs, schedule, and performance outcomes of major power-reactor programs were only marginally affected by the contracting procedures involved. Contracts reflected rather than affected project experience, because in most instances returns on investments could not begin to accrue until a project was completed. When project completion requires only slight additional expenditure, the calculated rate of return to the marginal additional investment is quite large. That is, it is often perceived that all of the expected benefits from a project depend on a small additional commitment of resources. Past costs are therefore not treated as lost or sunk but are assumed to contribute, together with the additional marginal investment, to final returns. Investors are reluctant to abandon projects before completion.

There is some ambiguity in the evidence. Even though contractual arrangements seem not to affect final outcomes, financial constraints can influence the choice. For example, Detroit Edison was able to continue putting money into the Fermi fast breeder reactor when costs substantially exceeded expectations because the Michigan Public Utility Commission allowed research and development to be treated as a cost that could legitimately be included in the price of electricity provided to the consumer. Another kind of incentive operated in the case of the Hallam reactor: The AEC preferred plant design tradeoffs that minimized

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[1] Ibid.

construction cost; but the operator of the plant, Public Power Consumers, was interested in lower operating costs. Some effect of contractual arrangements and financial incentives is passed on to final results, but the major determinant of project outcomes is to be found elsewhere.

All of the experience contracting for early nuclear power reactors suggests that incentive contracts followed costs and did not influence them. Overruns, defined as the difference between the actual cost and final adjusted contract cost, appear to be the residual variations remaining after final contract modification. Sharing ratios had very little relationship to cost growth or overrun. The contract type was strongly related to total cost growth, but the reasons for this outcome are not obvious. It may derive from an allocation of projects to contract type according to expectations of uncertainty. If those expectations were unrealistic, the contract type tended to be inappropriate.

III. INITIAL COMMERCIAL ACCEPTANCE

In 1962, the Atomic Energy Commission estimated that it had spent about $1.275 billion in the reactor R&D and demonstration programs and that industry (including the utilities) had invested not quite half as much. The rate of federal spending on civilian reactors was about $200 million a year, a small fraction of the total AEC budget, and again industry was spending somewhat less. Although Westinghouse had obtained commitments for two "large" plants in late 1962 and 1963 (San Onofre, 430 MWe; and Connecticut Yankee, 575 MWe), there was still no evidence that the utilities had become any more amenable to making major investments in nuclear energy; since 1955, one or two units a year had been ordered, all with some form of government subsidy, although in 1961 a California utility had announced its intention to build a 310 MWe BWR unit without government assistance.[1]

Utilities invested in a variety of reactors of different types and potential in the PRDP years between 1955 and 1963. The mix of reactor types and technical motivations obscures the relationship of that experience to subsequent investment decisions, except, perhaps, in those few instances when a utility's experience was particularly "bad" or exceptionally "good." All of the plants constructed were "small" (only one exceeded 200 MWe in capacity output) and all were to some extent supported by direct subsidies from the federal government. The required investments represented fairly small shares of the total financial resources of most of the utilities involved (although the second phase of PRDP investment obliged some small utilities to take risks they never should have assumed), and if there was no certifiable prospect of adequate financial return, at least there was an assumption that the "image" of a participating utility would somehow be enhanced in the process. After 1963, the premise that electrical energy could be generated by nuclear power stations at prices competitive with those of fossil fuel plants was widely accepted. And by 1963 it appeared to many investors

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[1] Bodega Bay, later canceled because of site problems.

that the engineering and technical feasibility of the LWR nuclear steam supply had been adequately demonstrated. If only one LWR of more than 200 MWe output had been completed in the United States before 1963, 53 more were to become operational by 1976; in that year 58 LWRs were operating and 53 more were under construction. In 111 instances, therefore, individual utilities or combinations of utilities concluded that it was to their advantage to invest in LWRs rather than in any of the other available alternatives.[1]

Many of the earlier decisions to invest in experimental, developmental, or demonstration nuclear power projects appear to have been motivated by the personal preferences of heads of utility companies. Probably no more than a dozen such decisions can be identified; they occurred early, and in the circumstances of the times the consequences of a faulty decision were unlikely to be catastrophic for the utility or unacceptable to its clientele.[2]

An analysis of the decision process affecting a number of utilities is useful when generalizations are sought. But the broader the generalization, the less applicable it may be to a specific situation. Each utility appears to be unique in its decision processes. Therefore it is most useful to ask not only why a nuclear plant was chosen, but also why a fossil-fuel plant was not chosen. The evidence suggests that utility decisions are driven as much by constraints as by relative preferences or hoped for profits.

The power generating mix evaluation that influences utility investment in one type of generating plant rather than another involves several factors--chiefly base load, peak capacity, and intermediate or cycling load. Each utility can calculate minimum demands for power over a period of a year. That capacity is called the *base load*. A maximum demand, required for a small fraction of each year, is termed *peaking*

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[1] *The Nuclear Industry, 1967*, AEC, November 1967, pp. 78-80. In the first nine months of 1967, 23 of the 41 fossil fuel plants ordered by utilities were "small" (less than 500 MWe), but only one of the 24 nuclear plants was of less than 500 MWe output.

[2] See Arturo Gandara, *Utility Decisionmaking and the Nuclear Option*, The Rand Corporation, R-2148-NSF, June 1977, pp. 56-58, *passim*, for a discussion of utility requirements and decision processes.

capacity. Whatever falls between those two points is the *intermediate* or *cycling load*. Peak load units must be quick starting and may have fairly small capacity because they are required to meet short duration load increments only. Because they are intended to be used infrequently and at irregular intervals, they should ideally have low per-kilowatt installed cost, which minimizes fixed carrying costs. Peak load units also provide standby reserves for system reliability. Generally speaking, gas or oil-fired turbine units in the 25 to 50 MWe range are widely considered to be best suited to such applications, but purchased power and exchange power are also used. Most utilities assume that selling electricity to their neighbors is insufficiently profitable to justify the construction of power generating capacity for that purpose alone, but if excess capacity is available it is more profitable to sell it than not. (Exchange power is a credit and borrowing operation that requires each utility eventually to return whatever power it has received.)

Intermediate load units generally are oil or gas-fired plants or combined cycle plants in the 200-400 MWe range. They can operate at less than full load without losing much efficiency, thus providing the flexibility needed to meet fluctuating and hourly daily load requirements.

Units intended to satisfy base load requirements normally have large capacity and can operate at full load for extended periods with low fuel costs. Such units tend to have high capital costs. Large fossil-fuel or nuclear plants generally serve the purpose. Since the early 1960s, the utility industry has chosen to assume that a nuclear plant best satisfies base load requirements, although until fossil-fuel costs increased dramatically in the early 1970s that premise was not obviously supported by experience.

Before a utility can rationally choose between a nuclear plant or a comparably sized fossil-fuel plant for base load requirement, it must take account of existing and projected demand trends and their uncertainties, of the capacity and performance of existing generating units, of the reserve generating capacity available, and of the unit size required to support the needed increment of base load. To some extent, unit-size determination is the key factor. Whether economies of scale can be realized in practice is not as certain as is sometimes assumed; nevertheless, the ordinary perception is that fossil and nuclear power stations of equal size have different cost components and that the long-term costs of nuclear power are lower--an assumption affected by a variety of factors. Assured access to fuel is one. Utilities in proximity to fairly cheap fossil fuel would presumably be less interested in investing in nuclear power. Utilities perceptive enough to have made adequate arrangements for obtaining nuclear fuel at controllable costs and otherwise at some disadvantage in bidding for supplies of fossil fuel would tend to favor the construction of nuclear power plants. Regional differences may have a considerable influence on the evaluation of such factors: The ready availability of hydroelectric power in the Pacific Northwest and the remoteness of fossil-fuel sources in the Northeastern part of the United States--and to a lesser extent in the extreme Southeast--exemplify regional preferences.[1]

The Bodega Bay award in 1961 (which led to nothing) had been General Electric's only major contract coup for several years when Westinghouse signed to build the San Onofre and Connecticut Yankee plants (1962, early 1963). Perhaps perceiving that nothing less than a heroic effort would break through the barrier of utility hesitancy, General Electric offered to build a 640 MWe power reactor at Oyster Creek, New Jersey, at a fixed price of $66 million. The price was calculated to provide for electricity generating costs slightly lower than those for electricity delivered to the same site by a fossil-fuel plant. Although expecting to lose some money in Oyster Creek, GE had calculated that a very small profit might be realized if the design costs of Oyster Creek could be spread over three similar plants. The agreement made GE responsible for the complete plant, for obtaining construction permits and operating licenses, and for all actions necessary to insure plant functioning at the time Jersey Central Power and Light Company, the buyer, accepted the installation. Oyster Creek was, therefore, a "turnkey" plant, the first.

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[1] Gandara, *Utility Decisionmaking and the Nuclear Option.*

The terms varied from place to place and time to time, but turnkey contracts along the lines of the first became the pattern for 12 later agreements between GE or Westinghouse and various utilities. GE publicly withdrew from turnkey enterprises in July 1966, after having contracted to build seven boiling water plants; Westinghouse, after agreeing to construct six pressurized water reactors between 1963 and 1966, followed suit.[1]

Several assumptions underlay the 1963 commitment. Four active vendors (General Electric, Westinghouse, Combustion Engineering, and Babcock and Wilcox)[2] assumed that, working in conjunction with the utilities, they could construct and operate nuclear power stations that would generate electricity at prices competitive with those of contemporary fossil-fuel plants. They also assumed that sufficient experience had accumulated in the demonstration projects to support confident estimates of the costs of designing, developing, building, and operating reactor-powered generating plants in the size range between about 400 and 1,000 MWe. Those four manufacturers, among the largest firms traditionally associated with the construction of power equipment in the United States, became the principal commercial suppliers of the new nuclear steam supply systems (NSSS). The third premise, which underlay confidence in cost predictions, was that the "balance of plant"--that portion of the nuclear power plants exclusive of the nuclear steam supply system--would in most respects resemble the turbo-generator systems of fossil-fuel plants of similar generating capacity. A fourth

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[1] The 13th plant in the turnkey series did not formally go under contract until the spring of 1967, but that was because the utility exercised an option with Westinghouse under the terms of a 1966 contract. Westinghouse still was willing to quote turnkey terms in the 1970s, but no domestic sales of turnkey plants had occurred after 1966. Some plants in Europe were constructed under such terms, however, Further, the San Onofre nuclear power station built by Westinghouse is not always counted as a turnkey plant; the Westinghouse offer was originally made in 1959-1960, and the utility (Southern California Edison) termed the agreement a "fixed price, not a turnkey contract." But conventional usage includes San Onofre in the turnkey set and that has been honored here. Finally, of the seven GE-built turnkey plants, four were sold to Commonwealth Edison.

[2] See App. A for a discussion of the roles and technical activities of those vendors.

assumption, implicit in many of the cost estimates of the period, was that as plants became larger, economies of scale could be expected. That is, the vendors and builders alike assumed that as larger plants were constructed, the cost of construction would be proportionately smaller, that the productivity of large plants would be proportionately greater, and that small plants would cost proportionately more to operate.

The rationale for the original contract between Jersey Central and General Electric was that the nuclear generating costs over the life of the plant would range from 3.42 to 3.97 mills per kwh, making it economically attractive.[1] Westinghouse offered turnkey contracts partly because of the General Electric precedent and the desire to remain competitive, but also because Westinghouse too saw no better way to overcome the reluctance of utilities to accept the financial risks associated with the new technology. Confident of their cost calculations, Westinghouse negotiators expected their initial contracts to be ultimately profitable. That proved to be the case for San Onofre and for Connecticut Yankee (not one of the turnkey plants) but for no later turnkey plants (see Table 1).

In the end, General Electric built and lost money on seven plants, each on the average larger than the pressurized water plants built by Westinghouse in the same period, and each sold at a somewhat lower price (about $110 per kilowatt for General Electric, and about $125 per kilowatt for Westinghouse).[2]

Between 1963 and mid-1966, various utilities also bought six non-turnkey plants from General Electric and Westinghouse, each roughly similar in size to the turnkey plants. They were priced at an average of about $25-$30 per kilowatt more than the turnkey plants. In 1967, the first year after the end of the brief turnkey era, GE and

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[1] "Report on Economic Analysis for Oyster Creek Nuclear Electric Generating Station," February 17, 1964, Jersey Central Power and Light Company.

[2] The costs presented in this section are *not* corrected for inflation but may be treated as constant dollars. Between 1963 and 1967, real inflation proceeded at a rate of 0.5 to 1.5 percent per year for most sectors of the U.S. economy. Uncertainty in data and "rounding" capture a larger share of the increases.

Table 1

PUBLISHED COST ESTIMATES FOR TURNKEY NUCLEAR POWER PLANTS[a]

NSSS Supplier	Plant Name	Size MWe	Contract Award	Estimated Cost/Millions[b]							
				1966	1967	1968	1969	1970	1971	1973	1974
GE	Oyster Creek	640	1963	66	67	83	83	91	91	91	91
W	San Onofre	430	1963	97	97	98	98	98	98	97	97
GE	Dresden 2	809	1965	79	79	82	84	94	100	100	100
W	Indian Point	873	1965	106	108	106	106	138	147	212	206
GE	Millstone 1	652	1965	81	85	84	90	92	92	97	97
W	Ginna	490	1965	63	65	65	65	65	65	83	83
W	Robinson 2	700	1966		76	76	76	76	76	78	81
GE	Dresden 3	809	1966		81	81	82	116	100	130	130
GE	Quad Cities 1	800	1966		90	88	88	106	100	150	150
GE	Quad Cities 2	800	1966		77	82	82	99	100	100	100
GE	Monticello	545	1966		74	74	89	89	89	105	105
W	Point Beach 1	497	1966		61	61	61	61	61	74	74
W	Point Beach 2	497	1967			54	54	54	54	54	88

[a] Extracted from yearly issues of *The Nuclear Industry* (AEC Annual Report).

[b] Published estimates by this source do not exist before 1966 or for 1972.

Table 2

ESTIMATED COSTS OF TURNKEY NUCLEAR POWER PLANTS[a]

Plant Name	Reactor Supplier	Size MWe	Contract Award	Estimated Cost Millions/$ (A)	Estimated Cost Kilowatt/$ (A)	Commercial Operation	Estimated Cost Millions/$ (B)	Estimated Cost Kilowatt/$ (B)
Oyster Creek	GE	640	1963	66	103	1969	83	130
San Onofre	W	430	1963	97	226	1969	98	228
Dresden 2	GE	809	1965	79	98	1970	94	116
Indian Point 2	W	873	1965	106	121	1973	212	243
Millstone 1	GE	652	1965	81	124	1971	92	141
Ginna	W	490	1965	63	129	1970	65	133
Robinson 2	W	700	1966	76	109	1971	76	109
Dresden 3	GE	809	1966	81	100	1971	100	124
Quad Cities 1	GE	800	1966	90	113	1972	150	188
Quad Cities 2	GE	800	1966	77	96	1972	100	125
Monticello	GE	545	1966	74	136	1971	89	163
Point Beach 1	W	497	1966	61	123	1970	61	123
Point Beach 2	W	497	1967	54	109	1972	54	109
TOTAL		8542						

[a] Taken from the same sources as Table 1.

Westinghouse non-turnkey plants were priced at about \$110-\$125 per kilowatt *more* than the turnkey prices of the previous year.[1] What this suggests, among other things, is that in mid-1966 both GE and Westinghouse had learned that their expectations of being able to build and deliver plants at costs near the prices they had bid were unrealistic. Clearly, both had expected to sell a few early plants below cost, but they also expected several later developments to provide some returns on the investment. In the event, none materialized. The premise that "several" plants of the same basic design would be built was flawed: Only one pair of pressurized water reactors and two pairs of boiling water reactors were built as turnkey plants, although design experience presumably had some later benefits. The assumption that construction costs would follow a learning-curve pattern, dropping \$25 per kilowatt in the first three years of construction experience, proved baseless. Instead, they increased by about \$75 to \$100 per kilowatt. An expected 30 to 40 percent increase in power rating after the first two or three plants had been built and operated never materialized either; efficiency improvements were offset by operating constraints. Such assumptions were derived largely from perceptions of experience in earlier nuclear plant construction and operation. But neither GE nor Westinghouse had completed, or even made much progress on, a plant as much as half as large as the smallest of the turnkey plants; and some were four times as large as the biggest

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[1] Although the costs (and prices) noted here are taken from public records, they nonetheless are to some extent speculative. The AEC consistently added to its cost tabulations for the 1960s the notation, "These are mostly unofficial figures taken from various published sources and are not necessarily on comparable bases." Neither the AEC nor any other agency concerned with cost comparisons successfully applied standard cost reporting methods, the turnkey contractors did not publicly state their real costs (which, of course, would have identified their real losses), and the utilities have not volunteered details (except, perhaps, to state utility commissions, in documents with "privileged" status). But the totals and the comparisons are entirely consistent with informal but highly credible information furnished to individual researchers, made available to industry study teams, and (more recently) indirectly confirmed by discussions during seminars and workshops. See Table 2 for details of reported prices and assumed costs.

plant either had undertaken before 1962.[1] Finally, and perhaps most important, the plant that had been bid was not often the plant that was built; unavoidable changes in design and construction contributed greatly to the cost growth.

Although the effects did not become pronounced during the period when turnkey contracts were still being offered, industry and the utilities alike had confident expectations of continuing low interest rates, stable labor and materials costs, and a steady increase in the demand for new electrical power sources.

By 1966, 30 months of construction experience had demonstrated that actual capital costs would exceed predicted costs (bid prices for turnkey plants) by a factor of two and that returns to scale would

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[1] Three problems of nuclear plant construction that had nothing to do with the nuclear reactor require notice. One stemmed from questions of steam quality, which directly influences the size and efficiency of a turbine. In general, as steam temperatures and pressures are lowered, so is turbine efficiency. Therefore, if equal output is wanted, larger turbines are required for low temperature, low pressure steam than for "high quality" steam. During PRDP years, the trend in fossil-fuel steam generation was toward markedly higher temperatures and pressures and greater efficiency. The introduction of "large" nuclear steam supply systems (characterized by "low quality" steam) confronted turbine manufacturers with the problem of scaling up "old" technology. Not only were there problems of building much larger "low efficiency" turbines than had earlier been attempted, but because low-temperature turbines were proportionately so much larger than high-temperature turbines, another difficulty resulted: Accustomed to measuring their manufacturing capacity in terms of "new" technology turbines, manufacturers unknowingly overbooked. Major delays and unexpectedly higher costs resulted. Similar problems resulted from early attempts to build "large" containment vessels in quantity; assumptions about manufacturing capacity and capability were sadly unrealistic. Again, the consequence was delay and cost growth. The third problem was the productivity of the production labor force during initial efforts to build commercial-scale nuclear plants. The jurisdictional boundaries between competing craft unions had been worked out on the basis of fossil-fuel plant designs; nuclear plants invoked new technology with undefined craft union responsibilities (were electrical wires run through high temperature tubing the responsibility of plumbers, pipefitters, or electricians--or in what order?). Chaos in construction schedules resulted. Eventually all three problems were sorted out, but by that time inflation, fossil-fuel price growth, environmental and safety questions, and similar problems began to induce a different form of cost growth.

not occur at the predicted rates.[1] Prices offered in 1967 indicated future expectations not only of substantially higher costs but essentially flat dollar-per-megawatt costs over a plant-size range between 500 and 1100 megawatts (see Fig. 3). Further, any expectation that the price rationalization of late 1966 had adequately compensated for earlier miscalculations also proved, in time, to be unfounded; light water reactor installations sold at 1967 prices eventually cost from $100 to $150 per kilowatt more than expected.[2] But by 1967, because only the nuclear steam supply system was being offered at a fixed price, total plant cost increases were borne not by the nuclear vendors alone but by the utilities as well. Contract flexibility provided for a much broader distribution of the product of cost growth.

At the end of the turnkey phase, contractor experience indicated that $220 per kilowatt was a representative average plant price for the purposes of capital cost estimation. With the exception of San Onofre, which carried the uniquely high 1963 estimated cost of $226 per kilowatt, all of the turnkey plants were sold at prices averaging about $113 per kilowatt. The difference between initial estimates and actual costs experienced is $100 to $103 per kilowatt more than estimated, 90 to 110 percent more than the initial estimates, and at least $875,000,000 more than the reported total prices of the plants. Although the evidence is not entirely consistent, it nonetheless suggests that GE and Westinghouse lost $875,000,000 to $1,000,000,000 in total, on the 13 turnkey nuclear plants--or, with San Onofre excluded, about $73,000,000 to $78,000,000 per plant.[3]

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[1] Which should not be interpreted as a suggestion that there were *no* returns to scale: no "small" (below about 500 MWe) plants were ordered after the initial stages of "commercialization." The utilities, the vendors, and, consequently, the market concluded (on good evidence) that "small" plants were not competitive with equal-size fossil-fuel plants. But in the late 1960s the general level of nuclear plant costs was rising so rapidly that a simple comparison of the per-kilowatt costs of "larger" (500-1250 MWe) plants does not show any significant differences.

[2] Adjusted for post-1967 inflation in labor rates and materials costs.

[3] Personal communication, John Simpson, Westinghouse Electric; data provided by S. M. Stoller Co., June 1976; "Report on ... Oyster Creek ...," February 17, 1964, *The Nuclear Industry, 1969*.

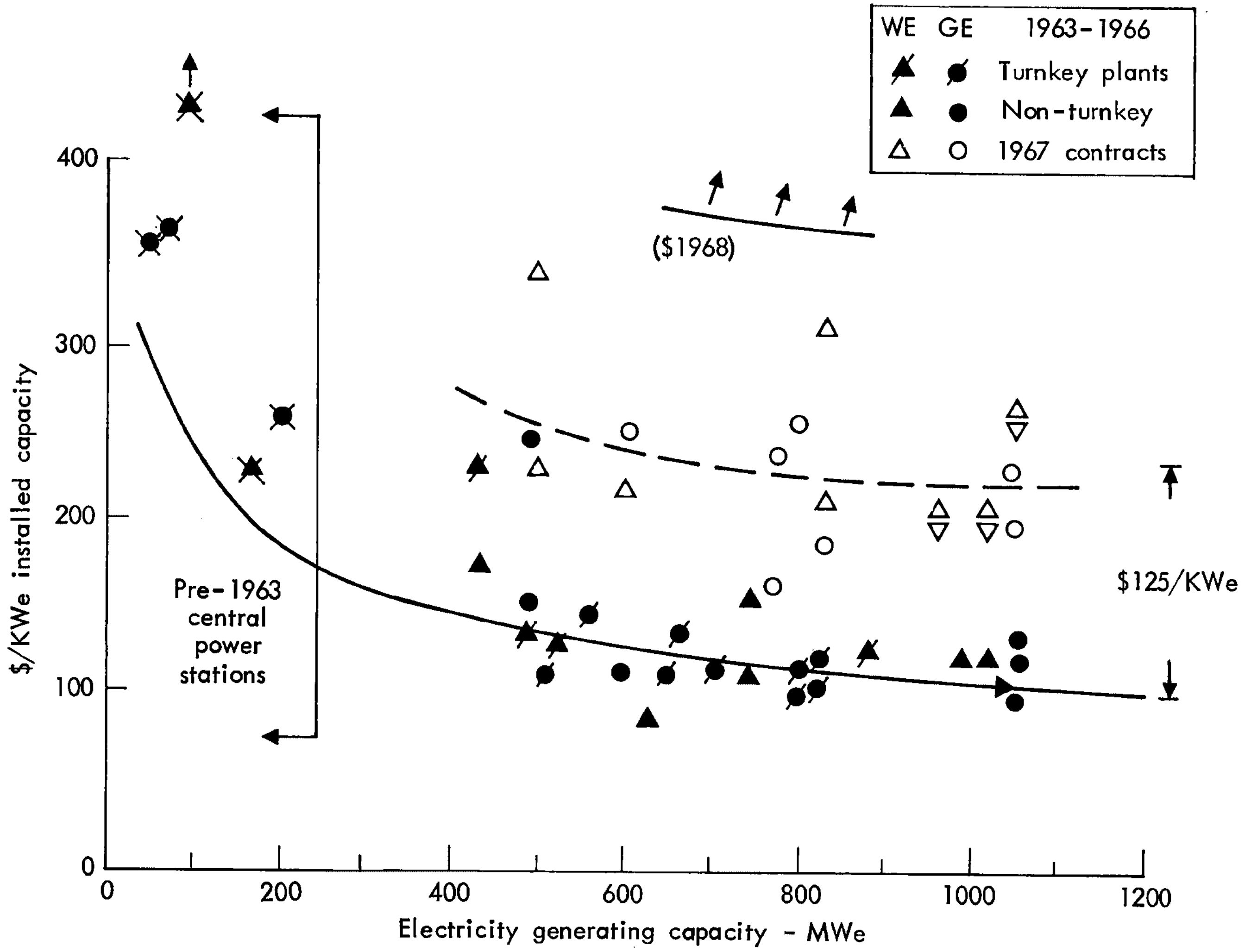

Fig. 3—Cost expectations and reality

The 1963-1967 turnkey plant prices were based on calculations that made nuclear power seem about 0.5 mills per kilowatt less costly than electricity generated by similarly sited fossil-fuel plants. If the total losses on the turnkey plants did not exceed $875 million, that nevertheless represented a "subsidy" from the developer-constructors of about 1.7 mills per kilowatt hour. Some, at least, of the turnkey plants would not have been economically competitive with fossil-fuel plants had the utilities been obliged to pay full costs; by the same token, few of the non-turnkey plants started between 1963 and 1967 could have been competitive, although by the time they actually began operating, five to seven years after the contracts were signed, substantial increases in both coal and oil prices had lessened the shortfall; fossil-fuel cycle cost increases thus offset nuclear plant capital cost increases.[1]

After the cost anomalies became apparent, turnkey nuclear plants no longer were offered at bargain prices. But in areas where fossil-fuel plant prices were only marginally more attractive than the apparent nuclear plant prices of 1968-1972, nuclear plants still were purchased. In all instances, the utilities had to pay full plant costs, assume responsibility for engaging and overseeing architect-engineers, and be prepared to absorb whatever unanticipated cost increases the construction process brought on. However, the accuracy of cost estimating did not greatly improve. The non-turnkey plants contracted for in 1966 were completed at costs averaging more than $110 a kilowatt above the original estimate. In the end, the turnkey plants and their non-turnkey equivalents of the same period cost about the same.[2]

Risk aversion was generally characteristic of utilities confronted with the choice between nuclear and fossil fuel before 1963, when the eventual cost of nuclear plants seemed very uncertain. (A factor in the reluctance of utilities to invest in nuclear power plants before

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[1] Fuel cycle costs are addressed in Sec. III.

[2] *Nuclear Power Economics*, Report of the Joint Committee on Atomic Energy, Congress of the United States, February 1968; *1966 Annual Report*, General Electric Company, New York, 1967, p. 10; see also "Current Status and Future Technical and Economic Potential of Light Water Reactors," AEC Report WASH-1082, March 1968.

1963 may also have been that prices appeared to be dropping.) The effect of the turnkey plant response was to transfer most cost risks to the vendors by putting an upper bound on the price. Nevertheless, between December 1963 and April 1967 when GE and Westinghouse sold 13 turnkey plants, the utilities bought 27 non-turnkey plants. Even during the period of most concentrated turnkey sales (between February 1965 and July 1966), General Electric sold fewer turnkey plants than non-turnkey plants. After the initial Oyster Creek sale in December 1963, GE sold only six additional turnkey plants, which suggests that turnkey plant offers were not alone responsible for inducing the utilities to view nuclear power as competitive. Nor does it appear that the utilities clearly preferred turnkey contracts to non-turnkey contracts when they were offered a choice: Either the utilities expected non-turnkey plants to cost less, or they assumed that the presumably small cost additive they accepted was offset in benefits by the greater design freedom provided in the more flexible non-turnkey contracts.[1]

One possible explanation for the absence of nuclear plant orders in the year following the Oyster Creek contract is that the coal industry reacted vigorously to the nuclear plant threat, offering substantial coal-price reductions to utilities known to be seriously considering investment in nuclear projects. Oyster Creek itself is a good example. While negotiating for a nuclear plant, Jersey Central Power and Light, which had been buying coal at a delivered price of 30-31¢ per million BTUs of energy content, received offers for coal delivered to the Oyster Creek site at a price of 26¢ per million BTUs. Other utilities may have used nuclear plant bids for leverage in their coal price negotiations, but that policy presumably became ineffective after 1965, when coal prices stiffened. Coal was then enjoying a record volume of expanding business, the asking price for nuclear plants had nearly doubled since the first offerings, and in consequence nuclear power was an

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[1] A. Demaree, "G.E.'s Costly Ventures into the Future," *Fortune*, October 1970; "Neck and Neck, and Breathing Hard," *Forbes*, September 1966. It is also conceivable that utilities expected prices to continue falling, or that they expected that by managing or subcontracting nuclear plant construction on their own they would spend less in the end than the nuclear reactor vendors.

obvious threat only in areas of high cost coal. With the national market for coal in the process of doubling every ten years, the coal industry appeared to be willing to write off those areas.[1] So, unable to count on declining or controllable coal prices, utilities again began to turn their attention to nuclear power in late 1965.[2]

Another tendency of mid-1965 may have influenced the turn toward nuclear power at that time. Prompted by the Northeast Blackout of 1965 and under pressure from the Federal Power Commission, the utilities began to move rapidly toward interconnection, forming regional councils and coordinating and submitting their plans for new bulk power facilities for review by the FPC. Regional pooling tended to make utilities look more favorably on nuclear plants. Perceived economies of scale make it appear that considerable operational cost savings might be realized for a broadly based, regional power economy; larger and presumably more economical power plants could be managed on a single system basis.

The development of pooling also offset one disincentive--decreased reliability--that a single utility had to confront when considering the nuclear option. Uncertainty about the on-line availability of nuclear power induced many utilities to look unfavorably on large nuclear plants that might have to provide more than 7 to 10 percent of peak demand, but regional pooling created the prospect of being able to call on a neighboring utility for power in case of a sudden nuclear plant shutdown. Joint participation also was an attractive way of minimizing the risk of investing in nuclear plants. During the first wave of nuclear plant announcements (1965 to 1969), 23 joint ventures were announced, and during the second wave (1970 to 1974), 39. Considered as a percentage of total plants ordered during each period, the percentage difference is only about 3.5, but growth has been steady: Between 1965 and 1974, the percentage of joint ventures has increased from 12.5 to 40 percent.

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[1] Although difficult to pin down, the political backlash of continuing coal-nuclear price competition may also have been influential.

[2] J. Hogerton, "The Arrival of Nuclear Power," *Scientific American*, February 1968, pp. 21-31.

Most early joint venture nuclear projects had the apparent purpose of distributing research and development risks among several participants. After 1963, many utilities accepted the presumption that nuclear power did not involve major technical risks and undertook joint ventures to spread the financial risks. Affirmation of this proposition can be found in the observation that joint ventures also tended to be more characteristic of large fossil-fuel plant construction as capital costs increased. Nevertheless, more utilities were involved with joint venture nuclear plants than with joint venture fossil-fuel plants (mostly coal-fired). Many of the coal-fired plants were mined-mouth plants, suggesting also that although financial risk was a consideration in such investment decisions, an effort to decrease fuel supply risks may also have been a major factor.

There was also a strong correlation between joint ventures and the continuing development of regional pooling. Further, the pooling of nuclear plants also speeded up commercialization in that it lessened a single utility's need to accumulate comprehensive nuclear expertise.[1]

Another factor that entered into the utility decision process was that regardless of whether the fuel source was nuclear or fossil-fuel, generating plants were increasing in size. With that increase, fossil-fuel plants began to lose some of their traditional attractiveness. In the early 1970s, the forced outage rate of fossil-fuel plants of more than 600 MWe was somewhat greater than that of smaller plants; indeed, by 1964 there was evidence that the utilities were already experiencing a higher than expected rate of forced shutdown in the operation of their newest, largest, and most sophisticated fossil-fuel plants. Although nuclear power did not yet offer a clearly better alternative, the problems of building and operating large fossil-fuel plants made nuclear power look increasingly attractive.[2]

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[1] S. Breyer and P. MacAvoy, "The Federal Power Commission and the Coordination Problem in the Electrical Power Industry, *Southern California Law Review*, 661 (1973).

[2] In retrospect that assessment appears to have been correct. Between 1965 and 1974, the operating availability and capacity factors were consistently higher for nuclear plants of 600 MWe or larger than for fossil-fuel plants of comparable size. V. S. Boyer, "The Economics of Nuclear Power," in *Third Congressional Seminar on the Economic Viability of Nuclear Energy*, Washington, D.C., 7 June 1976.

Ironically, by 1964 another element that strongly influenced a utility's decision to invest in nuclear power was increased public interest in the environmental effects of producing electricity. Nuclear plants were then seen as cleaner sources of power than fossil-fuel plants, neither polluting the air nor providing problems of fuel storage, fuel transportation, and waste sludge. As early as 1963, environmental concerns were high on the list of factors considered by Jersey Central Power and Light when it made the Oyster Creek decision. One utility chose to build a nuclear plant in 1966 after encountering objections to a proposed 600 MWe coal plant. Utilities were not insensitive to a growing tendency toward environmental legislation, local ordinances that set tight limits on emissions of sulphur oxide and other stack gases, the decreasing availability of low sulphur fuels, the high transmission costs and right-of-way complexities affecting mine-mouth plants, and proposals for increasingly stringent controls on strip mining. From 1965 to 1970, purchasing nuclear rather than fossil-fuel plants appeared to be the environmental path of least resistance.[1]

However surprising the cost outcome of the turnkey era and however varied the incentives of utilities through the 1960s, nonetheless after 1963 the size, scope, and importance of nuclear power programs increased greatly, if not steadily. In 1967, the plant capacity of newly ordered nuclear installations was equivalent to that of newly ordered fossil-fuel stations, although because of size differences more fossil-fuel plants went under contract. And that occurred before there was any significant experience with "large" nuclear plants. A falloff in orders occurred in 1968 and 1969, but an upward trend resumed in 1970; and for the next three years the plant capacity of newly ordered nuclear plants exceeded that of fossil-fuel plants once again. Little of that trend could be attributed to a clear and certain commercial advantage of nuclear over fossil-fuel power sources. Nevertheless, cost remained an obvious and important element in the continuing decision process.

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[1] "Report on Equipment Availability for the Twelve Year Period, 1960-1971," Edison Electric Institute, November 1971.

IV. THE COSTS OF NUCLEAR POWER

In 1967, *all* power plant construction cost estimates took an upward turn; the cost increases experienced to that time had largely affected nuclear plants alone. In March of that year, the Atomic Energy Commission completed a collection of cost data on which the first AEC cost study,[1] finally published in March 1968, was based. It purported to estimate the capital costs of large nuclear plants (800 to 1000 megawatts) and to compare them with the costs of equivalent fossil-fuel plants--although no "large" nuclear plants had yet been completed. The AEC then estimated that a 1000-MWe plant would cost roughly $135 per kilowatt.[2] A second study in March of 1970 (based on data from June 1969) concluded that a 1000-MWe plant would cost about $240 per kilowatt. The increase was attributed to higher direct costs (assumed to arise at least partly in a better understanding of what was actually required to build a nuclear plant), an increase in engineering construction costs blamed largely on the effort required to obtain licenses, extended schedules and salary increases and increased allowance for contingencies, a 1.5 percent increase in the interest cost of money, and inflation.[3]

A third study, begun in January 1971, was ready for publication in June 1972. At that point, the estimate for the 1000-MWe ideal plant was $350 per kilowatt. The increase over the previous estimate was credited to "latest safety requirement, codes, and standards...,"

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[1] "Current Status and Future Technical and Economic Potential of Light Water Reactors," AEC Report WASH-1082, March 1968 (this and later such reports will hereafter be cited as WASH-XXXX by date).

[2] The last turnkey plant offerings from GE and Westinghouse, in 1966, were at prices ranging from 75 to 85 percent of such estimates and the 1967 price offerings ranged from 125 to 175 percent. Plants started in 1967 actually cost about 65 to 80 percent more (in constant dollars) than the bid prices of that year, all of which suggests that although the cost growth problem had been acknowledged, its magnitude was still understated.

[3] WASH-1150, March 1970.

"environmental protection and licensing criteria," and the "current market conditions and cost data."[1]

Although the costing methods used in 1972 were more systematic and comprehensive than those used earlier, the estimates were promptly invalidated. By 1974, the AEC was ready to concede that "increases in reported power plant costs [have] continued to outpace expectations. Essentially all power plants under construction...[have begun] to show large cost overruns relative to their initial cost estimates."[2] The costs of plants scheduled to go into service between 1977 and 1981 were now estimated to range between $450 and $510 per kilowatt. The attributed reasons for the increase were not very different from those identified earlier: additional engineering, management, labor, and equipment and materials costs; increased escalation and interest owing to longer construction and licensing time requirements; and further inflation. By October 1974, the AEC had concluded that costs of $720 per kilowatt would be incurred for a 1000-megawatt plant that entered service in 1983. Inflation, characterized as "routine escalation," was for the first time identified as the principal reason for cost increases.[3]

The October 1974 estimates were based on a computerized cost model (named CONCEPT) tested against the reported costs of 20 non-nuclear power plants that had entered commercial service through the end of 1973. There was, of course, no reasonable correlation between the reported costs of the 13 turnkey plants and the costs generated by the model, but for 11 of the remaining 16 light water reactor plants in the data sample, the costs estimated by using the CONCEPT model fell within a range of 14 to 18 percent of reported actual costs. On the strength of such findings, the AEC concluded that the "CONCEPT code and its cost models provide a suitable method and data base for planning type estimates of capital costs of central station steam-electric power plants."[4]

That premise and its air of finality proved to be deceptive, notwithstanding the accompanying endorsements. The implication of the

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[1] WASH-1230, June 1972.

[2] WASH-1345, October 1974.

[3] Ibid.

[4] Ibid.

model was that some sort of cost stabilization had occurred that, except for interest changes and escalation (or inflation), would permit accurate estimating of the future costs of nuclear generating stations. But in constant dollars, the price of a nuclear steam supply system alone had increased by 55 to 60 percent in seven years. Associated costs increased commensurately.

There has been little expert agreement on the reasons why nuclear plant capital costs have increased so greatly since the early days of commercialization. One private study, using econometric analysis of deflated cost data, concluded that capital costs were increasing at $47/kw/year in 1973 dollars when the plants were equalized for size, region, and other pertinent variables.[1] Another concluded that the increase was about $60 per year in 1974 dollars.[2] AEC estimates of 1972 and 1974, using the same ground rules and postulating identical hypothetical plants (but for several different times and in current dollars), suggested that $40/kw/year was about right. When adjusted to 1975 dollars,[3] three of the four AEC estimates are highly similar.[4] Adjusting the independent estimates to 1975 dollars increases them by about 10 percent; they indicate that annual increases of $59 and $66 per kw have occurred (and still do); the AEC studies suggest a continuing average increase of about $40/kw/year in capital costs.

Part of the increase has been attributed to the costs of growing safety and environmental requirements; the later AEC studies specifically examined these items. For plants designed for commercial operation after January 1978, these items are identified as "adders due to safety and environment related items." (See Fig. 4.) Since these "adders" do not appear on earlier estimates, they are incremental to some unspecified level of expenditures for safety and environmental protection.

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[1] I. C. Bupp, Jean-Claude Derian, Marie-Paule Donsimoni, and Robert Treitel, "The Economics of Nuclear Power," *Technology Review*, February 1975.

[2] Unpublished study, S. M. Stoller Corporation, March 1975.

[3] Using the Handy-Whitman construction cost index, and removing allowances for current dollar escalation and its associated interest.

[4] WASH-1230, June 1972; WASH-1345, October 1974; WASH-1082, March 1968; WASH-1150, March 1970.

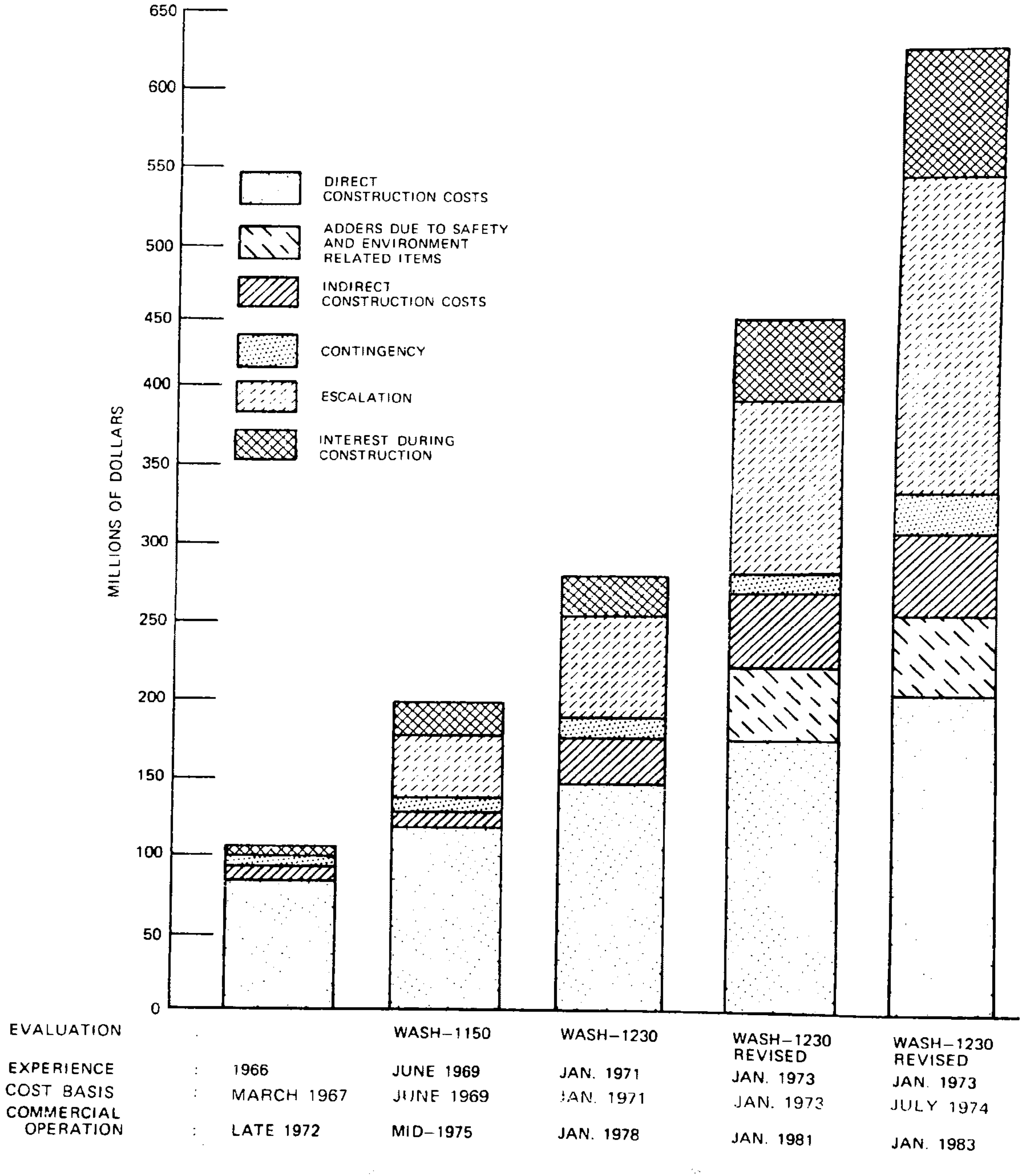

Fig. 4 — Comparison of coal-fired plant cost estimates (total investment cost for 1000-MWe units)

Source: WASH-1345

Statistical calculations suggest that lengthened construction time was responsible for about 25 percent of the observed cost increases, but the analysis also suggests that part of the cost increase arose in temporal factors unrelated to the duration of construction projects. Safety and environmental items contributed, as did increased design complexity, larger buildings, more bulk material requirements, and more stringent inspection and quality assurance programs. Safety and environmental concerns generated some of these cost increases; some also stem from attempts to improve plant availability and increase plant capacity.[1] How much still is uncertain. But it may also be the case that past cost growth tendencies are characteristic of a maturing industry subject to perturbation by the public, political forces, regulatory institutions, and changing technology. If some standardization of reactor design occurs, then construction times are likely to stabilize and costs will become more predictable. Unfortunately, the available data do not yet indicate when that may occur.

One participant in the period of commercialization from the early 1960s to the mid-1970s, put it this way:

> Construction costs have gone up out of all sight and reason, for an assortment of causes, and hardly any of the causes or the associated cost increments were perceived correctly as to nature, timing, or magnitude by the so-called experts. I don't expect I would have done it better, if I had been one of the cost estimators; it has been a wild dozen years in the construction business, even without the environmental and regulatory uncertainties of large power plants, both coal and nuclear. But the fact remains, utility executives would have done as well examining the entrails of strangled cats as studying their plant cost projections, when they had to decide what kind of plant to build.[2]

In general, inability to keep plant construction on schedule has been more troublesome for nuclear than fossil-fuel plants. Between 1965 and 1975, for example, American Electric Power Service Corporation completed construction of 11 fossil-fuel plants in a size range between 615

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[1] Bupp et al., "The Economics of Nuclear Power."

[2] Personal communication, J. M. Hendrie, Brookhaven National Laboratory, 11 October 1976.

MWe and 1300 MWe with an average completion date error of less than 50 days. Only four of the projects exceeded the scheduled completion date by more than two months, and one plant was completed 45 days ahead of schedule. In contrast, that utility had two unhappy experiences with nuclear plant construction. Its first, Don C. Cook-1, was completed three years behind schedule, and in 1976 the second was roughly five years behind schedule. The eventual cost of the complete dual plant project was expected to be at least three times the original estimate.[1] Although that was an extreme case, large differences were not uncommon.

By the early 1970s, capital and operating costs, in isolation, no longer exercised quite the dominant influence they earlier had in fuel cycle choices. The choice of a fossil-fuel plant in the mid-1970s seems to have been influenced more by fuel supply (and cost) uncertainties than by initial capital cost questions. What might have appeared to be inconsistent behavior on the part of the utility industry resulted in many cases from efforts to disaggregate. A single utility's decision for or against nuclear power could in many instances be explained by fuel supply history, plant location, past or present fuel commitments, or expectations of future access to fuel.

Although many utilities were concerned about oil and gas reserves during the 1960s and assumed that nuclear power might be a sensible hedge for the future, the reality of fossil-fuel shortages (or extreme price increases) was remote. If the purchase of a nuclear plant rather than a fossil plant might provide for fuel diversification, that was more commonly a by-product than an explicit element of the choice.

But as early as 1970, influenced partly by coal price increases, utilities began to take fuel diversification seriously into consideration when addressing choices between nuclear and fossil-fuel plants. Environmental concerns also had some influence on the 1970-1975 transition. In January of 1970, the National Environmental Policy Act (NEPA) was passed; in December 1970, the Environmental Protection Agency (EPA) was established; and early in 1971, judicial decisions in the case of *Calvert*

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[1] Theodore Barry and Associates, "Management and Operations Review of Indiana and Michigan Electric Company," December 1975; additional data provided by AEP Service Corporation Construction Department.

Cliffs and in the *Green County Planning Board* case alerted utilities to the prospect that environmental concerns could no longer be treated as secondary issues. In effect, those actions and decisions implied that the issue was no longer whether to respond to public and legislative clamor for environmental protection but how *best* to comply with *all* environmental regulations, including emission standards for sulphur dioxide and nitrogen oxides.

To satisfy the demands of the environmentalists for improved emission standards, the utilities had to switch fuel supply sources. A transition from high-sulphur coal to low-sulphur coal could mean buying from western rather than eastern coal fields (where the supply was more limited), which could mean higher transportation and mining costs. Notwithstanding the dramatic increase in oil prices after 1973, many utilities continued to convert from coal burning units to oil burning units. The switch from high-sulphur oil to low-sulphur oil also involved changing sources of supply while refineries were modified. Inevitably, the prices of both low-sulphur oil and low-sulphur coal rose sharply.

Again the prospects of difficulty in acquiring sources for and of controlling costs of fossil fuels increased the attractiveness of the nuclear option, and again an improvement in the trend of nuclear plant construction was noticeable. Even as capital costs continued to increase, utilities perceived that although nuclear plants had been no more than marginally cost competitive with fossil-fuel plants in the 1960s, and then only regionally, in the 1970s they would very probably represent the more economic choice.

Outside factors reinforced the trend. By the late 1960s good data were available for the first time to aid in evaluating the consequences of shifting to commercial-size reactors as power sources. The utilities tended to look on early nuclear plant construction experience as a transitory misfortune. By 1970, the lack of specialized components (such as pressure vessels) was no longer a major problem. Then, starting in 1971, the overall financial situation of the utilities began to improve. A slight increase in the return on common equity occurred; and almost without exception, utilities that applied for rate increases received them. The Middle East War of 1973 impelled an immediate and radical response; 30 of the 36 nuclear plants ordered in 1973 went on contract after the October war began. The embargo was not, of course, the sole motive. The increased fuel prices first induced by the embargo and later by OPEC prompted efforts to conserve energy and caused a decline in load growth, leading to somewhat decreased revenues and eventually to a decline in nuclear plant orders. Nonetheless, most utilities thereafter perceived the perils of dependency on a single fuel source and responded accordingly, although the subsequent cancellation of many of the plants ordered in the immediate aftermath of the 1973 war suggested that many utilities had placed orders to hedge against a most uncertain future, to secure "a place in the queue."

Although the returns were somewhat mixed, it nonetheless appeared that those utilities that for one reason or another had earlier moved toward fuel diversity survived the 1973-1974 financial crisis and energy crisis with less trouble than utilities primarily dependent on oil, or even upon natural gas. That experience had much to do with later choices of nuclear rather than fossil-fuel sources.[1]

FINANCING PLANTS

Financing a nuclear plant is in many respects similar to financing a large fossil-fuel plant; although there were capital construction cost differences favoring one or the other in the years after 1963, the additional costs generally associated with the more lengthy construction phase characteristic of nuclear plants were later offset by the requirement that fossil-fuel plants include provision for scrubbers, which made them about as expensive as nuclear plants.

Generally, utilities try to choose the lowest cost alternative when deciding what kind of plant to build, but a utility unable to raise the capital for one type of plant is usually unable to raise the capital for any. Starting in 1965, the cost of obtaining the capital required to finance all plant construction began to increase steadily and massively. The outcome was unfavorable for nuclear plants, which required the longest construction periods, but to some extent that was offset by the

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[1] Gandara, *Utility Decisionmaking and the Nuclear Option*, pp. 90-101.

post-1973 perception that uncertainties about both the price and availability of fossil fuel (chiefly but not exclusively oil) would make nuclear power cheaper in the long term.

During and after 1973, the increasing costs of oil and coal, the growing demand for emission control devices for fossil-fuel plants, and the decline in electricity demand that attended the 1973 oil crisis put many utilities in an awkward financial situation. To offset the regulatory lag that precluded immediate earnings relief, some turned to cost cutting. For practical purposes, that meant deferring construction plans to lessen cash outflow. In 1974 and 1975, the utilities canceled or delayed 190,000 MWe of electrical generating capacity, of which more than two-thirds was nuclear.

Post-1973 cash flow financial management problems induced utilities either to defer decisions for nuclear power or to opt for fossil power. Fossil-fueled steam generating plants cost from 20 to 30 percent less per kilowatt of capacity than did nuclear plants, and combustion turbines perhaps 70 percent less. When account was taken of the long lead times associated with nuclear plant construction, the substitution of fossil fuel for nuclear power became an attractive way of reducing the capital requirements of electric utility companies. The long lead times of nuclear plants had another influence; because the consequences of delay in a nuclear plant program could have no effect on total generating capacity for five to ten years, utilities have tended to delay new nuclear plant starts. A utility thus traded relief from current financial problems against the more remote and speculative problem of inadequate generating capacity at some future time. If projections of demand proved incorrect, and if additional generating capacity were later required on fairly short notice, the utilities had the option of starting fossil-fuel plants that could be completed in less time than nuclear plants. If a utility chose to delay still longer, the ultimate option of simply adding a low-cost combustion turbine plant (which required even less planning, construction, and installation time) could be adopted.

Such a strategy does not often produce an optimal mix of generating capacity, and the total cost of supplying power may ultimately increase because of higher fuel costs and inefficient operation. However, such expedients offered immediate financial relief, and that was the most pressing problem of the utilities in the years between 1973 and 1977.[1]

FUEL COSTS

Much of the attractiveness of using nuclear energy for generating electricity stemmed from the low cost of the fuel. From 1961 through 1967, the cost of boiler fuels for electricity generation in the United States averaged from 2.6 to 2.8 mills per kilowatt-hour, and within the United States ranged from 1.3 mills in Wyoming to 7.8 mills in Vermont. Studies by Jersey Central Power and Light Company in 1963 and the TVA in 1966 projected that nuclear fuel would cost from about 1.1 to about 1.9 mills per kwh.[2] From the standpoint of fuel costs alone, nuclear power promised substantial savings for many, if not most, areas of the country. But the cost of generating electrical energy was dependent on much more than fuel costs alone; operating and maintenance costs and capital outlays more directly influence the competitiveness of nuclear power.

For fossil-fuel plants, the cost of fuel is represented by the delivered cost of the material consumed and is roughly equal to extraction cost plus delivery cost. Because of the large quantities required for electricity generation, the transportation of gas, oil, and coal can have a substantial effect on the delivered fuel price.[3] That factor is so important that "mine-mouth" generating stations have been designed to burn coal at or near the mine because in many cases it costs less to transmit electricity than to move coal. Between 1961 and 1967, coal burned close to the mine cost between 1.3 and 1.6 mills per kilowatt-hour and oil consumed close to the well from 1.9 to 2.1 mills. In New England,

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[1] Ibid., pp. 36-51.

[2] Data provided by Edison Electric Institute, July 1976; "Report on Economic Analysis for Oyster Creek Nuclear Electric Generating Station," Jersey Central Power and Light Co., February 17, 1964; letter, D. C. Kull, General Manager, AEC, to E. J. Bauser, Executive Director, JCAE, 24 December 1969, in ERDA historical files.

[3] Although it presents complicated handling problems, nuclear fuel is cheap to transport: About 125 tons of coal are needed to generate the electricity that can be derived from one pound of nuclear fuel.

distant from either coal or oil sources, fuel costs averaged 3.5 to 4.2 mills per kwh with peak costs (in Vermont) of 6.1 to 7.8 mills.[1]

The fossil-fuel cycle is quite simple; fuels are extracted, transported, and burned; the gaseous wastes are discharged into the atmosphere and the solid wastes are disposed of locally. The nuclear fuel cycle is much more complex. Nuclear fuel must be mined, milled, converted, and sometimes enriched[2] before it can be formed into pellets, fabricated into fuel rods, and assembled into fuel elements. Wastes present difficult disposal problems. The cost of nuclear fuel depends on the costs of all of those factors and the capital charges associated with the fuel elements.[3]

For all practical purposes, the operating and maintenance costs required for nuclear and fossil-fuel plants during the 1960s were indistinguishable, averaging about 0.5 mills per kwh.

Charges against the capital investment in a nuclear generating plant are the largest fraction of the cost of generating electricity. Capital charges are equal to the capital costs of a plant multiplied by the fixed rate charge. Dividing capital charges by the number of kilowatt-hours generated annually by a plant is a method of apportioning such capital charges to the cost of produced electricity. Capital charges represent the sum of the cost of money, depreciation, federal income taxes, general taxes, and insurance premiums. Because they are independent of the number of kilowatt-hours produced annually, their contribution to total energy costs decreases as kilowatt-hours increase. Utilities therefore try to extract as much from their plants as plant capacity and good operating and maintenance practices will permit. Until the late 1960s, capacity factors of 80 to 90 percent were frequently assumed in making cost estimates, but for early nuclear plants they were often not realized. The consequences were significant: If a capacity factor of 80 percent were assumed, but only 40 percent were achieved, capital charges per kwh would double. In 1964, when the

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[1] See JCAE Report, "Nuclear Power Economics--1962 through 1967," February 1968.

[2] Enrichment is not essential for some fuel cycles, notably represented by the CANDU heavy water reactor.

[3] The calculation of fuel cycle costs is discussed in App. B.

commercial era in nuclear power production began, it was assumed that for a 500 MWe nuclear plant, capital charges would account for 50 to 60 percent of the costs, fuel for 30 to 40 percent, and operating and maintenance for 5 to 15 percent. The assumed cost of the produced electricity thus would average about 5.0 mills per kwh.[1]

REGULATION AND PROFITS

The *rate of return* allowed by public utility commissions determines the profit a utility earns. The *rate base* contains some measure of the value of the power plants, transmission lines, buildings, and other equipment a utility has acquired as a prerequisite of selling electricity. *Net operating income* is the result of multiplying the allowable rate base by the allowable rate of return.

Criteria for establishing a rate base vary from state to state. Currently 12 states use reproduction costs of facilities as a basis for valuation, 15 use original costs as the basis of that valuation, and 18 states adhere to no particular formula.

Because nuclear plants take more time for construction than fossil-fuel plants, the effect of allowing an addition to the rate base for "construction-work-in-progress" would be to make nuclear plants somewhat more attractive. An item called "allowance for funds used during construction" is another accounting variant that at first glance improves the utility's rate of return on investment. But in fact, that allowance is intended only to capitalize the cost of money relating to a construction program rather than to expense it. When it is capitalized as part of "construction-work-in-progress," the "allowance for funds used during construction" becomes a future claim on earnings realized when the completed construction is entered into the rate base. Including it in earnings calculations has the effect of creating doubt about the quality of earnings, which ultimately affects the utility's ability to raise capital.

The question of whether utilities should be granted higher allowances for research and development expenditures has troubled the industry for nearly a decade. Historically, utilities have spent only about one

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[1] "Analyzing Power Costs," *Nucleonics*, July 1964.

quarter of one percent of sales on research and development, commonly viewed as an activity not within the functional responsibility of a utility, although more recently an allowance of about 1 percent of sales has been accepted by many public utilities commissions. Nevertheless, the advisability of permitting a purchaser of what are allegedly fully developed items to charge off large sums to research and development remains at issue in many areas.

Fuel-adjustment clauses have also been controversial. The purpose of such a clause is to permit a utility to transfer to its customers the consequences of variations in fuel costs. In times of stable fuel costs, a fuel adjustment clause is of little consequence; that is not the case when fuel costs are rising (as in the mid-1970s). The argument against fuel adjustment clauses is that they weaken a utility's incentive to bargain with suppliers for lower fuel prices and thus shift increased fuel costs to the consumer without compensating allowances for economies of scale or improved technology. But with the coming of nuclear power and explicit fuel diversification strategies, the decision process has acquired a bias in favor of new generating facilities that use uneconomical fossil-fuel sources.

The accounting treatment accorded different fuel sources is not uniform. Fossil fuel is expensed and nuclear fuel is capitalized. Therefore, the fuel-adjustment clause permits fuel cycle costs for a fossil-fuel plant to be recovered immediately (which helps any utility with cash flow problems), but nuclear fuel price increases cannot be recovered until entered into the rate base--much later. Notwithstanding the controversy generated by the issue, the stakes are not so large that any major utilities treated the fuel-allowance clause as a factor in the decision for or against the nuclear option.

The fuel crisis in 1973 had another generally unanticipated effect on the expectations of utilities. Under pre-1973 conditions a utility might tend to expand its rate unnecessarily, at least partially influenced by "a goldplating effect"--pursuit of maximization of earnings for stock valuation and coverage. But after 1973, profit maximization may have been subordinated to other goals.[1]

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[1] Gandara, *Utility Decisionmaking and the Nuclear Option*, pp. 90-101.

V. REGULATION[1]

By the mid-1970s, four flaws in the process of commercializing light water reactors were retrospectively being attributed to the earlier actions or inactions of the Atomic Energy Commission. The first was that regulatory and licensing delays had slowed the competition of individual nuclear plants, thus extending their construction phases and significantly contributing to increased construction costs. A second was the questionable adequacy (or acceptability) of the safety standards imposed by the Atomic Energy Commission. Third, changes in AEC requirements, sometimes retroactive, were alleged to have substantially increased the expense and uncertainty of reactor construction. And fourth, the inattention of the Atomic Energy Commission to public demands for more comprehensive safety and environmental provisions was credited with causing a decline in public confidence in the AEC and the nuclear reactor industry.

Delays caused by design, construction, and supply deficiencies of various kinds clearly were greater than those imposed by regulatory requirements, but such requirements did contribute to the problem. Contrary to popular belief, however, environmentalists and intervenors were responsible for only a small part of the problem. The underlying cause of such delays appeared to be the rapid pace of evolution in the design of nuclear reactors, which in effect precluded the orderly development of objective licensing criteria and required a lengthy review of each new individual application. Understaffing and management problems within various of the regulatory divisions during the late 1960s and early 1970s probably contributed as well.

Although the nuclear power industry had an enviable safety record during the first 20 years of its operation under AEC control, in fact serious and legitimate questions recurrently arose concerning the safety of the reactor and its fuel cycle.[2] Again, the rate of

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[1] This section is based on Elizabeth Rolph, *Regulation of Nuclear Power: The Case of the Light Water Reactor*, R-2104-NSF, which should be consulted for greater detail.

[2] The safety features of nuclear plants, as they evolved, are treated in App. D.

technological evolution or, more properly, the rapidity with which reactor capacity grew, was of first importance. Operating experience continually uncovered new design and material deficiencies. Simultaneous development, testing, and commercial deployment might have been a sound commercialization strategy, but it presented additional risks for the general public. The AEC's commitment to an informal, personalized style of evaluating the adequacy of safety features discouraged investment in such analytical methods as probability and reliability studies.

To many, in retrospect, the AEC's safety R&D program seemed inadequate in scope and unresponsive to regulatory needs. The regulatory division had little control over the main program and proposed no important new safety initiatives. The regulatory staff was therefore unable to raise, explore, or resolve potential safety problems before they affected operating reactors, and division personnel lacked sound empirical data on which to base standards. The absence of a fully adequate safety research program particularly handicapped the regulatory division in developing defensible safety criteria for the control of serious accidents.

A third failing in the AEC's safety program, and one that promised eventually to become critical, was the Commission's inattention to problems of the fuel cycle. Quite obviously, if nuclear power was to become a significant source of electrical power in the United States, issues of fuel cycle safety would have to be addressed. The commercial development of the LWR was well underway before the AEC turned its attention to questions of waste disposal, commercial reprocessing, and plutonium recycle and safeguards--although it was apparent as early as 1960 that these were serious issues requiring a great deal of research and development attention.

Safety uncertainties and inadequacies might have become more serious if the public had not participated in the regulatory process. Not only did well-informed citizens' groups contribute substantively to the critique of existing standards, but the adversary proceedings prompted by citizen participation created a forum for airing differences in judgment among the parties involved, even among AEC scientists themselves.

Although increasingly stringent safety and environment requirements did substantially increase the plant costs and extend plant down-time, few of the changes between 1967 and 1976 could be attributed to an overzealous regulatory staff. Most stemmed from two other factors: reliance on general criteria backed by subjective staff assessments (rather than on empirical information) characterized the early years; and operating experience subjected to more sophisticated analyses eventually showed that the original assumptions had not been as conservative as once thought, which again caused standards to be tightened. Continuing technological evolution, lack of a good regulatory research and development program, and the need to rely on the operating experience of commercial reactors for empirical data guaranteed, in the end, that the regulatory division could never "catch up"; backfitting became an inevitable ingredient of the regulatory program.[1]

A third factor responsible to some extent for the backfitting after 1967 was the changing external environment. Activist environmental groups sought a more active role in enforcing regulation of nuclear power plant design, construction, and operation. These groups both reflected and in turn prompted increasingly conservative public responses concerning the safety and environmental hazards associated with nuclear power: Regulatory standards changed because public values changed.

The crisis in public confidence was slow to develop. Indeed, in its early years the AEC enjoyed strong public support. But a variety of factors combined to inhibit its authority and ultimately to induce Congress to disband the AEC and to separate regulation from R&D--and from advocacy. The frustrations experienced within the confines of the licensing process prompted the initial disaffection. Citizens' groups with genuine concerns found themselves struggling in a process that constrained their access to information, inhibiting their ability to debate many of their broader concerns. The outcome of this process frequently appeared to be preordained. Successive efforts by the AEC

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[1] "Hearings Before the Joint Committee on Atomic Energy on Licensing and Regulation of Nuclear Reactors," 90th Cong., 1st Sess., April 4, 5, 6, 20, and May 3, 1967.

to ignore changing public values, to avoid increased environmental responsibility (as opposed to radiological effects alone), and to limit participation in the licensing process only lent credence to the intervenors' allegation that the AEC was a captive of industry and was insufficiently concerned with the public welfare. The AEC's reluctance to strengthen radioactive effluent standards and its poor handling of early waste disposal controversies gave further support to that position. In spite of James R. Schlesinger's major efforts to reverse the slide after he became AEC Chairman in 1971, the public remained generally suspicious of the AEC's loyalties and objectives. The inevitable measure to restore public confidence was to repose regulatory responsibility in an agency free of responsibility for developing and promoting commercialization, the Nuclear Regulatory Commission (NRC).

The Atomic Energy Commission's performance as a regulatory agency drew mixed reviews. In its early years, the Commission responsibly supervised a nascent industry. Once the decision had been made to "learn on-line," it was important that the AEC acknowledge the gaps in its understanding by refusing to adopt fixed standards or to permit the siting of nuclear plants in an urban setting.[1] The subjective *ad hoc* safety evaluation procedure adopted during the early years served needs well enough while understanding of nuclear technology was deficient and license applications were few. But in pushing new nuclear technology into the private sector, the AEC may have committed two serious errors: abandoning substantial support of research and development work on LWR technology well before several major fuel cycle questions had been resolved, and failing to give its regulatory division access to an adequate R&D capability, one that would have permitted that division to make independent tests of the adequacy of safety features.[2]

Between 1967 and 1971, the Commission neither attempted to slow the rate of nuclear plant construction nor imposed standardization on the industry. The AEC also was unable to reorganize the licensing

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[1] Frequently apologetically, and perhaps not by design, the AEC did hold out against heavy pressure from the nuclear industry to adopt fixed standards and to permit urban siting.

[2] See S. M. Stoller Corporation, *Central Station Nuclear Power*, Boulder, Colorado, March 1976.

process or to devise acceptable objective measures on which safety evaluations could be based. Throughout, the Commission was passively reliant on the nuclear industry for operating data and for standards. And, perhaps most significant, the AEC made no substantial effort to accommodate changes in public values.

Between 1971 and 1974, the AEC significantly changed its procedures and attitudes. Some changes resulted from personnel shifts, notably Schlesinger's succession.[1] In any event, the Commission largely succeeded in accommodating to both changing public values and the growing numbers of applications for new plants. Better regulatory control of nuclear technology resulted. The Commission could no longer avoid confronting and dealing with pressing safety issues about which the public expressed ever greater concern.

The nuclear power industry was understandably willing to take risks somewhat larger than those the public proved willing to accept. The industry believed that nuclear technology was well in hand by the early 1960s, lack of operating experience with commercial-scale reactors notwithstanding. Pushing hard for approval of urban and seismic area siting, the industry pursued a rapid course of development even though the first phase of "large-scale commercial construction" involved no reactor plant less than twice as large as the largest of the plants built during the developmental period before 1963; some plants started during that period were more than five times as large. Although the industry's understanding of the requirements of constructing and operating "commercial-scale" nuclear plants increased rapidly during the first few years of construction and operation and its appreciation of standards and requirements changed appreciably during that period, it nonetheless resisted backfitting and the imposition of more conservative design requirements.[2] Although they argued that nuclear power posed no appreciable risks to the public, the utilities and the vendors were reluctant to proceed with the development and commercialization of light water reactor technology unless the federal government provided special liability coverage and limitations on corporate liability.

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[1] *Nucleonics Week*, October 18, 1971.

[2] JCAE Hearings, 1967, pp. 641, 659.

It would seem obvious that a regulatory agency responsible for a newly developed technology must retain procedural flexibility, but the principle sometimes is ignored by regulatory institutions under heavy pressure from both the regulated industry (to establish permanent and well-defined regulations) and its own staff (to assign clearly specified tasks and objectives to that staff). AEC experience demonstrates that regulatory management strategies that change as circumstances require are appropriate to an evolving technology entering commercialization.

It was not possible in the case of LWR commercialization to specify firm regulatory criteria until an appreciable quantity of operating experience had been accumulated; backfitting was an almost inevitable consequence. Indeed, in the circumstances, no other outcome could have or should have been expected.[1]

An adequate research and development program provides a regulatory body with the ability to develop information on which to base regulatory standards and to explore and resolve possible problems before they occur, or become pronounced, in operating plants. No regulatory body can rely on the industry to conduct such research voluntarily because the industry's research would inevitably be suspect as self-serving; industry tends to be interested in a more limited aspect of the overall problem than is a regulatory agency.[2]

"Undue risk" and "the adequate protection of the public health and safety" are by their very nature difficult if not impossible to define in advance of full understanding of the consequences and nature of the process being addressed, and definitions are likely to change with the passage of time. At best, expert opinion can identify a level of risk. Determining the point at which risk becomes "undue" requires subjective judgments that fall into the province of the political process. Hence, to the extent that subjective judgments are left to the discretion of regulatory agencies, such agencies must provide ways for the public to

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[1] Ibid., pp. 215, 274.

[2] F. C. Finlayson, "A View from Outside," *Bulletin of the Atomic Scientists*, September 1975.

express its own understanding of "undue risk" and thus be able to influence regulatory policy.[1]

As the nuclear case indicated, the public is not necessarily alert to the long-term implications of an embryonic technology, nor does the public generally have the technical competence to raise issues before the experts recognize them. Further, public concerns change. Therefore, to the degree that an agency has an obligation to protect the public's interest, a regulatory agency must remain flexible and must provide multiple points of public access. No other proceeding is acceptable in a democratic society.

As early as 1960, some observers had begun to question the appropriateness of merging the development and regulatory functions of the Atomic Energy Commission. Notwithstanding strong opposition from within the AEC, the following decade saw increasing support for measures to divide that organization along the lines of those functions. By the early 1970s, environmentalists had begun to question the advisability of entrusting regulation of an industry to the agency charged with sponsoring its growth.

By 1975, public skepticism concerning the AEC's ability to regulate in the public interest plus a perceived "energy crisis" that promised to push the federal government into support of several major energy development programs combined to lead to the dissolution of the AEC as it had originally been constituted. In 1974, a major reorganization bill passed the Congress, and the Energy Research and Development Agency (ERDA) and a separate Nuclear Regulatory Commission (NRC) emerged. ERDA added to the nuclear development responsibilities of the AEC a host of similar responsibilities for other technologies, although in fact none obviously carried the importance or emphasis accorded the further development of nuclear technology. The NRC fell heir to the AEC's regulatory responsibilities, which did not radically change in transition.

Six propositions appear to be supportable on the strength of experience in the development of commercial nuclear energy. First, strong, independent regulation of an evolving industry is essential to its

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[1] Robert Gillette, "Nuclear Safety: AEC Report Makes the Best of It," *Science*, January 21, 1973.

orderly commercialization. Second, a regulatory agency responsible for any rapidly developing technology must retain procedural flexibility. Third, a strong independent research and development capability is necessary for the creation and continuation of a strong, independent regulatory program. Fourth, the safety of any technology can be assessed only in the context of the full range of its required support components. Fifth, definitions of "undue risk" or "the inadequate protection of the public health and safety" are, and must be acknowledged to be, changeable and subject to political determination. Sixth, early active or energetic public participation in the regulatory process is necessary but not sufficient to guarantee that all issues of concern to the public will be aired.[1]

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[1] See Rolph, *Regulation of Nuclear Power*, pp. 79-81.

VI. OTHER NATIONAL EXPERIENCE

Many nations ultimately invested in nuclear power. Great Britain, France, the Soviet Union, the Federal Republic of Germany, and Canada were the major investors of interest, although other nations (Sweden, Italy, Taiwan, and Japan, for example) also invested heavily. Nevertheless, it was the British, the French, the Russians, the Germans, and the Canadians who pursued interestingly different courses with different outcomes. None of the strategies or approaches adopted by those countries was consistent with those applied in the United States. A broad assessment of how those several nations managed the development of vital national resources can offer some valuable insights into how differences in the management of high technology projects--in this instance nuclear energy--affected the outcomes of those programs. Such findings must be tempered by an awareness that national idiosyncrasies--economic, institutional, and technological--will dilute the applicability of generalizations to future circumstances.

There is nothing particularly surprising about the decisions or the decision processes that characterized early efforts to develop nuclear power sources by the United States, the Soviet Union, France, Britain, and Canada.[1] The United States continued its wartime research projects with some shift of emphasis toward propulsion for naval vessels and aircraft. With abundant resources, the nation could readily invest in a wide variety of experimental reactors; in due course, the pressurized water reactor became a serious contender for selection as an energy-generating device.

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[1] Development efforts in various countries are detailed in Arnold Kramish, *Atomic Energy in the Soviet Union,* Stanford University Press, Stanford, 1959; R. G. Hewlett and O. E. Anderson, Jr., *A History of the United States Atomic Energy Commission: The New World, 1939-1946,* Pennsylvania State University Press, University Park, 1962; Margaret Gowing, *Britain and Atomic Energy, 1939-1945,* Macmillan, New York, 1964; Wilfrid Eggleston, *Canada's Nuclear Story,* Clarke, Irwin and Co., Toronto, 1965; Bertrand Goldschmidt, *The Atomic Adventure: Its Political and Technical Aspects,* Macmillan, New York, 1964; Lawrence Scheinman, *Atomic Energy Policy in France Under the Fourth Republic,* Princeton University Press, Princeton, 1965; and V. S. Emelyanov, "Nuclear Energy in the Soviet Union," *Bulletin of the Atomic Scientists,* Vol. 27, No. 9, November 1971.

Although data on the elements of the Soviet decision process are lacking, it is reasonable to assume that the Soviet program also began with an extension of wartime research experience, not seriously constrained by resource limitations, into the development of commercial-scale reactors. The Soviet fondness for the graphite-moderated reactor may well have been another expression of the Soviet preference for simplicity and dependability in complex systems.

Although Great Britain had something of a technology advantage because of wartime nuclear weapons cooperation with the United States (and also benefited from a continuing good relationship with the Canadians), the French and British reactor programs were highly similar. Both nations chose to enter nuclear research for reasons of national security and national prestige. Further, owing to the extreme dependence of those two nations on imported fuel, both perceived a need for augmenting national power sources; in addition, neither country had access to enriched uranium. This convergence strongly argued that each nation's reactor program should initially be dedicated to producing weapons-grade plutonium, that investment would have to be limited to a few attractive reactor types (including a graphite-moderated reactor, because of its plutonium producing efficiencies and neutron economy), and that each nation would make an early and concerted effort to develop a nuclear reactor power system. That is precisely what happened.

The Canadian reactor program was also developed as a by-product of wartime experience; but the physical properties and availability of heavy water, the absence of enrichment facilities, and the abundance of natural uranium in Canada made the choice of a heavy water reactor almost automatic. Even less than the French and the British could the Canadians afford to invest in a large variety of reactor types--and they conducted no military program that could underwrite some of the costs.

Starting later than any of the other major participants, having been prohibited from early postwar research and having less of a scientific establishment to draw from, the Germans were able to avail themselves of sources of enriched uranium from America through the Atoms for Peace plan and EURATOM joint development program. Prohibited from exploring the weapons applications of nuclear energy, they concentrated entirely on its civilian potentials. Further, because they began a program of nuclear power development later than any other major participant, the Germans were able to choose among several competing reactor types that had been demonstrated earlier, thus profiting from both the experience and the investments of their neighbors and allies. To some extent then, their early handicaps were offset by later opportunities, which they skillfully exploited.

ORGANIZATIONS

The role of private industry in the development and commercialization of nuclear power varied widely among the several nations. In West Germany, the demands of private industry were instrumental in turning the government's attention toward the potential of nuclear research. It seems foolish to suggest that "private industry" played a role in the Soviet Union, because there was none; nevertheless, the Ministry of Medium Machine Building apparently had influence analogous to that of private industry in West Germany and the United States. Control and direction of nuclear energy programs were concentrated well toward the top in the Russian government, so the responsible Ministry did not have the influence or decision authority characteristic of the atomic energy agencies of the several Western nations; in terms of constituent self-interest, however, it appears to have acted much like Western industrial groups concerned with the promotion of nuclear energy.

Neither the central government of West Germany nor the utilities favored central planning in the nuclear sector. The first two small German reactors were built entirely with private funds under license from General Electric. (Of course, the utilities concerned were subsidized by state governments, which made them rather less than typical free enterprise institutions, but the distinction was important.)

In Canada, the device of a Crown Corporation provided for the continued participation of private groups with the central government in the development of sources of nuclear energy. Neither France nor England made even so slight a concession to the interests of the private sector. Both of those governments retained monopolistic control over all nuclear research and later "commercialization," treating private industry as a supplier of components.

Being wholly state controlled, neither the French nor the British utility sector had any independent role in the development of national nuclear programs. *Electricité de France* (EdF) held a legal monopoly on the production, transmission, and distribution of electricity in France. Its directors viewed nuclear power as too expensive and uncertain to warrant investment. Nevertheless, the future of nuclear power seemed promising enough to induce them to participate in an advisory group that brought together representatives of the French atomic energy agency (CEA), the EdF, and potential industry suppliers. For practical purposes, however, all major decisions were made by the central government. The British experience was similar. The only substantial contribution to either nation's nuclear program by private industry was in the final design and the construction of research facilities and reactors along lines chosen earlier by government authorities. In both nations, construction firms formed consortia that acted as industrial architects. Generally, they were responses to the expectation that the nuclear power industry would later become a major growth industry and provide a profitable demand for their services.[1]

EARLY DEMONSTRATION STRATEGIES

In many respects, the national strategies adopted by the various participants in moving toward the demonstration stage of reactor development were continuations of existing conditions and organizations. The United States and the Soviet Union undertook and continued research on an impressive variety of reactor designs and invented others as knowledge accumulated. Canada and France both operated on a much more constricted scale, in large part because of budgetary restrictions but also apparently by preference; each predictably settled early on a single reactor for development.

The British and German cases are less clear. Notwithstanding a very substantial investment in the research phase of reactor development,

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[1] J. E. Hodgetts, *Administering the Atom for Peace*, Atherton Press, New York, 1964.

the British eventually reduced their approach to a single reactor type. Great Britain's options were somewhat constrained by limited access to sources of enriched uranium, but the British were strongly motivated by perceived energy shortages and the desire to join the select group of nuclear powers as quickly as possible. Although the Germans might reasonably have chosen to pursue a single reactor strategy, using the products of earlier research elsewhere to guide them, German scientists were no more prescient than those of other countries in choosing among promised options of the late 1950s. They also were sensitive to the desire of German private industry to participate competitively in reactor development. Both circumstances supported a preference for having at least two or three different reactor types available when a final choice had to be made. Consequently the Germans did not initially favor a single reactor approach.

For practical purposes, the Americans, the Russians, and the West Germans had multiple research avenues open and attempted to exploit several of them simultaneously rather than to restrict themselves as did the French, British, and Canadians. Apparently confident that technical uncertainties were not critical, the British and the French, who had several options nominally available, initially chose to pursue the gas-cooled, graphite-moderated reactor. Having more limited financial and scientific resources, the Canadians could not support a multi-faceted development program. But they had a fair amount of experience in their wartime collaboration in the heavy water aspects of nuclear technology, so their decision to invest in a heavy water reactor was a product of choice and necessity.

The British and the French prototype commercial power reactors both went operational about ten years after the national decision to attempt such a feat; the Canadians spent nearly 15 years in the process. Whether the resources of the French or the British would have been sufficient to support multiple approaches is problematic; in any case, for various reasons that could scarcely have been foreseen, the single-focus Canadian approach proved successful, but similar French and British programs were far less so.

In proceeding from research and development to early demonstration, each nation attempted to determine if (or to prove that) the reactor it had chosen was operationally and economically feasible. Each built demonstration models of power reactors developed earlier in prototype. By the time the demonstrations had been completed, each nation had accumulated sufficient information to support a decision on whether to disseminate its chosen design. In no instance was the decision easy. The French and the British confronted a dilemma: to continue with reactors that showed no signs of demonstrating economic practicality or to abandon their first-chosen courses and opt for a design based on foreign technology. The Soviet Union demonstrated three different reactor types having at least modest operational capability and had to choose which to pursue. The Canadians were more or less in the position of the French and the British as regards choice, but all the available evidence suggested that they had chosen reasonably well in the first instance. Nevertheless, the Canadians and the British shared similar problems: Could the utility companies and the constructors of nuclear reactors be induced to proceed with the commercialization process? The Germans faced a similar situation with the interesting amendment that they had to choose among several foreign reactor technologies and a variant but nascent native technology.

In the end, the United States, the Soviet Union, and Canada constructed commercial-scale nuclear power plants that seemed, in the near term at least, to be capable of producing electricity at costs competitive with those of fossil-fuel plants. The Canadians, who had less to risk and more to lose if the choice proved faulty, had but two choices if they elected to "go nuclear":[1] either to proceed with the heavy water CANDU or to abandon an increasingly interrelated nuclear industry and deploy reactors of American design. There have been indications that Soviet authorities were not entirely at ease with progress in their nuclear power program when it seemed necessary to commit substantial resources to commercial-scale construction. Nonetheless, had the Soviets delayed, they would have been outdistanced in the development of a civilian nuclear technology; considerations of international prestige made that unpalatable.

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[1] The Canadians also had a most attractive hydroelectric option.

The Germans had concluded that one or another of the light water reactor designs offered the shortest, cheapest route to nuclear power generation and merely followed the American example in building both pressurized water and boiling water reactors, a strategy encouraged by multinational corporations of American origin and opposed by the French. The French nuclear fraternity and the Gaullist political establishment looked on the penetration of the American light water reactor into Europe as an affront to French science, the French gas-graphite design, and European unity. They nonetheless could not avoid realization that the preferred French design probably could not be successfully built on a commercial scale, temporarily swallowed national pride, and elected in 1969 to reject further investment in the gas-graphite reactor and build American designed light water reactors for near-term power generation. But sooner than others, they moved into accelerated--and costly--research and development focused on a fast-breeder reactor for future application to national power needs.

Although the Soviet Union chose to construct both pressurized water and light water graphite-moderated reactors in substantial numbers, their rationale remains uncertain. The pressurized water reactor probably was less expensive and operated somewhat more efficiently, but the light water graphite reactor was a better plutonium producer, was less complex, and might have seemed to be somewhat safer. Given that neither reactor provided a dominant solution and that both had a sizable group of advocates, one might speculate that Soviet policymakers preferred to let both developments continue rather than choose one over the other.

Although the Canadians spent far longer in proceeding from the start of their reactor development program to the construction of initial large-scale reactors, the constructed reactors encountered no significant technical or operating problems once they were completed. The design appears to have been basically sound, and the Canadians elected to exploit the advantage of standardization long before the United States did so. On a per capita basis, Canada led the world in the generation of nuclear power by 1974. The only major problem the Canadians encountered, rather unexpectedly, was a temporary shortage of deuterium oxide (heavy water). Foreign purchases and internal adjustments solved the difficulty temporarily, and a major construction program protected against its recurrence.

German transition to the construction of large-scale plants was perhaps the least complicated of any. The Germans had from the first intended to develop a cost-effective way of obtaining electricity from nuclear power plants. Most of their basic research was performed by firms with a strong interest in the commercial benefits of nuclear energy, firms that developed their own nuclear research facilities and focused on advanced technology reactors, including fast breeders. But for immediate purposes of power production, the Federal Republic chose to emphasize the same two reactors favored in the United States. Again, standardization was more pronounced than in the United States, partly because local German purveyors of electricity had less influence than American utilities on plant design and partly because standardization made economic sense to the Germans.

The British advanced gas reactor, chosen in 1968 in preference to a variant BWR, was an economic and technical failure. Well before the fuel crisis of 1973, the British had been forced by economic circumstances to combine their five principal nuclear firms into one consortium. By late 1973, in the wake of the fuel crisis of that year, Britain's Central Electricity Generating Board began to advocate that the United Kingdom adopt the pressurized water reactor as its principal power-generating resource. Confronted by rapidly rising demands for energy, the government actively considered a number of alternative reactor designs, including both versions of the American light water reactor, the steam-generating heavy water reactor, the CANDU, a high-temperature gas reactor, and a fast-breeder reactor. Notwithstanding the preference of the largest electricity-generating authorities in the United Kingdom for a PWR program, the Labour government eventually chose the hybrid steam-generating heavy water reactor for further development and construction rather than its competitor, the Westinghouse pressurized water reactor. The announced justification was "reliability" and the high relevance of British nuclear experience to the steam generator. One additional reason for the selection of the steam-generating heavy water reactor was the conviction of several leading nuclear authorities that it was safer than the PWR.[1] Other determinants included a British preference for cooperation with Canada rather than the United States, and British reluctance to surrender a heritage of independent nuclear research. Nevertheless, British nuclear technology had for the second time proved inadequate to the tasks levied on it, and the British had been obliged to choose a new reactor system to bridge the power deficiency created by the delayed availability of a fast-breeder reactor. One effect was that the British alone among the nations considered here still did not have a proven and fully demonstrated large reactor available by 1975, after nearly three decades of effort to make nuclear technology benefit the United Kingdom.

Although the de Gaulle government had in late 1967 reaffirmed the French allegiance to the French gas-graphite reactor design, even then there were indications that the government was moving toward acceptance of foreign nuclear technology. In 1968, the French nuclear community split on the issue. The government and the CEA continued to champion the native gas-graphite reactor; EdF and the nuclear industry favored the Westinghouse light water reactor. In 1969, the debate over the future course of French nuclear development reached the public press; in November, the Pompidou government announced that France was abandoning the gas-graphite reactor. The reasons were obvious: Experience to that point indicated that the light water reactor was 10 to 20 percent more productive than the gas-graphite reactor; the gas-graphite reactor was not as readily exportable; finally, as the French industrial consortia argued, extensive American and German commitments to the light water reactor guaranteed that the system would have more abundant technical support in the near future than any other reactor type. As was remarked at the time, "the ultimate decision by the French government...can be seen as a victory for pragmatism over economic chauvinism."[2]

The French and the British faced the same problem, the same set of decisions, at about the same time. The reactors each had developed

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[1] Norman Dombey and John Surrey, "Nuclear Reactors--Britain's Choice," *New Statesman*, Vol. 87, No. 2249, 28 April 1974, pp. 574-576.

[2] John Walsh, "Nuclear Power: France Forges Ahead," *Science*, July 1975, p. 340.

were technically and economically handicapped. In both countries, the electric utility industry expressed a strong preference for the American light water reactor. Both countries opted for the same long-term solution, to emphasize the eventual development of a breeder reactor; for the near term, they chose different courses.[1]

OUTCOMES

Some composite of technological nationalism, resource constraints, and budgetary constraints dominated the decisions of the Canadians, the French, the German, and the British. Appreciably less inhibited by the necessity of accommodating the costs of their nuclear investments to limited national resources, the United States and the Soviet Union pursued the development of several types of reactors until, for one reason or another, one or two approaches became most attractive. The widely held assumption that the choice of the United States was in some respects dominated by considerations of environment and safety is not well-founded. The choice of the LWR was made before environmental and safety considerations became of great public concern. In the Soviet Union, there is no evidence that public response was a significant factor in the choice of reactor type. In the United States, the decision was made early to choose reliable nuclear power rather than cheap nuclear power, at least for the early stages of commercialization. Consequently, there was little research and development support for alternatives to the light water reactor. A different investment decision might not have altered the outcome in any case. By 1963 the United States had begun the development and commercialization of two types of LWRs, the pressurized water reactor and the boiling water reactor. The enterprise of American industry had consequences that were both surprising and predictable. Not only was that commercialization effort directed almost entirely toward the exploitation of demonstrated LWR technology, but the sum and product of

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[1] Jules Gueron, "Atomic Energy in Continental Western Europe," *Bulletin of the Atomic Scientists,* Vol. 26, No. 10, June 1970; Scheinman, *Atomic Energy Policy in France,* Part 1; H. R. Nau, *National Politics and International Technology: Nuclear Reactor Development in Western Europe,* The Johns Hopkins Press, Baltimore, 1964, pp. 80-86; Duncan Burn, *The Political Economy of Nuclear Energy,* The Institute of Economic Affairs, London, 1967, pp. 82-84.

that enterprise proved so attractive that both French and German nuclear industries abandoned their independent designs in favor of constructing large-scale reactors on the American model.

To suggest that the "success" of a single nation's reactor development enterprise should somehow be measured by the acceptance of whatever reactor type emerged from that development process is to ignore a host of factors that distinguished the nuclear investment and nuclear enterprise of one country from those of another. The role of multinational corporations, the extent to which governments subsidized national and exported nuclear plants, and the pressures of the French for an all-Europe initiative are examples. The cost of independently developing commercial-scale reactor power can be enormous. If "success" is measured on a scale of enterprise variety, by 1976 only the Soviet Union and the United States had achieved success. The Canadians pursued the CANDU because they had limited choices and were realistic about the advantages and disadvantages of each; the persistent British pursuit of alternatives to the LWR can be best characterized as a function of scientific taste and national preference, without much regard for the contemporary realities of either technology or economics. The French, after investing extensively in technological nationalism, discovered that their needs exceeded their resources. The Germans, having briefly supported the French, apparently concluded that the costs of collaborating with the French in reactor development were substantially greater than the benefits. The withdrawal of German political, technological, and monetary support contributed to the eventual demise of the national French program.

Well in advance of the Americans, the Europeans appreciated that the appearance of an energy crisis (which is not necessarily the same as the fuel crisis that bloomed in 1973) could not forever be delayed. The Americans and the Russians had substantial untapped fossil-fuel reserves. Except for expensive coal and the prospect of North Sea oil fields, the European energy future was bleak. Whether publicly acknowledged or not, acquiring alternatives to fossil fuel was of increasing urgency to West European nations after 1960.

Although their ambitions were high and enterprise commendable, the West European nations were unable to command and control the resources essential to the independent development of nuclear energy cycles other than those first developed and exploited in the United States. Had only economics and technology been considered, Western Europe might have opted to follow the Soviet example. But politics forbade such emulation.

Analogies involving the commercialization of novel and "high" technology in the last three decades are civil air transports, computers, and nuclear energy. In all three cases the buyers, or consumers, were principally interested in the costs they incurred by the adoption of one approach or another. For a variety of reasons, the products developed by the Soviet Union have not been attractive to Western Europe in any of those three areas. In all three, West Europeans have attempted to develop independent approaches. In all three instances, the approaches pioneered and exploited first by the United States proved compellingly attractive. The explanations for those tendencies may draw the attention of economic analysts and historians for another generation. But for all practical purposes, the market provided by the United States supported the development and eventual commercialization of technology that was more attractive to prospective buyers than anything individual West European nations could develop by themselves. Except in a few instances of programs or enterprises consciously subsidized by Western European nations (with the acknowledged appreciation that the products--aircraft, computers, or nuclear power plants--would not be commercially attractive in a private enterprise system without a subsidy), no West European attempt to develop any of those technologies had even marginal "success" between 1950 and 1975.

Notwithstanding the barriers of nationalism, IBM came to dominate the computer market in Europe as in North America, no European builder of commercial transport aircraft was able to compete successfully with Boeing and Douglas, and Westinghouse plus General Electric (by licensing) all but monopolized the reactor market in Western Europe. True, some bastions were stubbornly defended. As late as the mid-1970s, the British, French, and Germans were still hopeful that the A-300B transport could recover some of the commercial airline market dominated by American manufacturers. But there was no real prospect that any single nation or combination of states could provide effective competition to IBM and the computer market. Despite a stubborn holdout by the British on grounds that had very little to do with practical economics or technology, only the American-developed LWR represented a commercially feasible investment for West European utilities.

In the case of nuclear reactors, a vast range of variables contributed to that outcome. The chief contributor, however, was the willingness of the government of the United States, of the several large commercial enterprises interested in selling reactor plants, and of the healthy and hungry utility complex of the United States to invest more in the development and exploitation of nuclear power energy sources than any single European nation could afford. Henri Spaack's dream of a unified Europe might have altered the arithmetic had it ever become reality, but it did not; single European nations could not absorb enough "native" reactors to insure their commercial success. Whatever its faults, the approach pursued by the United States led to the early availability of commercially feasible nuclear power. If, on theoretical grounds, the offerings of the Americans had less economic attractiveness than some of the alternatives, in both the United States and Europe, that attractiveness was in most instances insufficient. The British held out for reasons they considered sufficient. The rest of the world, outside the Soviet bloc, chose to follow the American example. The costs of competition were too high, not only for nuclear power stations but for aircraft and computers as well. Whatever the imperfections of the American development process, and they were many, the American choice inevitably became the choice of the rest of the free world. The sole exception in the cases examined above is Canada.

It has been argued that the British and French exclusion of private industry from their reactor program was a principal reason for the eventual failures of those national programs.[1] The argument does not of course apply to the Soviet Union. Nonetheless, although the evidence is scant, a comparison of the experiences of West European nations with those of the United States (and even of the Soviet Union) suggests that involving a number of participants, even competitors, is a reasonably sure way of guaranteeing that the most preferable of available technologies will be chosen for commercial development.

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[1] That argument is made by Burn, *The Political Economy of Nuclear Energy*.

"Preferable" is of course quantitatively undefinable. Preference can be an expression of national interest, of the predilection of one scientist, of the influences of one consumer, of the extent to which one's utility complex is concerned with the level of national unemployment, or of the cost of electricity to customers. Many other special preferences come to mind. Nevertheless, the market for reactors in the United States is larger than the market for reactors in Western Europe, and this alone has much to do with the final selection of process and approach. In a resource-rich environment, it is possible to conceive of a continuing competition, however imperfect, that will result in the selection of a "least objectionable" avenue of approach. Where only one avenue is being explored, anything not being supported by the establishment becomes less preferable by definition.

To judge the success of the American approach in terms of the acceptance of American products abroad is an imperfect standard. After all, what alternatives were readily available?[1] With the exception of the CANDU (an exception that did not become apparent until the late 1960s), no conceivable approach to the generation of nuclear energy on a commercial scale had the economic and technological attractiveness of the two principal variants of the American light water reactor.

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[1] The only foreign sales of the British Magnox reactor occurred before the LWR became a competitor.

VII. FINDINGS AND CONCLUSIONS

A parallel development strategy has been given much of the credit for the success of reactor commercialization in this country. Comparisons of U.S. with foreign experience and U.S. nuclear with U.S. defense program policies are often cited to that end. More than five principal avenues to commercially competitive nuclear power seemed open in the early 1950s, but 20 years later the LWR was the only healthy survivor.[1] None of the others had proved wholly adequate in various attempts to demonstrate commercial feasibility. The considerable scope of options created by the wide-ranging Power Reactor Development Program of the late 1950s appeared once more to demonstrate the wisdom of multiple approaches to uncertain technology; if one or two reactor cycles proved less than satisfactory, for reasons of technology or economics or timing, another was available and the total program could still go forward.[2] The generally disappointing experience of the British and the French in reactor development is frequently attributed to their supporting a single approach strategy, further reinforcing that judgment.

Other evidence encourages the ancient Scots' verdict, "Not Proven," at least for the U.S. power reactor program. Impelled as much by scientific nationalism as by economic constraints or technical advantage, the British twice and the French once invested national prestige and large resources in efforts to develop and market unique reactors. But so did the Canadians, who had the additional problem of a much less robust economy and the easy option of merely tapping the readily accessible U.S. reactor program. Yet even though not widely adopted outside Canada, the CANDU in time became a successful reactor--admittedly helped

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[1] Proponents of high temperature gas reactors--HTGRs--still expressed both optimism and confidence that the HTGR would in time prove to be both safer and more economical than the LWR, but by 1977 the prospect of further development was dismal.

[2] Arthur J. Alexander and Donald B. Rice, *Comments on LMFBR Cost-Benefit Analysis*, The Rand Corporation, P-5498, August 1975, make that point.

by changes in both the economics of nuclear reactors and the technology associated with them, although no more so than the LWR--which may say no more than that again the rule had an exception.

To what extent is the American experience relevant to the premise that a multiple approach strategy for reactors was a major contributor to American success? Would the outcome have been much different if in 1953 the AEC had decided that only the PWR would thereafter receive governmental R&D support? The BWR would perhaps have been handicapped, but considerable cost benefits might also have been obtained: Presumably none of the ultimately unsuccessful alternative reactor designs would have been carried to trial by PRDP, which would have appreciably lessened costs to the federal government, the developers, and the utilities. Had 1953-1963 investments in reactor development been channeled entirely into the LWR, would more rapid LWR progress have resulted, would more and more successful test reactors have been built, and could "commercial feasibility" have been realized earlier?[1]

PWR uncertainties of 1953 concerned not so much design feasibility, which had been experimentally demonstrated in the submarine reactor program, but engineering reliability and economic feasibility. Shippingport ultimately demonstrated the first (after 1956) and Yankee the second (after 1960). In such terms, then, the flaw in the British and the French approaches was not necessarily premature decisions to discard consideration of alternatives to the preferred designs, but a simpler matter of having made the wrong choice, or of having opted to proceed before real choices were available. All of which suggests that the Navy reactor program directed by Rickover did explore the available alternatives; all of the reactor types eventually tested in the PRDP had by 1953 been proposed for adoption, although some had been submitted to no more than laboratory-scale experimentation. Rickover's choice was an engineer's choice, conservative, unsupported by much economic analysis,

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[1] "Commercial feasibility" really meant, at the time, a *perception* of commercial feasibility, which ultimately induced General Electric and New Jersey Power and Light to invest in the Oyster Creek plant, or even the more cautious (but earlier) perception that induced Westinghouse and Southern California Edison to build San Onofre at a "fixed price" with almost no subsidy.

and characterized by what some critics later described as cavalier disregard for the reasoned advice of some of the nation's most eminent nuclear scientists. But in the end Rickover's choice proved to be good; by 1960 the residual engineering uncertainties of 1953 had been largely subdued, and if nuclear power was not cheap, at least it was reliable.

Decisions to press forward with demonstrations of alternative reactor design concepts while the LWR was steadily becoming more attractive may have been as much influenced by the institutional preferences of the several AEC laboratories as by the overall promise of those concepts. Advocacy reinforced by steady and substantial government funding was a marvelous spur to the continuation of developments that, in the judgment of some later critics, probably could not have sustained the test of an open marketplace.[1] Indeed, some alternatives might have developed greater attractiveness had not the AEC in the second round of the PRDP elected to solicit the support of small utilities for reactor technologies far riskier than the LWR. That incompatibility may have sealed the fate of the alternatives. Nevertheless, the availability of the LWR (which by 1958 extended to the PWR and the BWR) made it possible for the AEC to abandon less promising alternatives without regret and without concern for the ultimate soundness of the current approach to reactor commercialization. Other Western nations had few or no options.

Could a more effective approach have been designed for insuring a successful transition between proof of concept and commercial acceptance? Notwithstanding several encouraging demonstrations of the late 1950s (Yankee and Dresden seem particularly successful), the utilities entered the 1960s still cautiously reluctant to accept the risks of unsubsidized nuclear plant construction. Nor was the AEC anxious to underwrite the costs of still larger demonstration plants, however confident the predictions that "bigger" nuclear generating plants would be commercially

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[1] See Wendy Allen, *Nuclear Reactors for Generating Electricity: U.S. Development from 1946 to 1963*, R-2116-NSF; see also George Eads and Richard R. Nelson, "Governmental Support of Advanced Civilian Technology--Power Reactors and the Supersonic Transport," *Public Policy*, Summer 1971, pp. 405-427.

competitive with fossil-fuel plants. The coal industry, which stubbornly insisted that it was both unfair and unwise to subsidize its competitors, was influential in shaping the political climate; and the post-1960 willingness of coal operators to adopt sometimes unpopular measures that reduced the cost of coal provided evidence that cost competition would be real. Into the 1960s, the utilities remained fearful that unless privately funded commercial-scale nuclear plants were built, the government might in the end decide to fund something on the order of a nuclear TVA.

By early 1963 there was widespread agreement that if the capital costs of nuclear plants could be kept low enough, nuclear energy might indeed be competitive with fossil-fuel energy--at least in those sections of the country where transportation costs made fossil-fuel generating plants most costly to operate. The turnkey plant offers of 1963 provided an acceptable alternative to government subsidy: The developers agreed to guarantee completion and operability of "big" nuclear plants without financial risk to the buyers. Only two of the reactor builders, GE and Westinghouse, chose to make such offers. They presumably had confidence that their cost estimates were respectable and assumed that miscalculation would not have fatal financial consequences. But Westinghouse and GE were not alone in assuming--most unwisely--that plant costs were reliably predictable, that nuclear plants were not all that different from fossil-fuel plants, and that larger nuclear plants were little more than cost-effective, scaled-up versions of the smaller plants of the 1950s. Several utilities elected to build non-turnkey nuclear plants between 1963 and 1967, presumably concluding that their greatest experience would permit them to control costs more effectively than could comparative novices or, alternatively, preferring to retain direct control over plant design and construction. In the event, those contemporary turnkey and non-turnkey programs had similar cost outcomes, different mostly in that the developers paid for one set of overruns and the utilities the other. Both learned that estimating errors had costly consequences. Realization that the rationale that had encouraged early nuclear plant construction projects was critically flawed probably came to the utilities and the developers almost simultaneously. GE and Westinghouse reacted by either withdrawing from the turnkey plant market or increasing their bid prices. The utilities persisted: Nuclear plant construction continued, at a generally increasing rate, after 1966, even though capital cost estimating errors continued to flourish.

Had the world not changed, it is conceivable that the frighteningly costly experience of the 1963-1967 period might have brought nuclear plant construction to a halt, at least temporarily. But the capital cost issues that dominated consideration of the nuclear option until 1967-1969 were thereafter subordinated to other factors. Coal prices increased after 1965, and one of the early effects of the environmental movement was to make nuclear power seem more attractive, in some settings, than fossil-fuel power. A secondary and delayed consequence of the environmental movement (in the 1970s) was to force expensive changes on the design of fossil-fuel plants (mostly coal), again making the nuclear option seem attractive. Then, the oil crisis of late 1973 and the subsequent five-fold increase in the price of imported oil enhanced the cost competitiveness of nuclear plants once again. Finally, a growing realization that in the long term fossil fuels (chiefly oil and gas) might be in very short supply induced the utilities to assign greater weight to fuel diversification in their planning. In areas where fossil-fuel use did not involve excessive transportation costs, where low-sulphur fuels were in reasonably assured supply, or where nuclear plant construction experience had been consistently discouraging, nuclear plants still were not widely competitive with fossil-fuel plants by 1976. In areas where nuclear plant experience had been encouraging, and particularly where individual utilities had favorable early experience with nuclear plant construction and operation, nuclear energy was often favored (particularly in the southeastern region of the United States and in the cases of Northeast Utilities, Duke Power, Southern California Edison, and Commonwealth Edison). Low sulphur coal was not readily accessible to New England utilities, and elsewhere (notably Southern California) environmental considerations made expanded fossil-fuel use all but unacceptable.

Claims that environmentalist objections to nuclear power played any significant role in utility decisions on nuclear plant construction before 1970 are not supported by the evidence. Nor can much weight be given to arguments that licensing delays arising in cumbersome regulatory processes were singularly important in the early phases of commercialization. The conflict between the advocacy and the regulatory responsibilities of the AEC ultimately became so troublesome that the AEC itself was replaced by a pair of institutions, each responsible for one of those functions; but in retrospect, the ill effects of the original arrangement seemed not very pronounced before 1970. It is likely, however, that the consistent refusal of the AEC to accept responsibility for any but nuclear effects in earlier safety and environmental disputes worked ultimately to the disadvantage of the industry as a whole.

Unlike many other "high technology" enterprises fostered by government subsidy, LWR commercialization was not much troubled by technical uncertainty. Nor was the progress of commercialization seriously interrupted by the need to pause and redesign. That experience stands in pleasant contrast to the development of major systems under Department of Defense sponsorship. Indeed, the nuclear steam supply systems of the LWR plants were, compared with contemporary military systems, almost trouble free--a generalization that did not extend to several of the alternative nuclear plant designs demonstrated in the course of the PRDP phase. The important difference seems to be that until the construction of "large" reactors began in 1963, the development of LWRs, whether PWR or BWR, was a sequential process; that experience with experimental reactors was carefully evaluated before small demonstrators were attempted; and that successively larger and more complex installations were constructed at intervals that allowed for the incorporation of new design and engineering information developed in earlier phases. Such was not often the case with the alternative reactors; and, of course, the subordination of sequentiality to concurrency as a policy goal has frequently been identified as one of the chief defects of the usual process of developing military weapons.[1] In such circumstances, the absence of major technical problems in the post-1960 period of LWR commercialization is not as surprising as contemporary experience with other "high risk" technologies

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[1] Robert Perry et al., *System Acquisition Strategies*, The Rand Corporation, R-733-PR, June 1971, summarizes the considerable evidence to that point.

would suggest. Where technical problems developed (and they were not unknown), they tended to concentrate around functions, equipment, and effects not provided for when LWR commercialization accelerated, after 1963. Safety equipment was a principal focus. Lessening prospective harm to the local environment and the realization that protection of the environment had to be taken into account in nuclear plant planning had significant cost and schedule consequences. Nevertheless, no *major* technological defects were uncovered during post-1958 LWR development, and the construction and operation of commercial-scale LWR plants was comparatively untroubled by concern for design adequacy.[1]

One instance of what might have been described as "technical difficulty" did, of course, disturb the steady progress of LWR commercialization. It concerned chiefly the "balance of plant" (non-nuclear element), and it arose in the unwarranted optimism of both utility managers and architect-engineering specialists that nuclear plants could be built much as fossil-fuel plants had been built, that the nuclear heat source could be treated as a variant of a conventional steam generator. That proved to be far from the case. The consequences were vastly greater construction costs than had been expected and considerable delays in plant construction. Although some of the difficulties were of the "concrete and steel" type, most involved the far more complex piping, wiring, and control mechanisms required for nuclear plants. The requirements for precision fitting and for fail-free equipment were considerably more demanding for nuclear installations than for older fossil-fuel plants, and the difficulties of satisfying demands for high safety standards accounted for many of the cost and schedule overruns that marked the 1970s.

A second element of the problem arose in the assumption that large nuclear plants were merely enlarged copies of the smaller plants with which the industry had all its pre-1960 experience. Even though the

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[1] Some problems of technology appeared late: In 1977, at least 14 of the 38 operating PWRs were experiencing some operating difficulties that stemmed from the unexplained buildup of magnetite ("green grunge," in the vernacular of plant operators) on the support plates inside the steam generator portions of the NSSS, choking off the flow of heated and pressurized water. For Turkey Point plants III and IV, the cost of repair was estimated at $190 million per plant.

size of fossil-fuel plants had been steadily increasing in the 1950s, experience with plants larger than 500-750 MWe was limited--and for nuclear plants there was none. Nevertheless, the constructors, designers, and buyers set out to build plants ranging from 400 to 850 MWe, and 1000 MWe plants were designed and ordered two years before any installation larger than Dresden (200 MWe) had become operational. In the rush to obtain returns to scale, the industry ignored (or never noticed) the importance of sequential learning to the singularly good progress of early LWR development. Large plants were more difficult to build, had (contrary to expectation) lower reliability, and generated more costly (or not much cheaper) electricity than the less ambitious plants of the period. Although those consequences were in some respects attributable to faulty technological concepts, they could not be charged to bad design or faulty engineering. The cost consequences were much the same as for technically risky defense programs, and the fundamental cause may have been similar: unwarranted optimism about the predictability of outcomes. But, using the traditional definition, "high risk technology" was not really at fault.

To describe the course of LWR commercialization between 1946 and 1976 as conforming to a strategy would be putting overmuch emphasis on a process that was not coherently planned and could not be completely described except in retrospect. Nevertheless, elements of that approach had obvious benefits:

- The early evaluation (1948-1953) of the *practical* applicability of LWR concepts.
- Early small-scale tests of the critical components and processes (Navy reactor program and EBWR).
- Commitment to and follow-through of a "prototype" program (Shippingport, post-1953).
- Larger scale testing of the *central elements* of the PWR in a semi-operational setting (Yankee).
- Sequential development and demonstration, with some overlap, but nonetheless often permitting the results of one experiment to be evaluated and applied to the next in the series.

- Conservatism in design and engineering concepts during test and demonstration, although "off the shelf" technology was not generally exploitable (Shippingport and Yankee for the PWR, Dresden for the BWR).
- Selective and gradually decreasing government subsidies as the scale of demonstration and construction grew larger.
- Increasing dependence on the probable manufacturers for technical advances.

Those practices seem, on the whole, relevant to any technology-intensive development-demonstration program involving uncertainties of demand, cost, and commercial exploitability.

One other element of the approach had theoretical benefit but in fact probably was redundant:

- Multiple, parallel development and demonstration of nuclear alternatives to the LWR.

In other respects, the process included elements that might have been changed with benefit to both participants and outcomes:

- AEC insensitivity to the complex, non-political, institutional elements of the demonstration process (inappropriate coupling of high-risk demonstration plants with financially constrained small utilities).
- Reduction of R&D support, particularly for the safety elements of the light water reactor.
- Discontinuance of the demonstration program while some promising cycles still were incompletely developed (the HTGR and the heavy water reactor).
- Unrealistic expectations of cost competitiveness before other than "small" non-representative plants had been demonstrated (leading to the 1963-1967 construction cost debacle).
- AEC reluctance to accept responsibility for any effects of nuclear plant construction other than those involving nuclear safety (before 1971).

- Governmental indifference to the increasing public concern for safety (the ECCS problem) and environmental effects (Calvert Cliffs).
- Excessive confidence in the predictability of the future and prospects of LWRs (the fuel crisis of 1973 is an example of unforeseen but generally predictable events).
- AEC emphasis on reactor development without adequately addressing other elements of the nuclear cycle (enrichment, reprocessing, and waste management).

The most critical policy decisions appear to be those that can either prematurely discontinue support for a still promising but unproven technical concept, and those that unduly *extend* funding support for unpromising, adequately tested concepts.

The LWR experience has had some unexpected consequences for the future of other nuclear (and non-nuclear) options:

- Neither utilities nor manufacturers are likely to make major commitments to potentially high cost systems or concepts that have not been demonstrated at nearly full scale.
- Government subsidies of promising new approaches probably will have to be continued farther into the test, demonstration, and proof of commercial feasibility cycle than was the case for LWRs.

Some observations on other aspects of the initial commercialization of nuclear power also seem pertinent:

- Although British and French experience would suggest that uncritical reliance on one unproven reactor concept can have disastrous consequences, Canadian and U.S. experiences indicate that *careful* evaluation of feasibility and a *cautious, mostly sequential* approach can provide adequate safeguards.
- Final technical developments are best left to the prospective users and the vendors, who have a clear appreciation of

technical and economic goals, but continuing government participation in some aspects of the development-commercialization process is advisable, particularly where public interest (safety, environmental issues, etc.) are not necessarily congruent with private interest (rapid approval of construction plans, reluctance to modify apparently satisfactory operating installations).

And, finally, some general recommendations seem appropriate:

- Cost estimating accuracy is an essential aspect of successful commercialization; the development of appropriate costing methodologies should be emphasized in all future planning. Had the national and international energy environment remained stable, the financial crises of the early commercialization period (1963-1967) could well have caused the entire commercialization effort to fail.[1]
- Analyses of future energy requirements should include consideration of alternative futures, and programs should provide specifically for adjusting investments and goals to adapt to sudden or major changes in demand, price, or technology.
- Institutionally generated pressures for continued support of some special technologies should be discounted in evaluating the need for and feasibility of various approaches; functional rather than institutional budgeting may be most appropriate for technologies approaching the commercialization phase.
- The development of a complex technological system requires *balanced* effort in all of its principal elements.

To the extent that the commercialization of the LWR was successful, it succeeded because early uncertainties were reduced sequentially by experiment rather than by administrative fiat, and because it survived the harsh test of the marketplace. That appears to be a principal lesson for the future.

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[1] But had cost estimating been more accurate, the utilities might never have committed themselves to the first "large" plants, and the vendors probably would never have offered attractive turnkey terms.

Appendix A

TECHNOLOGY: THE REACTORS AND THE PRINCIPAL VENDORS

Westinghouse, working from a base of knowledge accumulated in the naval reactors program, designed and built the first "full scale" nuclear power plant at Shippingport and, although thereafter participating in other reactor developments, remained committed to the pressurized water reactor design. The first true member of the Westinghouse series of PWRs was Yankee (185 MWe), with a nuclear steam supply system (NSSS) distinguished from that of Shippingport by an improved core design (low enrichment uranium dioxide clad in stainless steel rather than a highly enriched seed with a natural uranium blanket), the use of boron in solution in the reactor coolant (for cold shutdown), and magnetic jacks in place of earlier control rod drives. The steam generators, with vertical U-tubes, improved on earlier naval reactor designs, permitting arrangement of the NSSS within a single containment building (in contrast to the multiple structures at Shippingport).

Yankee and several other early Westinghouse reactors experienced fatigue failures of supporting structures that incurred unforeseen flow-induced vibrations. Extended shutdowns were required for repair or modifications.

Following Shippingport and Yankee, Westinghouse designed and built a succession of plants with increasing power rating and evolving technology. (See Table A.1.)

San Onofre and Haddam Neck (also called Connecticut Yankee) were nearly concurrent and basically similar plants improved from Yankee by better thermal features, pumps, and other details. The use of rod-cluster control rods without followers reduced the power peaks associated with earlier cruciform control plates and permitted the use of a much shorter reactor pressure vessel. The walls of fuel element cans were removed, since they were no longer required as control element guides, with consequent improvement in neutron economy. The larger number of small absorber elements more effectively distributed through the core, together with new in-core instrumentation, resulted in better

Table A.1

WESTINGHOUSE PLANTS--PWR

Plant	Start Year	Operating Year	Elec. Power	Thermal Power	Efficiency	Height	Core Diameter	Volume	Fuel Inventory	Power Density		Burn-up	No. of Loops
			MWe	MWth	%	m	m	m^3	tonnes	kw/l	kw/kg	MWd/te	
Shippingport	1955	1958											
Yankee (Rowe)	1957	1/61	185	600	30.8	2.3	1.9	6.5	20,700	92	28.9	25,000	4
Haddam Neck	1/64	1/68	600	1825	32.7	3.07	3.03	22.3	75,000	82	24.3	30,000	4
San Onofre	5/64	2/68	450	1350	33.4	3.07	2.82	19.0	57,000	71	23.6	30,000	3
R. E. Ginna	2/64	5/70	470	1520	30.9	3.66	2.44	17.2	52,000	88	27.0	29,000	2
H. B. Robinson 2	4/67	1/71	730	2200	33.1	3.66	3.04	26.6	71,400	83	30.8	31,000	3
Surry 1	4/68	10/72	820	2440	33.6	3.66	3.04	26.6	70,000	92	34.8	31,000	3
Zion 1	2/68	8/73	1050	3250	32.2	3.66	3.55	35.6	99,000	91	32.8	22,000	4
Trojan	10/69	9/75	1130	3425	33.0	3.66	3.45	34.2	101,000	100	33.8	24,000	4
Callaway City 1 (SNUPPS)	1976	1982	1150	3425	33.6	3.66	3.45	34.2	95,000	100	36.0	25,000	4
South Texas	1976	1982	1250	3800	32.9	4.27	3.45	39.9	110,000	100	34.5	25,000	4

MWe = Megawatts electric
MWth = Megawatts thermal
m = meters
m^3 = cubic meters

tonnes = metric tons (1000 kg)
kw/l = kilowatts/liter
kw/kg = kilowatts/kilogram
MWd/te = Megawatt days/metric ton

thermal performance of the core and improved fuel management over the life of the core.

Some of these novel features proved difficult to perfect and delayed commercial start-up. The new reactor coolant pump seals failed repeatedly during initial testing at the plant. Early operation of San Onofre was delayed by a major failure of control wiring due to overheating and a resulting fire--an example of the numerous difficulties with nonnuclear equipment on the periphery of the NSSS that from time to time caused extended outages.

The R. E. Ginna, Point Beach 1, and H. B. Robinson 2 plants were nearly contemporary. The primary system loops had a near-standard configuration, which did not change greatly thereafter. Zircalloy-4 cladding was used rather than the stainless steel typical of earlier plants. The difficulties encountered in those plants were partly associated with some of the technological advances. Steam generators experienced stress-corrosion cracking of tubes and failure of major structural elements (later attributed to manufacturing problems with increasingly large components). The fuel elements suffered from fuel-cladding interaction and wall collapse; redesigned fuel cores with higher density fuel pellets and internally pressurized fuel rods were used in later reloads.

More recent Westinghouse plants have identical NSSSs and nearly identical balance-of-plant designs. Fuel elements were changed to lessen the potential damage from a loss-of-coolant accident, and thermal shields (which failed during service in earlier plants) were replaced by neutron shield pads. A variety of other improvements to increase reliability and availability were made as operating experience with earlier plants accumulated. Later design improvements concentrated on reducing refueling time requirements, the principal contributor to scheduled outages in modern plants.

The General Electric Company, the larger U.S. supplier of conventional utility equipment, was already involved in the nuclear field in a major way when the Atomic Energy Act of 1954 went into effect. The firm had operated the plutonium-producing reactors at the Hanford Engineering Works since the end of World War II and developed and built submarine propulsion reactors for the Naval Reactors Branch.

The first General Electric approach to civilian nuclear power was an aborted effort to develop an intermediate-spectrum plutonium-breeding power reactor, expected to have good nuclear performance and high thermal efficiency. When new nuclear data showed that approach to be impractical, General Electric turned to other reactor systems, including a variant of the Hanford graphite-moderated plutonium production reactor cooled by pressurized light water in zirconium alloy pressure tubes, and subsequently the boiling water system.

The boiling water reactor, under development at Argonne National Laboratory, had progressed through various stages to the Experimental Boiling Water Reactor. Because of its implications for submarine propulsion, PWR technology was still largely classified, but General Electric had ready access to BWR technology.

In 1954, General Electric responded to a request from Commonwealth Edison (Chicago) with two proposals, one for a pressurized, graphite-moderated, water cooled reactor, another for a boiling water reactor, which the utility selected. That action, the agreement to build what became Dresden I, settled General Electric's nuclear future. The GE commitment to the BWR appears to have been based on three primary considerations: attractive technical features (simplicity, lower reactor pressure, and thinner pressure vessel wall thickness for a given turbine inlet pressure); availability of a substantial technical base in the continuing development program at Argonne; and the customer's preference.

Dresden itself was intended to be an initial demonstration, not necessarily a full commercial plant. Once Dresden began, General Electric undertook a major effort to develop larger, economically competitive BWR plants by the late 1960s. A comprehensive, orderly development program, called Operation Sunrise, became General Electric's preferred device for seeking that end.

The evolution of the LWR system could have proceeded along any of several parallel or alternative technical design paths. Sunrise was to be a program for parallel exploration of those paths through reactor experiments or pilot plants, evolutionary or demonstration plants, and finally a "target plant" large enough and advanced enough in performance to be cost competitive with fossil-fuel plants in some areas.

The developmental and evolutionary stage plants were intended to be "small," to keep the total program costs down. Because of their modest size (less than 200 MWe) and because of the higher costs associated with novel components, General Electric did not expect those plants to be economically competitive power producers. Perhaps because of that, the utility industry proved most reluctant to participate in Project Sunrise.

After Dresden, General Electric built Humboldt Bay, the only natural circulation reactor (without primary pumps) and the first to use a pressure-suppression pool as part of the containment system. The next BWR, Big Rock Point, had a very high power density and forced circulation, providing a very useful testbed for further development and demonstration of zirconium-clad oxide fuel. Owing to the absence of utility support, the hoped-for evolutionary plants in the Sunrise series were never built.

Having been unsuccessful in inducing the utility industry to support the Sunrise program, General Electric concluded that its best chance lay in selling a target plant--a fairly large installation that could compete directly with fossil-fuel plants. Oyster Creek was the result.

The Oyster Creek plant incorporated a direct-cycle boiling reactor. The dual cycle had been used in Dresden because General Electric was not then certain of assured reactor stability in a large (200 MWe) direct-cycle installation. All the Sunrise alternatives to forced circulation were dropped from further consideration.

The principal new technical features of Oyster Creek were its size (600 MWe), its use of forced circulation with five loops, the use of pressure suppression containment, and--for the first time--a fairly extensive group of emergency core cooling systems (ECCS).

Table A.2 lists important characteristics for a succession of General Electric BWR designs as they evolved between 1955 and 1972. Progress was substantial. Output and efficiency grew, the specific power in the fuel increased twofold, power density in the core nearly doubled, expected burn-up attainable from the fuel more than doubled, fuel center line temperature was reduced, and the heat transfer system was vastly simplified.

Table A.2

GENERAL ELECTRIC PLANTS--BWR

Plant	Start Year	Operating Year	Elec. Power	Thermal Power	Efficiency	Height	Core Diameter	Volume	Fuel Inventory	Power Density		Burn-up	No. of Loops
			MWe	MWth	%	m	m	m^3	tonnes	kw/l	kw/kg	MWd/te	
Dresden 1 (BR-1)	2/57	6/60	210	690	30.4	2.7	3.3	23.1	57,600	33	12.0	12,000	4
Oyster Creek (BR-2)	3/64	12/69	670	1930	34.7	3.66	4.07	47.6	125,000	40	15.5	15,000	5
Quad Cities (BR-3)	3/66	1/73	850	2510	33.8	3.66	4.82	67.0	155,000	39	16.2	19,000	2
Brown's Ferry 1 (BR-4)	2/67	7/74	1100	3290	33.4	3.66	4.82	67.0	169,000	49	19.5	19,000	2
La Salle 1 (BR-5)	2/71	1979	1120	3290	33.8	3.66	4.78	65.5	149,000	50	22.1	27,600	2
Perry 2 (BR-6)	10/74	1980	1250	3580	35.0	3.76	4.65	62.5	138,000	57	26.0	28,000	2

MWe = Megawatts electric
MWth = Megawatts thermal
m = meters
m^3 = cubic meters

tonnes = metric tons (1000 kg)
kw/l = kilowatts/liter
kw/kg = kilowatts/kilogram
MWd/te = Megawatt days/metric ton

Such developments and plant rating increases were also accompanied by responses to the growing requirements for more extensive nuclear safeguards: redundant high pressure core sprays, coolant injection systems, automatic depressurization valves, and large feedwater storage systems. Improved containment structures had elaborate provisions for assuring leak-tightness.

The General Electric experience seemed to demonstrate that a determined developer who was not too sensitive to the cost uncertainty associated with high-risk plant programs could build a succession of increasingly large, increasingly complex nuclear power plants without having to invest in a series of exploratory plants. But it is also apparent that General Electric lost between $500 million and $750 million on its first set of seven turnkey plants, a sum that might be described as the price of forcing entry to a field in which a major competitor had an apparent technical advantage derived from a succession of increasingly larger plants.

Combustion Engineering, a traditional supplier of fossil-fueled boilers for the utility industry, built such major components as reactor pressure vessels in the early 1950s but avoided greater involvement until 1959. In that year, C-E acquired General Nuclear Engineering, a small firm founded by Walter H. Zinn, who had previously been director of Argonne National Laboratory and who had pioneered the development of the BWR there. But not until 1966 did C-E sell a complete NSSS--the 820 MWe PWR of the Palisades plant (Consumers Power Company), in Michigan.

C-E, with Zinn as vice president for nuclear activities, somewhat ironically chose to build PWRs. The choice, made after extensive studies of both systems, was apparently based on the conviction that the PWR would be more reliable, freer of corrosion problems, and face less difficulty from water radiolysis and radioactive gas effluents than the BWR.

In order to be competitive, C-E had to enter the field by way of a large (820 MWe) first plant and thus was unable to benefit from small-scale projects of the sort GE and Westinghouse had experienced. The NSSS provided by C-E was not novel. C-E tended to favor larger control rods than Westinghouse and to make all core internals from Zircalloy to maximize neutron economy. C-E plants had two steam generators, which increased in size as the plant rating grew. (See Table A.3.)

Table A.3

COMBUSTION ENGINEERING PLANTS--BWR

Plant	Start Year	Operating Year	Elec. Power	Thermal Power	Efficiency	Height	Core Diameter	Volume	Fuel Inventory	Power Density		Burn-up	No. of Loops
			MWe	MWth	%	m	m	m^3	tonnes	kw/l	kw/kg	MWd/te	
Palisades	2/67	2/72	788	2200	35.5	3.48	3.35	30.7	84,000	72	26	26,000	2
Maine Yankee	11/68	1/73	860	2440	35.3	3.6	3.5	34.6	87,000	71	28	30,000	2
Calvert Cliffs	7/68	1975	845	2560	33.0	3.5	3.5	32.5	83,000	79	30		2
Arkansas One-2	1/72	2/78	925	2760	33.5	3.81	3.45	35.5	87,000	78	32	33,000	2
San Onofre 2	6/74	6/80	1140	3390	33.7	3.81	3.45	35.5	89,000	95	38	34,500	2
Pilgrim 2	1974	1982	1150	3460	33.6	3.81	3.45	35.6	93,400	97	37	31,000	2
Palo Verde 1	1975	8/82	1300	3800	34.2	3.81	3.63	39.4	99,300	96	38	33,200	2

MWe Megawatts electric
MWth = Megawatts thermal
m = meters
m^3 = cubic meters

tonnes = metric tons (1000 kg)
kw/l = kilowatts/liter
kw/kg = kilowatts/kilogram
MWd/te = Megawatt days/metric ton

The firm of Babcock and Wilcox was the largest supplier of fossil-fueled boilers in the United States and built steam generators and pressure vessels for the early experimental reactors but initially had no major prime role in power reactor development. The first large Babcock and Wilcox utility project was quite unconventional. Although the Indian Point 1 plant for Consolidated Edison, started in 1957, was a PWR, it was based on a uranium-233, thorium fuel cycle, and was coupled to an oil-fired steam superheater. The thorium-uranium cycle was chosen because it offered the prospects of better neutron economy than the low-enrichment uranium cycle adopted for other LWRs. The advantage proved, in time, to be illusory, and Indian Point 1 was converted to a simple enriched-uranium-fueled PWR.

After Indian Point 1, Babcock and Wilcox made no utility offers for some years. In the interim, the firm actively pursued another advanced cycle, the "spectral-shift" reactor, which used a varying mixture of heavy and light water as the moderator, again with the goal of improved neutron economy and accompanying fuel cycle benefits. Although this system was supported to a limited extent by the AEC, it never attracted utility interest, probably because of its complexity. Concurrently, Babcock and Wilcox participated actively in the development of the PWR for the nuclear powered *Savannah*, later working on other advanced maritime reactors. The second Babcock and Wilcox sale was the 900 MWe Oconee 1 plant for Duke Power, intended to be the first of three identical units.

The Babcock and Wilcox plants are generally similar to other PWRs. Perhaps their outstanding unique feature is the steam generator, which is of the once-through rather than recirculation type. A once-through system permits some steam superheat even though the reactor outlet temperature is not raised; this results in a modest increase in turbine cycle efficiency.

Appendix B

FUEL CYCLE COSTS

Fuel costs have been assumed to be small and constant, and operating and maintenance costs have been assumed to be the smallest contributor to the electricity costs and to have the least potential for variation. But the circumstance that fuel costs were small and fairly constant in the past is no guarantee that they will remain so.

Figure B.1 is a diagram of the nuclear fuel cycle for a 1000 MWe LWR. The steps shown may be aggregated into five categories:

1. Yellowcake cost (includes mining and milling)
2. Conversion
3. Enrichment
4. Fabrication (includes fuel preparation)
5. Recovery (includes shipping, reprocessing, reconversion, and waste disposal).

The sum of these five costs equates to the fuel cycle cost if no credit is assumed for the sale of by-product plutonium to the government. For the purposes of demonstrating cost sensitivity to the fuel cycle, the sale of plutonium is not assumed. However, at the present purchase price of $7.50 per gram, the sale of plutonium reduces the cost of the electricity by about 0.25 mills per kilowatt hour. To demonstrate the sensitivity of electricity costs to variables in the fuel cycle, cost estimates for an LWR scheduled for initial operation in 1980 have been selected. These estimates have included the best judgments of the most probable cost of each segment of the fuel cycle, and have also included a high variant case. Table B.1 lists these costs for each of the five major categories. Using the estimated probable costs, the total cost of electricity is 34.3 mills per kilowatt hour, of which the fuel cycle costs represent 4.33 mills or 12.6 percent. When the high variant costs are substituted, the cost of electricity becomes 38.28 mills per kilowatt hour, of which 8.31 mills, or 21.7 percent, arise in the fuel

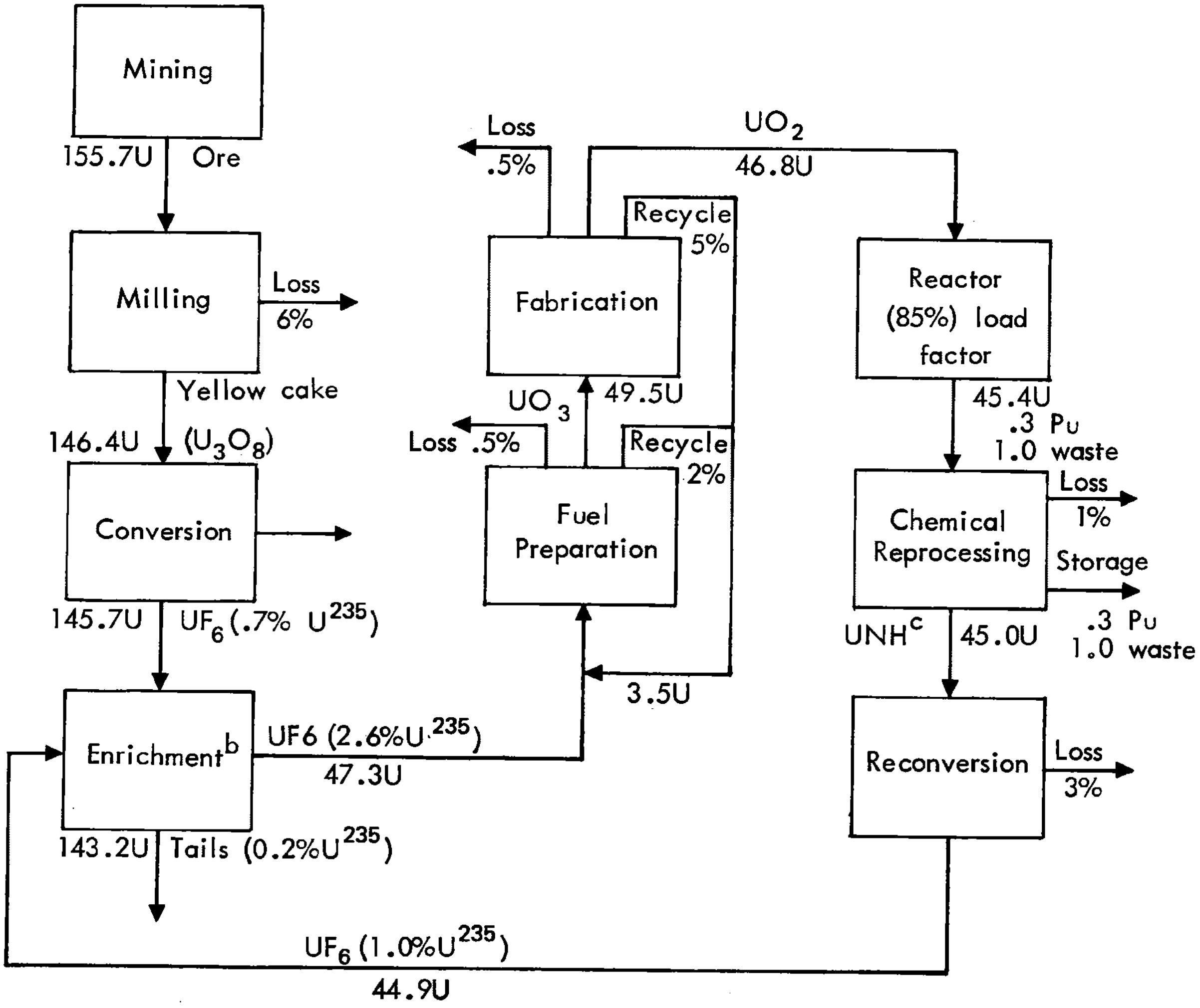

Fig. B.1 — Equilibrium fuel cycle flows for a typical 1000 mW LWR (Without Pu recycling)[a]

[a] Flow volumes are stated in metric tons of contained U or Pu per year and pertain to the pressurized-water type of LWR.

[b] Separative work equals 139.4 MT/yr for the feed and tails assays shown.

[c] $UO_2(NO_3)_2 \cdot 6H_2O$.

SOURCE: WASH-1099.

Table B.1

ESTIMATED UNIT COSTS FOR FUEL CYCLE

Item	Cost, $ Per	Estimated Costs per Unit, 1980 Dollars	
		Probable	High Variant
Yellowcake	Pound	21.00	65.00
Conversion	Kilogram uranium	3.75	7.20
Enrichment	Separative work units	90.00	130.00
Fabrication	Kilogram uranium	100.00	169.00
Recovery	Kilogram heavy metal	132.00	205.00

Table B.2

EFFECT OF CHANGES IN THE COST OF FUEL CYCLE SEGMENTS

Item	Probable Cost, Mills/kwh	Energy Cost, if Segment Cost Doubles	% Increase	Energy Cost, with Segment Cost Increasing Tenfold	% Increase
Yellowcake	1.07	35.37	3.12	43.93	31.2
Conversion	0.07	34.37	0.20	34.93	2.0
Enrichment	1.69	35.99	4.92	49.51	49.3
Fabrication	0.67	34.97	1.95	40.33	19.6
Recovery	0.83	35.13	2.42	41.77	24.2
Total	4.33	38.63	12.60	73.27	126.3

cycle. The substantial increases in each segment of the fuel cycle cause only about a 12 percent increase in the cost of generated electricity because the fuel cycle is only a small fraction of the total costs. This sensitivity is analyzed further in Table B.2, where the result of first doubling, then increasing *tenfold*, each of the five segments of the fuel cycle is estimated. The information presented in Table B.2 further attests to the insensitivity of the costs of electricity to the fuel cycle. Increasing the cost of each segment of the cycle to ten times original value only causes the electricity cost to slightly more than double. Large uncertainties may indeed characterize the costs of individual segments of the fuel cycle, but changes in these costs are not likely to cause substantial increases in the cost of the electricity that is generated.

Appendix C

OPERATING EXPERIENCE

By March 1976, 52 light water reactors were in commercial operation in the United States. Operating experience had been complex and varied. Numerous plants had experienced extended shutdowns for modification or repair. Nevertheless, the summary operating statistics are rather useful. A measure of the performance of the NSSS itself is the reactor availability factor, defined as the ratio between the number of hours the reactor is available to provide power and the hours in the period. Cumulative reactor availability (Fig. C.1) falls in a band centering about 75 to 80 percent. Considering the scatter of the data, there seems to be little difference between the reliability of the BWR and the PWR, nor does the reliability appear to have changed observably during the decade that large plants have come into operation.

The availability of the entire unit generally runs about 5 percent below that of the reactor itself, and the capacity factor (the actual generation divided by the maximum dependable capability) is generally about 10 percent lower yet.

Larger, newer fossil plants have lower availability than similar smaller units, and their capacity factor is also lower. The availability and capacity factor of the nuclear plants has become equivalent to that of contemporary large fossil plants.

Nuclear plants have regular, fairly extended planned shutdowns for refueling and concurrent other planned maintenance, but refueling shutdowns tend to be more protracted than those required for maintenance of fossil plants. The forced outage rate, as differentiated from these scheduled outages, is shown in Table C.2 for both types of plants.

The decreasing reliability of fossil plants may be due to their increasing size, or it may be related to the fact the the larger plants are generally those more recently installed. The reliability of the reactors seems to be somewhat better than the reliability of the modern, large fossil boilers they replaced in generating stations.

Table C.1

POWER PLANT RELIABILITY
1965-1974
(percent)

Plant	Operating Availability	Capacity Factor
Fossil		
130 - 199 MWe	84.3	72.5
200 - 389 MWe	81.7	71.1
390 - 599 MWe	74.9	63.4
> 600 MWe	65.2	58.1
Nuclear		
all	68.9	59.6

Source: Edison Electric Institute, 1975.

Table C.2

FORCED OUTAGE RATE
(percent)

Plant	Boiler/Reactor	Turbine	Generator	Total
Fossil				
130 - 199 MWe	2.5	0.6	0.2	3.6
200 - 389 MWe	3.6	1.0	0.3	5.3
390 - 599 MWe	5.6	2.5	0.8	9.5
> 600 MWe	9.3	3.4	3.5	15.8
Nuclear				
all	6.5	3.2	0.8	11.4

Appendix D

NUCLEAR PLANT SAFEGUARDS

The evolutionary growth of the LWRs in rating and operating characteristics was attended by the addition of a group of plant features together called the "engineered safeguards."

The defense-in-depth design philosophy of U.S. reactors extended to three levels of safety: (1) highly reliable, prudently designed systems for safe normal operation; (2) numerous, redundant instrument channels and associated reactor control systems leading to safe shutdown under abnormal conditions; and (3) a variety of features to mitigate an accident and contain its consequences if the first two levels both failed in their intended purpose.

The complex of engineered safeguard features of a typical LWR thus includes:

- a system for rapid shutdown of the reactor (SCRAM);
- a system for assuring that the reactor core can continue to be cooled (ECCS);
- systems for cooling and reducing the pressure in the containment vessel after an accident;
- systems for removing radioactivity from the containment atmosphere; and
- a containment structure that prevents release of radioactivity to the environment.

The earliest approach to safeguard against a reactor accident was largely based on remote siting. In the late 1940s the AEC used a formula that evidently required an exclusion distance of 5.5 miles (an area of some 15000 acres) for a 100 MWe plant.

The concept of exclusion distance was replaced by the concept of tight containment. The first such structures were the steel sphere for the West Milton SIR naval reactor and the multiple structures for the steam generators and the reactor at Shippingport.

The first demonstration plants (Indian Point 1, Dresden 1, and Yankee) were housed in steel-lined containment structures designed to withstand the consequences of a large primary system rupture. To limit the internal pressure after an accident, external or internal containment cooling systems were provided--spray systems to cool the exterior of the containment structure or water coolers and fan systems within the structure. Beginning with Humboldt Bay, all BWR plants included some type of pressure suppression pool to absorb the energy and contain the steam pressure resulting from reactor depressurization. The PWRs relied on either internal sprays or ice condensers for pressure suppression and energy absorption.

The building atmosphere control grew to include chemical additions to the building spray systems (particularly to cope with radio-iodine release in the event of an accident), systems from reducing hydrogen concentrations before combustible limits were reached, and charcoal trap hold-up systems to slow the rate of release of non-condensible radioactive gases.

The first element of an emergency core cooling system, beyond the normal multiplicity of primary coolant systems, which all the reactors had, was provided for Dresden 1: a spray system located in the pressure vessel immediately above the core, fed from three pumps large enough so that only two would serve emergency needs. All plant designs included some version of a coolant "make-up" system that could cope with small leaks.

As commercial LWRs began a rapid growth in power ratings in the mid-1960s, the AEC became concerned about the adequacy of containment structures in the event of a major loss-of-coolant accident (LOCA) and an ensuing core melt-down. In 1967 the "Ergen Committee" concluded that a molten (and possibly dispersed), large high-power-density core was likely not to be containable. An emergency core cooling system (ECCS) was deemed necessary to ensure core integrity in the event of rupture in the main coolant piping and to provide continued heat removal capacity after the accident.

The Ergen report and subsequent AEC regulations led to significant improvements in the ECCS of the larger nuclear power plants. The hypothetical accident against which protection had to be provided was a double-ended failure of a main primary pipe at the most disadvantageous point in the loop. As the systems evolved, the major improvements included: (1) increasing the quantity and rate of coolant injection into the reactor vessel following a LOCA; (2) assuring reliable energy supply to all active ECCS components from either on-site or off-site power sources; (3) providing redundant instruments and components for the core cooling function; and (4) protecting the core intervals and other critical systems from damage following postulated pipe rupture.

By the 1970s, all PWR and BWR nuclear power plants had been equipped with ECCS in addition to earlier engineered safeguards. A PWR emergency core cooling system typically included numerous independent passive and powered coolant supplies. In the event of a large primary system rupture, coolant would first be injected into the core, during the "blow-down" phase, from separate nitrogen pressurized accumulator tanks, one for each loop. Redundant high-pressure low-flow coolant injection systems would supply make-up coolant if the leak were small and reactor pressure did not fall appreciably. Redundant high-flow low-pressure systems would continue to pump water through the core after the blow-down phase of a large rupture.

The BWR ECCS was similarly composed of numerous redundant elements. Emergency coolant, after a break in the main recirculation pipe, was provided from the feedwater system, the high pressure core spray, two low pressure core sprays, and a low pressure coolant injection system. An automatic reactor depressurization system assisted coolant injection systems.

Such engineered safeguards evolved as a part of the design progress on both LWR types. Earlier plants were retrofitted as additional requirements were imposed by AEC regulations. However, the adequacy of such provisions for emergency cooling continued to be questioned in the late 1960s, so in 1971 the AEC--after extensive hearings--promulgated a still more conservative set of acceptable criteria for the design and performance of the ECCS. Although manufacturers and operators insisted that the LWR designs satisfied such criteria, opponents of nuclear power remained unconvinced. Their chief contention has been that the computer routines used to calculate ECCS and core behavior were of dubious validity in the absence of adequate experimental verification.